Essays on Trade and Environmental Policy

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Contents

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Abstract

Recently, a border carbon adjustment (BCA), which is a type of the tariff, has received attention, as the European Commission plans to impose them on countries that do not make efforts to decrease their greenhouse gas emissions. Since governments cannot regulate foreign countries' carbon emissions directly, border carbon adjustment can act as an alternative policy. In this dissertation, I explore the possible effects of the BCA based on a trade model, check the effects of a unilaterally stricter environmental policy, and lastly examine a trade policy that considers local pollution.

In the first chapter, I explore the effect of a carbon tax and BCA on exports, technology adoption, welfare, and emissions under the asymmetric heterogeneous trade model of Melitz (2003). Specifically, to solve the asymmetry in the variable costs due to the environmental policy, I use the graphical analysis method in Unel (2013), following a similar setup to that of Cui (2017). As well as calibrating the model, I achieve several results with welfare and policy implications. First, the model suggests that firms in both the home and foreign country tend to adopt high technology because of the home country's stricter environmental policy, and the imposition of BCA stimulates this technological upgrade further for the home country. Second, as a result of a higher emission tax, the home country is worse off from consumption, whereas the foreign country can enjoy higher welfare from its consumption. The imposition of BCA can alleviate this by leveling the playing field. Third, the home country's unilateral higher emission tax turns out to reduce the home country's emissions, mostly from the 'mass effect' and the 'price effect.' Part of this reduction is offset, however, by 'carbon leakage' from an increase in foreign exports. The BCA effectively counters this 'leakage problem,' but it relocates the emissions back to the home country, and thus the total emissions increase slightly. While it is hard to rationalize BCA from an environmental perspective, the home country can still have enough incentive to impose a BCA, since it can help to restore the home country's competitiveness, which is linked to the recovery of the utility from consumption.

In the second chapter, I test the effect of a unilaterally stricter environmental policy. Korea accounted for about 1.6% of the world's GHG emissions between 2000 and 2019 and ranked seventh

(600 $MtCO_2$) in terms of CO_2 emissions in 2017. Considering the high level of industrial emissions and the increased concerns about climate change, Korea has adopted both a target management system (TMS) and an emission trading system (ETS) to reduce GHG emissions. Compared to TMS, which is regarded as a preparatory stage, an ETS system is regarded as more genuine in Korea, so I test the effect of the ETS on both GHG emissions and economic performance. Using firm-level data, I find that both GHG emissions and revenue decreased for business-reporting firms after the introduction of an ETS, but they did not decrease for facility-reporting firms. This is related to the firm size: as more facility-reporting firms are small, they relied more on the purchase of allowances rather than investing in measures to reduce emissions. In terms of exports, I could not find a significant decrease attributable to ETS regulation or evidence of the 'pollution haven hypothesis.'

In the third chapter, I explore tariff decisions based on the political economy model when a country considers local pollution. I extend Grossman and Helpman's (1994, 1995) 'Protection for Sale' model to incorporate the externalities in consumption and product regulation. As I add externalities and regulations, optimal tariffs become higher than in the original model, and domestic regulations are determined by the political economy considerations.

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CHAPTER 1

Introduction

The seriousness of global warming is beyond doubt,[1] and the first-best policy for global warming is to impose the Pigouvian tax on all greenhouse gas emissions, which is set to be the marginal social cost of a unit of greenhouse gas emission. However, it is hard to draw an agreement across countries to impose the Pigouvian tax for several reasons.[2] Barrett (2005) explains these by contrasting the differences between the Montreal Protocol, which was successful in preventing the use of ozone-depleting substances, and the Kyoto Protocol (and following Paris Agreement), which deals with the climate change problem. The global warming and ozone layer depletion problems have the common properties of global pollution, but they are quite different in their details.

1.1. Global Warming and Ozone Depletion Problems

First and foremost, the marginal damage of climate change is different across countries and regions. This heterogeneous aspect of climate change is well addressed in Alvarez and Rossi-Hansberg (2021). They showed that in extreme cases, the currently cold regions can get some benefits from global warming, although other regions, such as the oceanic regions, will suffer more. Therefore, this heterogeneity of damage is the first hurdle to cooperation among countries. On the contrary, ozone layer depletion has a direct effect on human health, such as causing cancer and even death from exposure to UV radiation, and this effect is almost uniform across regions.

In addition, the abatement cost of ozone layer–depleting substances is lower than that of greenhouse gases, and the benefit of preservation of the ozone layer is huge and direct. With the relatively

[1] According to the Intergovernmental Panel on Climate Change (IPCC, 2018), a $1.5°C$ increase in the average temperature above the pre-industrialized level can be lethal, and at present, it is around $1.0°C$ above (range of $0.8°C$ to $1.2°C$). IPCC expects that if the current trend of greenhouse gas emissions continues, the temperature rise will reach $1.5°C$ between 2030 and 2052.

[2] Weisbach et al. (2020) stated that *"Global climate negotiations have given up trying to achieve a uniform approach to climate change, such as a harmonized global carbon tax. Instead, current negotiations focus on achieving uniform participation, with each country pursuing its own approach and its own level of emissions reductions."*

lower cost, the incentive to free-ride for ozone layer protection is lower. Therefore, under the Montreal Protocol, countries had enough unilateral incentive to decrease the use of ozone depleting substances. In addition, the Montreal Protocol had strategic features which helped the success of the protocol, such as the subsidy to developing countries that did not have enough capacity to implement it and the credible threat of reducing trade with the countries that did not participate.

On the contrary, the damage from global warming appears in the long term, and the negative effects are relatively slow, but the costs of reducing greenhouse gases (GHGs) are huge compared to the preservation of the ozone layer. Therefore, it is not easy to draw a complete compromise between countries. In the Kyoto Protocol, each country could set its own emission cap, which is called 'pledge and review,' so it is hard to make stricter pledges to prevent climate change. In addition, the protocol does not have enough incentive mechanisms to enforce compliance like the Montreal Protocol. The United States' decline to ratify the Kyoto Protocol and its withdrawal from the Paris Agreement in 2020 show well the fragility of this type of agreement.[3]

To supplement the weakness of the limitation of this 'pledge and review' method, other legally feasible efforts have been explored, which accompany the unilateral domestic efforts, in practical sectors and academia. Among them, Weil (2018) proposes four policy alternatives. The first one is 'strategic emissions abatement policies,' which means that the active participating countries condition their reduction pledges on other countries' emission levels. The second is to link these GHG reduction efforts to other geopolitical issues like trade. The idea of the carbon tariff or border carbon adjustment (BCA) belongs to this category. The next one is the introduction of 'globally harmonized carbon pricing,' and the last one is establishing a 'sovereign global climate authority' whose decisions each country must follow.

1.2. Pros and Cons of the BCA

The pros and cons of the BCA are well summarized in Böhringer et al. (2016). They find the grounds which rationalize the BCA as follows. The first one is that the BCA can act as the second-best policy to prevent carbon emissions, which contribute to global warming and threaten

[3]The US withdrew from the Paris Agreement in 2020 (Matt McGrath, "Climate change: US formally withdraws from Paris agreement," BBC, 2020 Nov. 4) and later rejoined the agreement under the next administration (Veronica Stracqualursi and Drew Kann, "US officially rejoins the Paris climate accord," CNN, 2021 Feb. 19).

people's health. As governments cannot regulate the carbon emissions of foreign countries directly, the BCA can act as an alternative, even though it is not the first-best because it does not address the problem directly. Another merit of the BCA is that it is politically attractive because it can protect the import-competing industries. Import-competing industries can be disadvantaged if they are not under the same regulations as foreign exporters.

They also point out the practical problems with the BCA, such as the difficulties with controversies over calculating the level of tariffs. As supply chains today are long and complicated, it is hard to discern what fraction of carbon emissions is attributable to the country that will be charged with the BCA. It is also controversial whether the BCA is designed to be in accordance with GATT rules.[4] There is a possibility that a country facing the BCA may try to divert its exports to countries which do not impose the BCA. Then the effectiveness of the policy can be limited.

However, despite these controversies around the BCA, it turns out to be the most realistic policy alternative. Among Weil's (2018) alternatives, countries do not consider the first one, and the last two are more challenging than the first two. Considering the practical efforts so far, the carbon tariff or the BCA seems to be the most realistic policy option, and interest in the BCA has been spiked by the European Union's recent announcement that it will implement this policy soon.[5] Therefore, it is meaningful to check and analyze the economic effects of the BCA and to research the trade policy as a tool to counter the environmental problem.

This paper consists of three chapters. In the first chapter, I explore the effect of a carbon tax and a BCA on exports, technology adoption, welfare, and emissions under the asymmetric heterogeneous trade model of Melitz (2003). In the second chapter, I test the effect of the unilaterally stricter environmental policy using firm-level data from after the introduction of the Korean emission trading system. In the third chapter, I explore the tariff decision based on the political economy model when a country considers local pollution.

[4]There are some reviews about the legal issues of BCA. Helm et al. (2012) and Horn and Sapir (2013) argue that it is possible to design a WTO-compatible BCA by ensuring that the BCA is not used for protectionism. Balistreri et al. (2019) argue that the BCA can be consistent with GATT by the exceptions outlined in Article XX, especially covered by paragraph *(b) "necessary to protect human, animal or plant life or health"* or paragraph *(g) "relating to the conservation of exhaustible natural resources"*.

[5]The EU announced the 'European Green Deal' in July 2021, which is also called 'Fit for 55' because they are planning to reduce greenhouse gas emissions to 55% of 1990 levels. In this plan, they included steps to implement the 'Carbon Border Adjustment Mechanism,' a type of BCA.

CHAPTER 2

Border Carbon Adjustment (BCA) in the Heterogeneous Firms Trade Model

2.1. Introduction

In this chapter, I will explore the economic effects of the carbon tax and border carbon adjustment (BCA), which is a type of carbon tariff that applies the domestic carbon price to imports but does not include a rebate on exports.[1] BCA was adopted in the EU airline industry in 2012. Initially, every airline departing from or arriving to Europe had to have some carbon allowances, which could be traded in the EU emission trading system (ETS),[2] regardless of the airline's country. Although this application of EU ETS has been limited to the aviation within the EU area since 2016, this effort is regarded as a success because they induced a global measure, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), adopted by the International Civil Aviation Organization (ICAO).

Much research related to carbon tariffs analyzes the economic and environmental effects of the current system (especially focusing on the EU or, in the case of the US, California state, as the EU and California are the most active in trying to reduce greenhouse gases) and compares them

[1]Elliott et al. (2012) categorize three kinds of carbon tax systems. The first one is a production tax imposed on home production for carbon emissions. The second one is the border tax adjustment (BTA), which is basically a tax on carbon emissions for domestically produced goods with adjustments. The adjustments include a tax on imports from countries which do not impose the carbon tax or do not adopt any effort to reduce carbon emission. If the foreign exporting country adopts a lower carbon tax than the home country, the home country can impose the difference as an adjustment. It can also include a rebate to domestic firms for their exports to foreign countries which do not impose a carbon tax. Therefore, if this system includes the export rebate, it is like a carbon tax on domestic consumption and no carbon tax on foreign consumption. However, according to Cosbey et al. (2019), export rebates for a carbon emission trading system (ETS) can be considered as prohibited export subsidies, so in this paper, we excluded these rebates. The last system is a tax on extracting fossil fuels.

[2]The ETS is a market for allowances, so it is not the same as a carbon tax, but as buying allowances also levies a burden on the firms, in this paper, I use them interchangeably. ETS works based on the *'cap and trade'* principle (European Commission, https://ec.europa.eu/clima/policies/ets_en, visited on Mar. 31, 2020). A cap is a total amount of a type of greenhouse gases, set by the EU. At the beginning, firms receive some allowances to emit, and then this permit can be traded on the market. The cap decreases over time, so firms should reduce their emissions accordingly. If a firm can succeed in reducing its emissions enough, it can save its allowances for future emissions or sell them on the market. If it fails, it should pay some cost to buy more allowances.

with the effects of the other policy alternatives. Many of them focus on the role of carbon tariffs as a solution to the problem of 'carbon leakage.' 'Carbon leakage' means that the decrease in carbon emissions because of the measures taken in one country is offset by an increase in carbon emissions from the foreign countries which do not impose such restrictions.[3] Fowlie (2009) found that there is substantial greenhouse gas emission leakage in California's electricity sector because of the exemptions for out-of-state producers. However, in the survey of Zachmann and McWilliams (2020), it is hard to observe severe leakage problems because of the EU's current environmental policies. This is mainly because the portion of carbon tax is relatively small among the operating costs. Zachmann and McWilliams (2020) points out that there are many factors other than carbon price which determine the competitiveness of an industry, such as infrastructure, geography, raw materials, and labor availability. Based on this, we can think that Fowlie (2009) could have gotten different results because she examined interstate leakage. We can expect the competitiveness factors to be similar in the same country.[4]

Even though the current carbon tax burden is not high enough to cause severe emission leakage across countries, we can expect that the situation can change in the future. The damage from climate change and the cost of reducing additional greenhouse gas emissions are expected to rise.[5]

[3]Under the condition that the carbon pricing system varies across countries, there can be a problem of carbon leakage. Zachmann and McWilliams (2020) explain that there are direct and indirect leakage channels. The direct channel also has two avenues, the 'pollution haven' hypothesis and the 'Porter hypothesis.' The 'pollution haven' hypothesis means that as the EU imposes a higher carbon price domestically, the EU can decrease domestic carbon emissions, but this policy increases the imports of carbon-intensive goods from countries which have lower or no carbon prices. The 'Porter hypothesis' acts opposite to the 'pollution haven' hypothesis. Faced with a higher carbon price or higher environmental regulation, firms can innovate, thus improving their production process, using energy more efficiently, and reducing pollutants. The 'Porter' hypothesis thus reduces carbon emissions without carbon leakage, and if the technology is spread to foreign countries, it can reduce their carbon emissions too. Indirect leakage happens because of the change in the world price of fossil fuels. Domestic demand for fossil fuels decreases because of domestic measures to decrease carbon emissions; thus, the world price of fossil fuels decreases. Then, the foreign demand for fossil fuels increases, and foreign countries produce more energy-intensive goods.

[4]This is consistent with the survey by Cherniwchan et al. (2017), although they investigated the literature on whether the 'pollution haven effect' and 'pollution haven hypothesis' exist. The 'pollution haven effect' means that stringent environmental regulation weakens the comparative advantage in that country. In that survey, it is a settled question that this effect exists, but this effect is not large enough to change the flow of trade. The 'pollution haven hypothesis' means that environmental regulation changes the comparative advantage, so the country with the higher environmental regulation tends to reduce its production of pollution-intensive goods, and the country with lower environmental regulation tends to increase its production of dirtier goods. According to Cherniwchan et al. (2017), there is little evidence that trade liberalization has shifted the production of dirtier goods to lower-environmental-regulation countries.

[5]This is pointed out in much literature, such as in Kolstad and Toman (2005). The marginal cost of CO_2 emission reduction increases as the needed amount of reduction increases. As the amount of CO_2 accumulates, the effect of climate change becomes more apparent; for example, we witnessed increased flooding, melting glaciers, and wildfires in the late 2010s. As time goes by, the needed amount of reduction increases, thus increasing the reduction cost.

In this chapter, I will explore the economic effects of the carbon tax, whether the leakage problem exists, and if it exists, whether the border carbon adjustment can address the problem in the context of Melitz (2003)'s trade model.

2.2. Literature Review

Much research about the carbon leakage problem and the BCA uses the computable general equilibrium (CGE) model because the carbon leakage problem arises under the open economy, and the CGE model is good at capturing this global property of carbon leakage. Especially, it can consider not only the direct leakage problem but also the indirect leakage problem, as it considers the effects of the policies in a general equilibrium framework.

Balistreri et al. (2018) suspect that the reason why many CGE model-based analyses get low leakage might be a common assumption used in the model, which is the Armington trade model structure. They instead experiment with the impact of the unilateral imposition of carbon pricing under the CGE model using the Heckscher–Ohlin trade model structure and using Melitz (2003)'s monopolistic competition trade model structure. Then, they compare the results with those under the CGE model using the Armington trade model structure. They find substantial carbon leakage in the simulation under the Heckscher–Ohlin trade model structure and Melitz (2003)'s model structure, and especially, Melitz (2003)'s model structure showed the highest carbon leakage. Thus, they argue that the CGE models need to incorporate the recent developments in the trade theory, such as Melitz (2003)'s model structure, when conducting climate policy effect analysis.

Elliott et al. (2012) analyze the effects of a carbon tax and BCA to deal with carbon leakage. They employ a two-country, three-good CGE model to explain the economic logic of the BCA and simulate the effects. They find that the price elasticity of energy supply is important in carbon emissions. If it is low, a carbon tax and BCA have little effect on carbon emission and leakage, so when conducting carbon policy, it is important to pay attention to the energy supply. They also find that under the carbon tax levied on production using fossil fuels, the leakage rate is between 15% and 25%, where carbon leakage is defined as 'the increase in emissions in the non-taxing region as a fraction of emissions reductions in the taxing region.' Based on this, they simulate the effect of BCA and find that it could reduce carbon leakage substantially.

Balistreri et al. (2019) search for the optimal level of the BCA. They argue that the carbon price imposed on imports should be lower than the domestic carbon price. Balistreri et al. (2019) get this result based on Markusen (1975)'s model, which they extend by adding the GATT commitment constraint. By introducing this commitment, they remove the strategic incentive to distort the tariffs. However, their result contradicts the presumption of most BCA literature that carbon tariffs should be imposed at the levels that make the carbon prices at home and in foreign countries the same. This means that if the domestic carbon price is higher than that of a foreign country, the carbon tariff should be equal to the difference between them. The intuition behind their argument is based on the indirect carbon leakage channel that is mentioned above. If the home country is a large country, the carbon tariff reduces the domestic demand for the imports; then, the price of the goods decreases in the global market. As a result, the foreign consumption of carbon-intensive goods increases, offsetting the effectiveness of the carbon tariff. Thus, they argue that if we set the border carbon tariff as the difference between the domestic and foreign carbon prices, it is like we are seeking a term of trade gain using carbon tariffs, so the optimal level of carbon tariffs should be lower than that. They confirm this result in their CGE model simulation.

Because preventing climate change has a property of public good for each country, there is a problem of free-riding. If a country pays the abatement cost of greenhouse gases, the benefits are shared across the world. Thus, without proper agreements among countries, uncooperative results are more likely. Therefore, some literature pays attention to the indirect role of BCA so that countries can overcome this prisoner's dilemma and induce global cooperation to reduce greenhouse gases.

The idea of using carbon tariffs to change the trade partner country's behavior is already mentioned in Baumol and Oates (1988). They argue that if there are transnational externalities, threatening to impose tariffs or other sanctions like quotas or outright import prohibitions can be effective ways to induce the polluting countries to cooperate. Here, the affected commodities need not be the pollution-generating goods, so their idea is similar to that of Nordhaus (2015) in the next paragraph. They also emphasize the importance of the number of tariff-imposing countries, because the more tariff-imposing countries, the more pressure the exporting country will face, so it is more probable that they will take cooperative actions.

Nordhaus (2015) proposes a climate club as a solution to the global warming problem. In the climate club, countries should set their domestic carbon prices at least as high as the club's target price, which is set to effectively handle the problem. However, this can incur additional cost to the participating countries because when countries choose not to participate, they can set their carbon price at the minimum and can benefit by free-riding on the participants' efforts. Therefore, an international coalition without sanctions on non-participants can easily dissipate to the equilibrium where countries opt out of the club and try minimal abatement efforts. For the possible sanctions, Nordhaus (2015) first considers the carbon tariff, but it turns out to be less effective than a uniform tariff on all imports from non-participants. If the coalition uses a uniform tariff on all imports as a punishment, they could prevent a breakaway more effectively, even if at a low level around 2%. Thus, he argues that forming a climate club and punishing the non-participants with a uniform tariff is an efficient method to reduce greenhouse gas emissions.

Helm et al. (2012) suggest that we need to think about the carbon tariff differently from the conventional thought that it is a trade impediment. Instead, they argue that free trade without carbon pricing is like providing a subsidy to the greenhouse gas emitters. If we think this way, the absence of a carbon tariff induces 'too much' trade and carbon emissions, which reduces welfare. Using a simple political game theory model, they show that carbon tariffs or BCAs can lead countries without proper carbon pricing to introduce similar carbon pricing domestically or to participate in globally agreed measures to reduce greenhouse gas emissions. Therefore, under Helm et al. (2012)'s argument, even without the 'carbon leakage' problem, carbon tariffs can be used as a trigger for countries to take proper actions.

Böhringer et al. (2016) also focus on the role of carbon tariffs as a threat to induce the non-regulating countries to take actions to reduce greenhouse gas emissions. They divided countries into coalition (Annex-I countries, which agreed to abate greenhouse gas emissions under the Kyoto Protocol) and non-coalition countries. They set up a simultaneous game similar to Helm et al. (2012) and calculated the payoff of policy choices using the CGE model. In the Nash equilibrium, the carbon tariff threat was credible, and China and Russia (non-coalition and high GHG-emitting countries) would choose to adopt binding abatement targets.

On the other hand, there is some research that analyzes the relationship between trade and the environment based on Melitz (2003)'s trade model. The survey by Cherniwchan et al. (2017) introduces possible explanations by the extension of this model. Among them, Kreickemeier and Richter (2014) explains that the effect of trade on pollution can be described as having two channels. Trade liberalization improves the average productivity, and this higher productivity decreases pollution, but the 'scale effect,' which is the result of the increased production, raises pollution. The foreign country can also be influenced by the trade policy, so they show the possibility that even though domestic emissions can be decreased by trade, total emissions can increase.

Cui et al. (2012) and Cui (2017) incorporate environmental pollution and the firm's technology choice into Melitz (2003)'s trade model. Based on their model, Cui et al. (2012) conclude that more productive firms are likely to adopt environmentally friendly technology and to export. Also, using US manufacturing industry data, they support their theoretical findings. Cui (2017) employs a similar model and argues that firms' technology adoption and export decisions are affected by the factor biases of the technology. In the simulation of the model, he shows that bilateral stringent environmental policy could improve welfare globally, but unilateral action can deteriorate the welfare of the imposing country, whereas the foreign country can enjoy the welfare improvement by free-riding.

Baldwin and Ravetti (2014) check the impact of trade liberalization on GHG emissions in the context of Melitz (2003)'s trade model with country asymmetries. They show that trade liberalization can improve the environment by matching more productive firms with cleaner technologies and suggest that trade liberalization with transfers of environmentally friendly technology can be a good policy solution.

The preceding research considered only usual tariffs, assumed to be iceberg costs that melt away during transportation. Therefore, considering a carbon-specific tax and border carbon adjustment in similar frameworks is worth doing. Here, I adopt a model like that of Cui (2017) and analyze the effect of a unilateral stringent environmental policy and border carbon adjustment using the graphical analysis method like Unel (2013).

2.3. Description of the Model

For the description of the model, I mainly follow the method and notation of Melitz (2003)'s model explanation by Feenstra (2015), Cui (2017), and Bernard et al. (2007b).

2.3.1. Preferences. The individuals in two countries can consume and produce one non-polluting good, such as an agricultural good, and a continuum of differentiated manufacturing goods with the additional component of climate damage. I assume that this negative externality is additive as in Fowlie and Muller (2019). Thus, the two countries share the same utility as below.

$$U = \left[\int_0^n q(v)^{(\sigma-1)/\sigma} dv \right]^{\mu\sigma/(\sigma-1)} Y^{1-\mu} - \beta(E + E^*), \tag{2.1}$$

where $q(v)$ is the quantity of manufacturing goods consumed and Y is the quantity of the non-polluting good consumed, n is the number of manufacturing goods, $\sigma > 1$ is the elasticity of substitution between manufacturing goods, and μ is the share of income spent on manufacturing goods. For the third component, E, E^* is the total greenhouse gas emissions, both home and foreign. β is the monetized marginal damage of pollution and represents the social cost of greenhouse gas emissions, such as human health deterioration and concerns regarding increasing temperatures. This marginal social cost of a unit of GHG emissions is uniform due to their global nature. The emissions happen in both countries, and an individual's consumption is assumed to affect the level of externality very little. Conversely, the existence of this component of climate damage does not affect an individual's choice of consumption.

2.3.2. Production. To produce q^Y units of the non-polluting good, ℓ^Y of labor is needed.

$$q^Y = \ell^Y, \tag{2.2}$$

In addition, the non-polluting good is assumed to be produced in a perfectly competitive market, and it is further assumed that the input and output relation is one for one, thus the factor price of the labor is equal to 1 ($w = 1$); then, the price of the non-polluting good is 1, as the labor is the only input, and the input price is equal to 1. In addition, we also assume this good is freely traded, and the factor price of this good is equalized across the countries, so the factor price of the labor in the foreign country is also equal to 1 ($w^* = 1$). With this numeraire, and the assumption that laborers can freely move across the sectors in a country, the factor prices of the labor for the manufacturing goods production are also equal to 1.

To produce manufacturing goods, ℓ of labor is needed; the process of the production also creates the emission of CO_2. To incorporate this pollution, Shapiro (2016) assumes that the emission is proportional to the production, Copeland and Taylor (1995) and Forslid et al. (2014) treat the emission as the needed input. Here, I follow the latter approach, so the manufacturing goods are produced by the constant elasticity of the substitution production function, which uses labor and emission as the input.

$$q_j(\varphi, \ell, e) = \varphi(\ell^{\frac{\eta-1}{\eta}} + [a_j e]^{\frac{\eta-1}{\eta}})^{\frac{\eta}{\eta-1}}, \quad j = l, h \tag{2.3}$$

where $0 < \eta$, φ is the firm's productivity as in Melitz (2003), and a_j is the abatement efficiency as in Cui (2017). Then, the cost is the function of the factor price of the labor (w) and pollution (τ), abatement efficiency (a_j,), and productivity (φ).

$$C_j(\varphi, q_j, \tau) = \frac{1}{\varphi}(w^{1-\eta} + \left[\frac{\tau}{a_j}\right]^{1-\eta})^{\frac{1}{1-\eta}} q_j = \frac{c_j q_j}{\varphi}, \quad j = l, h \tag{2.4}$$

where the unit cost is $c_j(w, \tau) = (w^{1-\eta} + (\tau/a_j)^{1-\eta})^{\frac{1}{1-\eta}}$. By normalizing the wage, we can further simplify the variable cost as $c_j(\tau) = (1 + (\tau/a_j)^{1-\eta})^{\frac{1}{1-\eta}}$. Firms can choose the level of efficiency by choosing different levels of the fixed cost of the investment ($j = l$, which represents low efficiency, and $j = h$, which represents high efficiency). For high abatement efficiency (a_h), bigger investment (f_h) is needed, and for low abatement efficiency (a_l), lower investment (f_l) is enough. I further assume that all the fixed costs are composed of the labor employment, and the investment in high technology is proportionate to the low-technology investment ($f_h = hf_l$, for $h > 1$) as in Unel (2013). As stated above, firms can choose the level of abatement technology investment, f_h or f_l. This investment determines the level of the abatement technology, and higher investment guarantees higher abatement efficiency, thus lower unit cost, which means that if $f_h > f_l$, then $a_h > a_l$, thus $c_h(\tau) < c_l(\tau)$. The investment in energy- or fuel-efficient technology can be an example of higher abatement efficient technology because efficient energy or fuel use decreases emissions too.[6] Thus, the decision to upgrade from low to high technology is the choice between the combination of low fixed cost (f_l) and high variable cost ($c_l(\tau)$) and that of high fixed cost (f_h) and low variable cost ($c_h(\tau)$).

In addition to the abatement investment, f_e needs to be paid before a firm enters the market. Also, firms should pay a fixed cost of f_x to sell their goods in the foreign market. This fixed cost is needed because a higher distribution cost is needed abroad, and a higher cost is required to adjust to the foreign customers' preferences and so on. In addition, there are 'iceberg' trade costs which reflect trade barriers, so $t > 1$ units should be shipped to ensure that one unit can be arrived at the importing country, which means that $t - 1$ units melt away during shipment. Since the purpose of this paper is to analyze the effects of environmental policies, I will add the assumption that all the parameters are symmetric except the environmental policy, the emission tax (τ and τ^*), to simplify the analysis.

The utility maximization between the manufacturing goods and non-polluting good gives us the total demand for the non-polluting good, $Y = (1 - \mu)X$, where X is the total expenditure in the home country. We further assume that the source of the consumption comes from the wage, and the emission tax is only used to control the level of emission, so it is assumed to melt away like the 'iceberg cost' tariff. Then, total expenditure is the same as the number of laborers, so $R = L$; then, the demand for non-polluting good is

$$Y = (1 - \mu)X, \tag{2.5}$$

The utility maximization for the constant elasticity of the substitution (CES) function gives us the representative consumer's demand for the manufacturing goods (v).

$$d(v) = \mu X \frac{p(v)^{-\sigma}}{P^{1-\sigma}}, \tag{2.6}$$

[6]The replacement of an old lighting system with LEDs (light emitting diodes) requires an initial investment, such as retrofitting cost, but it saves on electricity use and maintenance costs afterwards, and eventually CO_2 and other pollutants' emissions (Ganandran et al., 2014).

where P is the price index represented as below.

$$P = \left[\int_0^n p(v)^{1-\sigma} dv \right]^{\frac{1}{1-\sigma}}, \tag{2.7}$$

where n is the number of varieties.

From here, as in much literature, I will denote the variety (v) the same as the productivity (φ). As the demand function is CES, profit maximization in the monopolistic competition market gives us the result that the price of the manufacturing good is a constant markup over the marginal cost.

$$p_{jd}(\varphi) = \frac{\sigma}{(\sigma-1)} \frac{c_j}{\varphi} = \frac{c_j}{\rho\varphi}, \quad \text{then,} \quad \frac{c_j}{\varphi} = \rho p_{jd}(\varphi), \tag{2.8}$$

where $\rho = 1 - 1/\sigma$. Then the profit from the domestic sales is

$$\pi_{jd}(\varphi) = p_{jd}(\varphi) q_{jd}(\varphi) - \frac{c_j}{\varphi} q_{jd}(\varphi) - f_j = \frac{r_{jd}(\varphi)}{\sigma} - f_j, \quad \text{for} \quad j = l, h, \tag{2.9}$$

where $r_{jd}(\varphi)$ is the revenue from the domestic sales ($r_{jd}(\varphi) = p_{jd}(\varphi) q_{jd}(\varphi) = \mu X P^{\sigma-1} \left(\frac{\rho\varphi}{c_j}\right)^{\sigma-1}$). In the case of exporting goods, reflecting the iceberg cost, the export price is

$$p_{jx}(\varphi) = \frac{\sigma}{(\sigma-1)} \frac{tc_j}{\varphi} = \frac{tc_j}{\rho\varphi}, \quad \text{then,} \quad \frac{tc_j}{\varphi} = \rho p_{jx}(\varphi). \tag{2.10}$$

Given the fact that firms have paid a fixed amount of abatement investment for production, the firm's profit from the export is

$$\pi_{jx}(\varphi) = p_{jx}(\varphi) q_{jx}(\varphi) - \frac{tc_j}{\varphi} q_{jx}(\varphi) - f_x = \frac{r_{jx}(\varphi)}{\sigma} - f_x, \tag{2.11}$$

where $r_{jx}(\varphi)$ is the revenue from the domestic sales ($r_{jx}(\varphi) = p_{jx}(\varphi) q_{jx}(\varphi) = \mu X^* (P^*)^{\sigma-1} \left(\frac{\rho\varphi}{tc_j}\right)^{\sigma-1}$).

From the demand in (2.2) and prices in (2.8) and (2.10), we obtain the relationships between revenues and quantities as below.

$$\frac{r_{jk}(\varphi_1)}{r_{jk}(\varphi_2)} = \left(\frac{\varphi_1}{\varphi_2}\right)^{\sigma-1}, \quad \frac{r_{hk}(\varphi)}{r_{lk}(\varphi)} = \left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}, \quad \frac{r_{jx}(\varphi)}{r_{jd}(\varphi)} = t^{1-\sigma}, \quad \frac{q_{jk}(\varphi_1)}{q_{jk}(\varphi_2)} = \left(\frac{\varphi_1}{\varphi_2}\right)^{\sigma}, \tag{2.12}$$

where $j = h, l$ and $k = d, x$.

2.3.3. Equilibrium Conditions.

Zero Cutoff Profit (ZCP) Conditions. To produce the manufacturing goods with low technology, the profit using low technology should be greater than 0, so the zero cutoff profit condition for the low technology is

$$\pi_{ld}(\varphi_l) = \frac{r_{ld}(\varphi_l)}{\sigma} - f_l = 0, \quad \text{which is,} \quad \mu X P^{\sigma-1} \left(\frac{\rho \varphi_l}{c_l(\tau)} \right)^{\sigma-1} = \sigma f_l. \tag{2.13}$$

For the foreign country,

$$\pi_{ld}^*(\varphi_l^*) = \frac{r_{ld}^*(\varphi_l^*)}{\sigma} - f_l = 0, \quad \text{which is,} \quad \mu X^* P^{*\sigma-1} \left(\frac{\rho \varphi_l^*}{c_l^*(\tau^*)} \right)^{\sigma-1} = \sigma f_l. \tag{2.14}$$

If the low-technology firm wants to export, the profit from exporting should be greater than 0, so the zero cutoff profit condition of the export is

$$\pi_{lx}(\varphi_x) = \frac{r_{lx}(\varphi_x)}{\sigma} - f_x = 0, \quad \text{which is,} \quad \mu X^* (P^*)^{\sigma-1} \left(\frac{\rho \varphi_x}{t c_l(\tau)} \right)^{\sigma-1} = \sigma f_x. \tag{2.15}$$

The zero cutoff profit condition of the export for the foreign country is

$$\pi_{lx}^*(\varphi_x^*) = \frac{r_{lx}^*(\varphi_x^*)}{\sigma} - f_x = 0, \quad \text{which is,} \quad \mu X P^{\sigma-1} \left(\frac{\rho \varphi_x^*}{t c_l^*(\tau^*)} \right)^{\sigma-1} = \sigma f_x. \tag{2.16}$$

Lastly, if a firm adopts high-technology production, the profit from the high-technology production should be greater than that from the low-technology production. Thus, the high-technology cutoff adoption condition is

$$\begin{aligned}
&\pi_{hd}(\varphi_h) + \pi_{hx}(\varphi_h) - \pi_{ld}(\varphi_h) - \pi_{lx}(\varphi_h) = \\
&\frac{\mu X}{\sigma} \left(\frac{P\rho}{c_l(\tau)} \right)^{\sigma-1} \left(\left[\frac{c_l(\tau)}{c_h(\tau)} \right]^{\sigma-1} - 1 \right) \varphi_h^{\sigma-1} + \frac{\mu X^*}{\sigma} \left(\frac{P^*\rho}{t c_l(\tau)} \right)^{\sigma-1} \left(\left[\frac{c_l(\tau)}{c_h(\tau)} \right]^{\sigma-1} - 1 \right) \varphi_h^{\sigma-1} \\
&- (f_h - f_l)
\end{aligned}$$

$$= (1 + t^{1-\sigma}\Lambda) \frac{\mu X}{\sigma} \left(\frac{P\rho}{c_l(\tau)} \right)^{\sigma-1} \left(\left[\frac{c_l(\tau)}{c_h(\tau)} \right]^{\sigma-1} - 1 \right) \varphi_h^{\sigma-1} - (h-1) f_l = 0, \tag{2.17}$$

where $\Lambda = \frac{X^* P^{*\sigma-1}}{X P^{\sigma-1}}$, which represents the relative competitiveness, and $f_h - f_l = (h-1)f_l$ is the additional fixed investment to upgrade the technology from low to high. To get the cutoff productivity levels, it is convenient to calculate their proportions using the ZCP conditions above.

$$\begin{aligned} \left(\frac{\varphi_l}{\varphi_x}\right)^{\sigma-1} &= \frac{\Lambda}{t^{\sigma-1}}\frac{f_l}{f_x}; \quad \left(\frac{\varphi_l}{\varphi_h}\right)^{\sigma-1} = \left(1+t^{1-\sigma}\Lambda\right)\left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1}-1\right)\frac{1}{(h-1)}; \\ \left(\frac{\varphi_h}{\varphi_x}\right)^{\sigma-1} &= \left(\frac{1}{1+t^{\sigma-1}\Lambda^{-1}}\right)\left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1}-1\right)^{-1}(h-1)\frac{f_l}{f_x}. \end{aligned} \tag{2.18}$$

As we have three zero cutoff productivity points, we have three groups of firms which survive in the market. The first one is the low-technology firms which serve the domestic market only, the second one is the low-technology firms which serve both the domestic and foreign markets, and the last one is the high-technology firms which serve both the domestic and foreign markets ($\varphi_l < \varphi_x < \varphi_h$). Another division, under which some high-technology firms can export and all exporting firms adopt high technology ($\varphi_l < \varphi_h < \varphi_x$), is also possible. However, as the previous one is consistent with the empirical evidence (Bustos, 2011; Unel, 2013) and Cui (2017) adopt the previous division, I also follow this division. The cost structure which satisfies this division can be found easily with the relationship above and is already solved by Cui (2017), which is

$$t^{1-\sigma}\Lambda f_l^{\sigma-1} < f_x^{\sigma-1} < f_l^{\sigma-1}(h-1)(1+t^{\sigma-1}\Lambda^{-1})^{-1}\left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1}-1\right)^{-1}. \tag{2.19}$$

Thus, we assume that this condition holds.

The ZCP condition for technology upgrade can also be represented differently.

$$\begin{aligned} \pi_{hd}(\varphi_h)+&\pi_{hx}(\varphi_h)-\pi_{ld}(\varphi_h)-\pi_{lx}(\varphi_h) = \\ &\frac{r_{hd}(\varphi_h)}{\sigma}+\frac{r_{hx}(\varphi_h)}{\sigma}-\frac{r_{ld}(\varphi_h)}{\sigma}-\frac{r_{lx}(\varphi_h)}{\sigma}-(f_h-f_l)=0, \end{aligned}$$

which is,

$$r_{hd}(\varphi_h)+r_{hx}(\varphi_h)-r_{ld}(\varphi_h)-r_{lx}(\varphi_h)=\sigma(h-1)f_l. \tag{2.20}$$

If we rewrite this using the relationships between revenues in (2.12) and ZCP conditions from (2.13) to (2.16), we get

$$\varphi_h = (h-1)^{\frac{1}{\sigma-1}}\left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1}-1\right)^{\frac{1}{1-\sigma}}\left(\varphi_l^{1-\sigma}+\frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.21}$$

In the same way,

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)} \right]^{\sigma-1} - 1 \right)^{\frac{1}{1-\sigma}} \left(\varphi_l^{*1-\sigma} + \frac{f_x}{f_l} \varphi_x^{*1-\sigma} \right)^{\frac{1}{1-\sigma}}. \tag{2.22}$$

As we can see, the cutoff for upgrading technology (φ_h) is positively related to the additional fixed investment ($h-1$) and inversely related to the ratio of the two variable costs ($\frac{c_l(\tau)}{c_h(\tau)}$), and it depends on the low-technology adoption and exporting cutoffs. The first two relations fit our intuition that if the additional investment for high technology is more costly, firms will be less likely to adopt higher technology. Also, if the difference of the variable costs between high technology and low technology is larger, firms will have more incentives to adopt high technology.

Free Entry Condition. We also assume that in each period, δ firms exit the market among existing firms. Thus, a firm's value is 0 if it draws a productivity which is below the zero-profit cutoff productivity. If a firm draws a productivity higher than the cutoff, the firm's value is the future profit discounted by the probability of death (δ).

$$v_i(\varphi) = \max \left[0, \sum_{s=0}^{\infty} (1-\delta)^s \pi_i(\varphi) \right] = \max \left[0, \frac{\pi_i(\varphi)}{\delta} \right] \tag{2.23}$$

Under monopolistic competition, there is free entry when the existing firms make positive profit, and this happens until the expected value of entry is equal to the sunken entry cost, so we can get the free entry (FE) condition.

$$[1 - G(\varphi_l)] \frac{\bar{\pi}}{\delta} = f_e, \tag{2.24}$$

where $\bar{\pi}$ is the expected profit which has successfully entered the market and $G(\varphi)$ is the cumulative distribution function of φ, thus the distribution function of φ is $g(\varphi)$. Then, the remaining work is to get this expected profit ($\bar{\pi}$). The distribution of the ex-post productivity level after the entrance is the conditional distribution of $g(\varphi)$, such as $\gamma(\varphi) = g(\varphi)/1 - G(\varphi_l)$. Then, following Bernard et al. (2007b), the expected profit is the weighted average of the profit from the domestic market using low technology, the profit from the export market using low technology, and the additional profit using high technology from both markets.

$$\bar{\pi} = \int_{\varphi_l}^{\infty} \pi_{ld}(\varphi)\gamma(\varphi)d\varphi + \int_{\varphi_x}^{\infty} \pi_{lx}(\varphi)\gamma(\varphi)d\varphi + \int_{\varphi_h}^{\infty} [\pi_{hd}(\varphi) + \pi_{hx}(\varphi) - \pi_{ld}(\varphi) - \pi_{lx}(\varphi)]\gamma(\varphi)d\varphi.$$

Substituting this into the FE condition in (2.24),

$$\delta f_e = \int_{\varphi_l}^{\infty} \pi_{ld}(\varphi)g(\varphi)d\varphi + \int_{\varphi_x}^{\infty} \pi_{lx}(\varphi)g(\varphi)d\varphi + \int_{\varphi_h}^{\infty} [\pi_{hd}(\varphi) + \pi_{hx}(\varphi) - \pi_{ld}(\varphi) - \pi_{lx}(\varphi)]g(\varphi)d\varphi. \tag{2.25}$$

For more specification, we follow Chaney (2008), which assumes that φ follows the Pareto distribution; thus, the probability density function is $g(\varphi) = \theta\varphi^{-(\theta+1)}$, $\theta \geq 1$ and the cumulative density function is $G(\varphi) = 1 - \varphi^{-\theta}$. Thus, $1 - G(\varphi_l) = \varphi_l^{-\theta}$ is the probability that a firm enters the market successfully. Using this function, we can find the cutoff productivity level under the equilibrium. To get finite cutoff productivity, $\theta + 1 > \sigma$ is also assumed. With the Pareto distribution, the free entry condition becomes

$$\frac{\sigma - 1}{\theta + 1 - \sigma}\left[\varphi_l^{-\theta} f_l + \varphi_x^{-\theta} f_x + \varphi_h^{-\theta}(h-1) f_l\right] = \delta f_e. \tag{2.26}$$

Trade Balance Condition and Non-polluting Goods Market Clearing. To close the model, we will use additional conditions. The first one is the trade balance condition, which means that the sum of net exports of the non-polluting good and those of manufacturing goods is equal to 0. As the non-polluting good can be produced with one unit of labor, if we denote k as the fraction of workers working in manufacturing goods, $(1-k)L$ is the total production for the non-polluting good. As the demand for this good is $(1-\mu)X$ from (2.5), the net export of home country from this good is $(1-k)L - (1-\mu)X$. Then, the balanced trade condition is

$$R_x + (1-k)L - (1-\mu)X = R_x^*, \tag{2.27}$$

where R_x and R_x^* are the aggregate revenue earned by the home and foreign firms from the manufacturing goods' exports. This also holds from the foreign perspective, so $R_x = R_x^* + (1-k^*)L - (1-\mu)X^*$. In the symmetric case, the revenues from the exports at home and abroad are the same,

$R_x = R_x^*$. Therefore, $(1-k)L = (1-\mu)X$, which means that the production and the consumption of the numeraire good are the same. Alternatively, there is no trade in the numeraire good. Combining the two balanced trade conditions gives us the market clearing of the non-polluting good, where the world demand for this good and the world supply of this good are equal.

$$(1-\mu)X + (1-\mu)X^* = (1-k)L + (1-k^*)L.$$

This means the demand for non-polluting goods worldwide is the same as worldwide production of this good. If we follow the assumption that all the expenditure is from wage ($X = L$), the above balanced trade condition is

$$R_x + (\mu - k)L = R_x^*,$$

and the market clearing condition is $2\mu = k + k^*$.

Mass of the Firms. The mass of the firms in a steady state is determined such that the flow of successful entry is equal to the flow of exit from the existing firms, so the condition is

$$\delta M = M_e[1 - G(\varphi_l)] = M_e \varphi_l^{-\theta}, \quad \text{then,} \quad M = \frac{M_e \varphi_l^{-\theta}}{\delta},$$

where M_e is the mass of the entering firms, M is the mass of the existing firms. The second equality is from the Pareto distribution. Using the full employment condition, we can get the mass of the entry (M_e) as below.[7]

$$M_e = \frac{(\sigma - 1)kL}{\sigma f_e \theta}. \tag{2.28}$$

Then, to calculate the mass of the firms, we need to calculate k and k^*. From the market clearing condition above, $k + k^* = 2\mu$. The revenue from the exports is $R_x = \bar{r}_x M$, and the total revenue is $R = \bar{r}M = kL$, so $M = kL/\bar{r}$. Then, the trade balance condition is now

$$\frac{\bar{r}_x k}{\bar{r}} + \mu - k = \frac{\bar{r^*}_x k^*}{\bar{r^*}}.$$

[7]The details of the derivation are in the appendix.

Substituting $k^* = 2\mu - k$ into the above gives us

$$k = \mu\left(\frac{1-2z^*}{1-z-z^*}\right) = \mu\left(1 + \frac{z-z^*}{1-z-z^*}\right),$$

where $z = \bar{r}_x/\bar{r}$ and $z^* = \bar{r^*}_x/\bar{r^*}$. Therefore, what is remaining is to calculate the average revenues, and we can get them as below,[8] and we can also get the foreign country's average revenue in the same way.

$$\bar{r}_d = \frac{\sigma\theta f_l}{\theta+1-\sigma}\left\{1 + \left[\frac{\varphi_h}{\varphi_l}\right]^{\sigma-\theta-1}\left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\},$$

$$\bar{r}_x = \frac{\sigma\theta f_x}{\theta+1-\sigma}\left[\frac{\varphi_x}{\varphi_l}\right]^{-\theta}\left\{1 + \left[\frac{\varphi_h}{\varphi_x}\right]^{\sigma-\theta-1}\left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\}.$$

2.3.4. Stricter Environmental Policy. With the equilibrium conditions above, in the next section, we will consider the different environmental policy scenarios. First, the environmental policies at home and in foreign countries are symmetric, so they impose the same emission tax ($\tau = \tau^*$). Second, we will test the case when the home country imposes a unilateral stringent environmental policy, which means it has a higher emission tax than the foreign country($\tau^* < \tau$), and see whether the emission leakage problem is observed. For the last case, I will suppose that under the former condition, the home country imposes the border carbon adjustment for the imports to the home country, especially checking whether this policy can prevent the leakage problem to some extent.

Effects on the Individual Firms' Variable Cost and Cost Ratios. We will explore the overall effects of the stricter domestic environmental policy on the market in the next section. Before doing that, we will check the effects on the individual firms here. The effect of the increase of the emission tax (τ) on variable cost is obvious, as this is the increase of the input price for emissions, so it raises the variable cost.

$$\frac{\partial c_i(\tau)}{\partial \tau} = (w^{1-\eta} + (\tau/a_i)^{1-\eta})^{\frac{1}{1-\eta}-1}\frac{\tau^{-\eta}}{a_i^{1-\eta}} > 0. \tag{2.29}$$

Here, we will check the effect of the emission tax(τ) on the variable costs ratio between the high technology and the low technology ($\frac{c_l(\tau)}{c_h(\tau)}$), too. As $\frac{c_l(\tau)}{c_h(\tau)} = \frac{(w^{1-\eta}+(\tau/a_l)^{1-\eta})^{\frac{1}{1-\eta}}}{(w^{1-\eta}+(\tau/a_h)^{1-\eta})^{\frac{1}{1-\eta}}}$, when we take the

[8]The details of the calculation are in the appendix.

partial derivative with respect to τ,

$$\frac{\partial c_l(\tau)/c_h(\tau)}{\partial \tau} = \frac{w^{1-\eta}(w^{1-\eta}+(\tau/a_l)^{1-\eta})^{\frac{1}{1-\eta}-1}}{\tau^{\eta}(w^{1-\eta}+(\tau/a_h)^{1-\eta})^{\frac{1}{1-\eta}+1}}(a_l^{\eta-1}-a_h^{\eta-1}). \tag{2.30}$$

The sign of the above partial derivative depends on the scale of η. When $\eta > 1$, as $a_l < a_h$, the sign of the above is negative, which means that as the price of emissions increases, the relative cost difference between high technology and low technology decreases. When $\eta = 1$, the sign of the above is zero, which means that the change of the emission price does not affect the relative cost difference between high technology and low technology. When $\eta < 1$, as $a_l < a_h$, the sign of the above is positive, which means that as the price of emissions increases, the relative cost difference between high technology and low technology increases. These three cases are the special cases where the high technology is emission-biased, Hicks-neutral, and labor-biased in Cui (2017). He classifies these three cases, but empirical works such as Kreickemeier and Richter (2014) and Baldwin and Ravetti (2014) support that the higher technology is cleaner than the lower technology. I will focus on the last case ($\eta < 1$) from now on and will further assume that $\frac{\partial c_l(\tau)}{\partial \tau} > \frac{\partial c_l(\tau)/c_h(\tau)}{\partial \tau}$, which means that the increase of the variable cost by low technology is greater than the increase of the variable cost ratio due to the increase of the emission tax.

2.4. Equilibrium Results of the Unilateral Environmental Policy on the Cutoff Productivities

2.4.1. Domestic and Foreign Cutoff Productivities Interactions. Here, we explore the interactions between the domestic cutoff productivities and the foreign ones, as in Unel (2013). To do this, we combine the ZCP condition of the exports from the perspective of the foreign country (2.16) and domestic ZCP condition for the low technology (2.13); we get the result below.

$$\varphi_x^* = \left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}} \frac{c_l^*(\tau^*)}{c_l(\tau)} t\varphi_l, \quad \text{in the same way,} \quad \varphi_x = \left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}} \frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*. \tag{2.31}$$

I multiplied the above two equations, and their product is

$$\frac{\varphi_x^*\varphi_x}{\varphi_l^*\varphi_l} = \left(\frac{f_x}{f_l}\right)^{\frac{2}{\sigma-1}} t^2. \tag{2.32}$$

As the cutoff productivities for exports are higher than those of low-technology adoption ($\varphi_l < \varphi_x$ and $\varphi_l^* < \varphi_x^*$), (2.29) should be greater than 1, thus, $\left(f_x/f_l\right)^{\frac{1}{\sigma-1}} t > 1$. In addition, with some algebra,[9] the below also holds.

$$\left(\frac{f_x}{f_l}\right)^{\frac{\theta-\sigma+1}{\sigma-1}} t^\theta > 1. \tag{2.33}$$

2.4.2. Cutoff Productivities for Low Technology Adoption. With the above condition in (2.33), we can rewrite (2.21) and (2.22) as below.

$$\varphi_h = (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1} - 1\right)^{\frac{1}{1-\sigma}} \left(\varphi_l^{1-\sigma} + \left[\frac{c_l(\tau)}{c_l^*(\tau^*)} t\right]^{1-\sigma} \varphi_l^{*1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.34}$$

In the same way,

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1\right)^{\frac{1}{1-\sigma}} \left(\varphi_l^{*1-\sigma} + \left[\frac{c_l^*(\tau^*)}{c_l(\tau)} t\right]^{1-\sigma} \varphi_l^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.35}$$

As we have the relations of φ_x with φ_l^* in (2.31) and φ_h with φ_l, φ_l^* in (2.34), we can represent the FE condition of (2.26) with φ_l, φ_l^*.

(2.36)

$$(h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\varphi_l^{1-\sigma} + \left[\frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*\right]^{1-\sigma}\right)^{\frac{1}{\kappa}} + \varphi_l^{-\theta} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} \left(\frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*\right)^{-\theta} = \frac{\delta f_e}{\chi f_l},$$

where $\chi = \frac{\sigma-1}{\theta-\sigma+1} > 0$, $\kappa = \frac{\sigma-1}{\theta} > 0$. For the foreign country's perspective, we have the symmetric equation.

(2.37)

$$(h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\varphi_l^{*1-\sigma} + \left[\frac{c_l^*(\tau^*)}{c_l(\tau)} t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}} + \varphi_l^{*-\theta} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} \left(\frac{c_l^*(\tau^*)}{c_l(\tau)} t\varphi_l\right)^{-\theta} = \frac{\delta f_e}{\chi f_l}.$$

As in Unel (2013), the above two equations (2.36) and (2.37) characterize the negative or inverse relationship between the domestic and foreign low-technology cutoff productivities. First, I will start the analysis by finding the equilibrium in the symmetric case, as Unel (2013) did. We already

[9] We take the multiple of $\theta > 0$ on the previous inequality, then multiply it by f_l/f_x; then we have $\left(f_x/f_l\right)^{\frac{\theta-\sigma+1}{\sigma-1}} t^\theta > f_l/f_x$. Therefore, the sufficient condition for (2.33) is $f_l/f_x > 1$. When $f_l/f_x \leq 1$, which means that $f_x \geq f_l$, (2.33) holds as $\theta - \sigma + 1 > 0$ and $\sigma - 1 > 0$.

assumed that the fixed cost and the parameters are the same, but here, we further assume that the other variables, such as the variable costs, are also the same ($c_l(\tau) = c_l^*(\tau^*)$ and $c_h(\tau) = c_h^*(\tau^*)$). Then, as all parameters are symmetric, $\varphi_l = \varphi_l^*$. Starting from here, if we draw the curves of equations (2.36) and (2.37) on the plane consisting of φ_l on the x-axis and φ_l^* on the y-axis, we get the intersection of these two curves at a 45-degree line. We check the slope of these two curves at the intersection by taking total derivatives and using the property of the 45-degree intersection ($c_l(\tau) = c_l^*(\tau^*)$, $c_h(\tau) = c_h^*(\tau^*)$, and $\varphi_l = \varphi_l^*$). Then, (2.36) gives us

$$\left|\frac{d\varphi_l^*}{d\varphi_l}\right| = \frac{\lambda + 1}{\lambda t^{1-\sigma} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} t^{-\theta}}, \tag{2.38}$$

where $\lambda = (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(1 + t^{1-\sigma}\right)^{\frac{1}{\chi}}$. Taking the total derivative of (2.37) gives us

$$\left|\frac{d\varphi_l^*}{d\varphi_l}\right| = \frac{\lambda^* t^{1-\sigma} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} t^{-\theta}}{\lambda^* + 1}, \tag{2.39}$$

where $\lambda^* = (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(1 + t^{1-\sigma}\right)^{\frac{1}{\chi}}$. Because $t > 1$ and, by (2.33), $\left|d\varphi_l^*/d\varphi_l\right| > 1$ for (2.38) and $\left|d\varphi_l^*/d\varphi_l\right| < 1$ for (2.39), thus, if we draw a curve of φ_l on the horizontal axis and φ_l^* on the vertical axis, the slope of (2.36) is steeper than that of (2.37) at the 45-degree intersection point. As is pointed out in Unel (2013), the complete description of the equilibrium can hold when the conditions below are satisfied. As we can see in Figure 2.1, there exists an equilibrium only if the two curves intersect. Therefore, the range of τ should be within the range where these two curves intersect. For a given τ^*, denote $\varphi_l(\tau^*)$ as the solution to (2.37) when $\varphi_l^* = 1$, and denote $\varphi_l^*(\tau^*)$ as the solution to (2.37) when $\varphi_l = 1$.[10] Further denote $\underline{\tau_l}(\tau^*)$ as the solution to (2.36) when $(\varphi_l, \varphi_l^*) = (\varphi_l(\tau^*), 1)$. Then, if $\tau < \underline{\tau_l}(\tau^*)$, the two curves of (2.36) and (2.37) do not intersect. In the same way, we can define $\overline{\tau_l}(\tau^*)$ as the solution to (2.36) when $(\varphi_l, \varphi_l^*) = (1, \varphi_l^*(\tau^*))$. Then, if $\tau > \overline{\tau_l}(\tau^*)$, the two curves of (36) and (37) do not intersect. Thus, the condition that there is an equilibrium from (2.36) and (2.37) is

$$\underline{\tau_l}(\tau^*) \leq \tau \leq \overline{\tau_l}(\tau^*) \tag{2.40}$$

[10]As the Pareto distribution is defined for $\varphi \in [1, \infty]$, 1 is the minimum value for φ.

Following the interpretation of Unel (2013), we can interpret (2.40) as the way of ensuring that

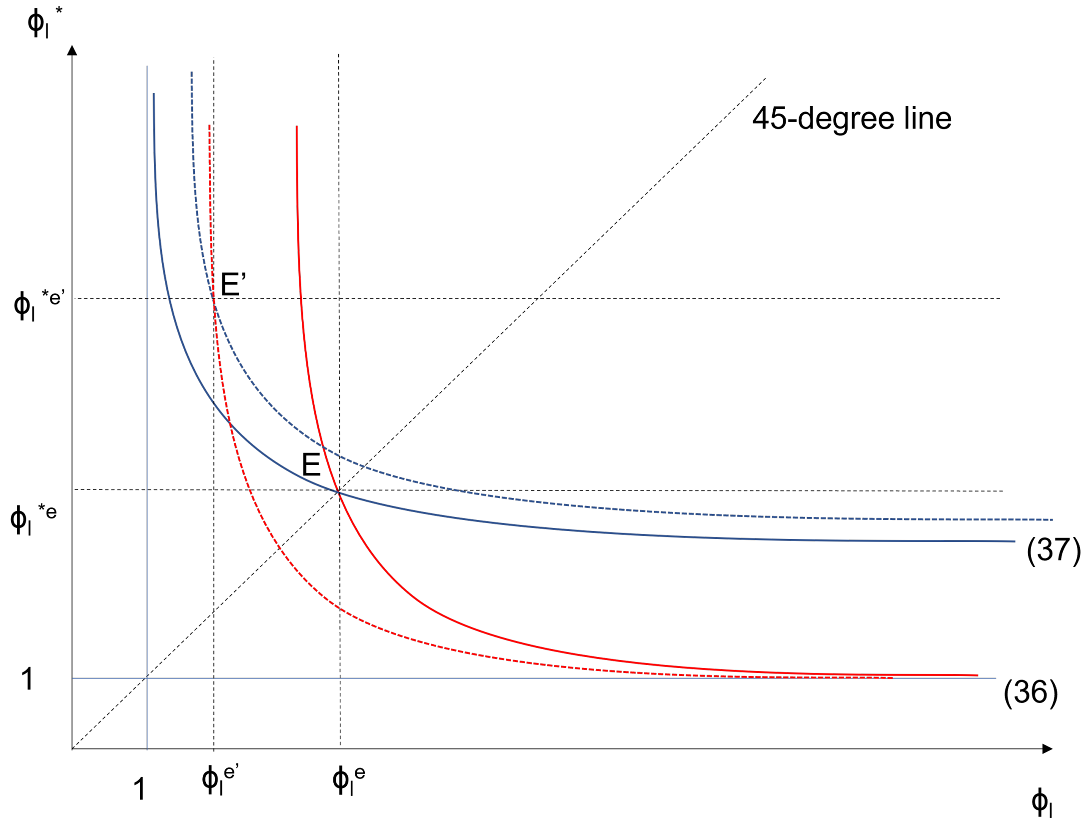


FIGURE 2.1. The Interactions of Low-Technology Adoption Cutoffs

the difference of the emission taxes should not be too large. When the domestic emission tax is too high ($\tau > \overline{\tau_l}(\tau^*)$), all the manufacturing goods are produced in the foreign country, and when the domestic emission tax is too low compared to the foreign country ($\tau < \underline{\tau_l}(\tau^*)$), all the manufacturing goods are produced in the domestic country. Thus, we exclude these extreme cases and assume that (2.40) holds.

We will explore the case of asymmetry in the emission prices ($\tau \neq \tau^*$). Given that the foreign environmental policy is fixed at the level of the symmetric case (τ^*), suppose that home adopts a stricter environmental policy, thus $\tau > \tau^*$. Then, as a result, $c_l(\tau)$ and $c_h(\tau)$ increase, thus, $c_l(\tau) > c_l^*(\tau^*)$ and $c_h(\tau) > c_h^*(\tau^*)$. In addition, as we assume the high technology is environmentally friendly, $c_l(\tau)/c_h(\tau)$ also increases. Because there is no change in τ^*, $c_l^*(\tau^*)$, and

$c_h^*(\tau^*)$, $c_l^*(\tau^*)/c_h^*(\tau^*)$ remains the same. Given these changes, the effect of the increase in τ can be represented as the shift of the two curves as depicted in Figure 2.1.

The initial equilibrium starts at E, where (2.36) and (2.37), the two solid lines, intersect. As a result of the increase of τ, (2.36) shifts to the left and (2.37) shifts to the right, as represented by the dotted lines.[11] The new equilibrium (E') shows that the domestic low-technology adoption cutoff (φ_l) decreases, whereas the foreign low-technology adoption cutoff (φ_l^*) increases.

Behind this result, there are changes in the mass of firms at home and in foreign countries. Faced with a higher cost, the average expected profit of the manufacturing firms at home decreases. Thus, there are exits among the existing firms at home. We do not derive this analytically here, but we can confirm it from the simulation in the following section. This induces some firms which were previously below the cutoff entry productivity to enter the market. If we interpret this result based on equation (2.27), it is the case that the home country produces fewer manufacturing goods than before, so it net imports the manufacturing goods and net exports the numeraire good.

Alternatively speaking, the above results are because the home country firms now face a higher cost, so their expected return decreases and the price index of the home country increases. This results in a lower real wage. Also, in the following subsection, we will see that because of this policy, the home country's exports decrease (φ_x increases); thus, the demand for labor and real wages will decrease. This induces the firms which were previously below the cutoff entry productivity to enter the market.

On the contrary, the foreign country gets relative competitiveness in manufacturing; thus, the average expected profit of the manufacturing firms increases. Thus, there are entries in the manufacturing goods' production. Thus, the competition in the foreign country is more severe, so more low-productive firms in the foreign country now exit the market. If we interpret this in the context of the trade flow, the foreign country produces more manufacturing goods than before, so it net exports the manufacturing good and net imports the numeraire good.

[11] The proof and details of the curve shifts are in the appendix.

2.4.3. Cutoff Productivities for High-Technology Adoption. We will check the change of φ_h^* first. To do that, we first take the log of (2.22), then take the derivative with respect to τ.

$$\frac{1}{\varphi_h^*}\frac{d\varphi_h^*}{d\tau} = \left(\varphi_l^{*1-\sigma} + \frac{f_x}{f_l}\varphi_x^{*1-\sigma}\right)^{-1}\left(\varphi_l^{*-\sigma}\frac{d\varphi_l^*}{d\tau} + \frac{f_x}{f_l}\varphi_x^{*-\sigma}\frac{d\varphi_x^*}{d\tau}\right). \tag{2.41}$$

We also take the derivative of the FE condition in (2.26) for the foreign country with respect to τ.

$$\varphi_l^{*-\theta-1}\frac{d\varphi_l^*}{d\tau} + \frac{f_x}{f_l}\varphi_x^{*-\theta-1}\frac{d\varphi_x^*}{d\tau} + (h-1)\varphi_h^{*-\theta-1}\frac{d\varphi_h^*}{d\tau} = 0. \tag{2.42}$$

We substitute $\frac{f_x}{f_l}\frac{d\varphi_x^*}{d\tau}$ in (2.42) with the one in (2.41). Then,

$$\left\{\left(\varphi_l^{1-\sigma} + \frac{f_x}{f_l}\varphi_x^{1-\sigma}\right) + (h-1)\frac{\varphi_x^{*\theta+1-\sigma}}{\varphi_h^{*\theta}}\right\}\frac{1}{\varphi_h^*}\frac{d\varphi_h^*}{d\tau} = \underbrace{\left(\frac{\varphi_l^{*\theta+1-\sigma} - \varphi_x^{*\theta+1-\sigma}}{\varphi_l^{*\theta+1}}\right)\frac{d\varphi_l^*}{d\tau}}_{\text{expected profit increase(-)}}. \tag{2.43}$$

The terms in front of $\frac{d\varphi_h^*}{d\tau}$ are all positive. The terms in front of $\frac{d\varphi_l^*}{d\tau}$ are negative, as $\varphi_l^* < \varphi_x^*$ and $\theta + 1 - \sigma > 0$. Given $\frac{d\varphi_l^*}{d\tau} > 0$, we can conclude that $\frac{d\varphi_h^*}{d\tau} < 0$. Now we have that, because of the increase of the emission tax (τ), φ_h^* decreases, so $\varphi_h^{*e'} < \varphi_h^{*e}$. The reason φ_h^* decreases is related to the increase of the expected profit from exports. Because the foreign firms now have more competitiveness in the export market (home country) because of the higher emission tax at home, the adoption of the high technology brings them higher profit from exports, so more firms tend to adopt the high technology.

To check the change of φ_h, we take similar steps as in the case of the foreign country. We first take the log of (2.21), then take the derivative with respect to τ.

$$\frac{1}{\varphi_h}\frac{d\varphi_h}{d\tau} = -\frac{1}{\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1}\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-2}\frac{dc_l(\tau)/c_h(\tau)}{d\tau} + \left(\varphi_l^{1-\sigma} + \frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)^{-1}\left(\varphi_l^{-\sigma}\frac{d\varphi_l}{d\tau} + \frac{f_x}{f_l}\varphi_x^{-\sigma}\frac{d\varphi_x}{d\tau}\right). \tag{2.44}$$

We also take the derivative of the FE condition in (2.26) with respect to τ.

$$\varphi_l^{-\theta-1}\frac{d\varphi_l}{d\tau} + \frac{f_x}{f_l}\varphi_x^{-\theta-1}\frac{d\varphi_x}{d\tau} + (h-1)\varphi_h^{-\theta-1}\frac{d\varphi_h}{d\tau} = 0. \tag{2.45}$$

We substitute $\frac{f_x}{f_l}\frac{d\varphi_x}{d\tau}$ in (2.45) with the one in (2.44), and arranging the terms,

(2.46)

$$\left\{\left(\varphi_l^{1-\sigma}+\frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)+(h-1)\frac{\varphi_x^{\theta+1-\sigma}}{\varphi_h^{\theta}}\right\}\frac{1}{\varphi_h}\frac{d\varphi_h}{d\tau}=$$

$$\underbrace{-\frac{1}{\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1}\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-2}\left(\varphi_l^{1-\sigma}+\frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)\frac{dc_l(\tau)/c_h(\tau)}{d\tau}}_{\text{technology upgrade incentive(-)}}+\underbrace{\left(\frac{\varphi_l^{\theta+1-\sigma}-\varphi_x^{\theta+1-\sigma}}{\varphi_l^{\theta+1}}\right)\frac{d\varphi_l}{d\tau}}_{\text{expected profit decrease(+)}}.$$

This is like (2.43), except for the first term in the second line, which is coming from the cost ratio change due to the emission tax hike in the home country. The terms in front of $d\varphi_h/d\tau$ and $\frac{dc_l(\tau)/c_h(\tau)}{d\tau}$ are all positive, and the terms in front of $d\varphi_l/d\tau$ are negative because $\varphi_l<\varphi_x$ and $\theta+1-\sigma>0$. Given the fact that $\frac{d\varphi_l}{d\tau}<0$, and the assumption of $\frac{dc_l(\tau)/c_h(\tau)}{d\tau}$, the sign of $\frac{d\varphi_h}{d\tau}$ can be determined by the relative scale of the two terms in the second line. The first term is related to the cost ratio increase due to the higher emission tax (the variable cost of the high technology is cheaper than that of the low technology), so this term acts to encourage high-technology adoption ('technology upgrade incentive'), whereas the second term is related to the expected profit decrease. As we have seen in the low-technology adoption case, the home firms' expected profit decreases due to the higher cost, so they cannot afford to adopt the high technology. Therefore, the home country's high-technology adoption cutoff is determined by these two forces.

2.4.4. Cutoff Productivities for Exports. As in Unel (2013), the change of the export cutoffs can be analyzed by the two equations in (2.31).

$$\text{(2.31)}\quad \varphi_x^*=\left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}}\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l,\qquad \varphi_x=\left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}}\frac{c_l(\tau)}{c_l^*(\tau^*)}t\varphi_l^*.$$

In the right equation, given the increase of φ_l^* and $c_l(\tau)$, φ_x increases. We can call the effect of the increase of φ_l^* 'more competition from the foreign market,' and the increase of c_l, the 'loss of the relative competitiveness' due to the increased burden of the emission tax. As a result of these two combined effects, it is harder for the home firms to export. In the left equation, given the decrease of φ_l and increase of $c_l(\tau)$, φ_x^* decreases. We can call the effect of the decrease of φ_l 'less competition from the home market,' and the increase of c_l, the 'gain of the relative competitiveness' because the home country's loss of relative competitiveness means the opposite gain to the foreign country. As a result of these two combined effects, more foreign firms can export now.

2.5. Stricter Environmental Policy with the Border Carbon Adjustment

In this section, we will explore the case where the home country imposes a border carbon adjustment on the imports from the foreign country alongside a higher domestic carbon tax. As we assumed for the domestic emission tax and tariff, the border carbon adjustment is assumed not to create any tariff revenue; it is only used to control the level of emissions. Therefore, the difference from the previous section is that the foreign country is forced to apply the new emission tax (τ_b^*) to the production for their export. This new emission tax is higher than that for the domestic production of the foreign country, and at maximum, it can be the same as the emission tax in the home country,[12] so ($\tau^* < \tau_b^* \leq \tau$). Then, foreign firms apply the following costs to their exports: $c_l^*(\tau_b^*) > c_l^*(\tau^*)$, $c_h^*(\tau_b^*) > c_h^*(\tau^*)$ and $c_l^*(\tau_b^*)/c_h^*(\tau_b^*) > c_l^*(\tau^*)/c_h^*(\tau^*)$.

2.5.1. Equilibrium Conditions. The equilibrium conditions, which are affected by this policy change, are as below. The ZCP condition of the foreign country's export changes to

$$\pi_{lx}^*(\varphi_x^*) = \frac{r_{lx}^*(\varphi_x^*)}{\sigma} - f_x = 0, \quad \text{which is,} \quad \mu X P^{\sigma-1}\left(\frac{\rho\varphi_x^*}{tc_l^*(\tau_b^*)}\right)^{\sigma-1} = \sigma f_x, \tag{2.47}$$

using the property that $c_l^*(\tau) = c_l(\tau)$. The ZCP condition of the foreign country's high-technology adoption is

$$r_{hd}^*(\varphi_h^*) + r_{hx}^*(\varphi_h^*) - r_{ld}^*(\varphi_h^*) - r_{lx^*}^*(\varphi_h^*) = \sigma(h-1)f_l,$$

which is,

(2.48)

$$\frac{\mu X^*}{\sigma}\left(\frac{P^*\rho}{c_l^*(\tau^*)}\right)^{\sigma-1}\left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1\right)\varphi_h^{*\sigma-1} + \frac{\mu X}{\sigma}\left(\frac{P\rho}{tc_l^*(\tau_b^*)}\right)^{\sigma-1}\left(\left[\frac{c_l^*(\tau_b^*)}{c_h^*(\tau_b^*)}\right]^{\sigma-1} - 1\right)\varphi_h^{*\sigma-1}$$
$$= (h-1)f_l,$$

[12]If the home country imposes a border carbon adjustment which makes the foreign export emission tax higher than their domestic emission price, it will not be persuasive, and it will be hard to justify the purpose of imposing the BCA.

Then, by combining the ZCP condition of the export in one country and the other country's ZCP condition for the low technology, we get the result below.

$$\varphi_x^* = \left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}} \frac{c_l^*(\tau_b^*)}{c_l(\tau)} t\varphi_l, \quad \text{in the same way,} \quad \varphi_x = \left(\frac{f_x}{f_l}\right)^{\frac{1}{\sigma-1}} \frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*. \tag{2.49}$$

Thus, because of the BCA, the foreign exporters face the same cost as the home country producers, so compared to equation (2.31), the left equation has changed in the above. As we did in the previous section, we rewrite φ_h^* below using the ZCP conditions, like equation (2.35).

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left\{ \left(\left[\frac{c_l^*(\tau_b^*)}{c_h^*(\tau_b^*)}\right]^{\sigma-1} - 1 \right) \frac{f_x}{f_l} \varphi_x^{*1-\sigma} + \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1 \right) \varphi_l^{*1-\sigma} \right\}^{\frac{1}{1-\sigma}}. \tag{2.50}$$

To get the FE condition for the foreign country, we start from equation (2.25) of the foreign country.

$$\delta f_e = \int_{\varphi_l^*}^{\infty} \pi_{ld}^*(\varphi) g(\varphi) d\varphi + \int_{\varphi_x^*}^{\infty} \pi_{lx}^*(\varphi) g(\varphi) d\varphi + \int_{\varphi_h^*}^{\infty} [\pi_{hd}^*(\varphi) + \pi_{hx}^*(\varphi) - \pi_{ld}^*(\varphi) - \pi_{lx}^*(\varphi)] g(\varphi) d\varphi.$$

With the Pareto distribution, the free entry condition becomes

$$\frac{\sigma-1}{\theta+1-\sigma} \left[\varphi_l^{*-\theta} f_l + \varphi_x^{*-\theta} f_x + \varphi_h^{*-\theta} (h-1) f_l \right] = \delta f_e. \tag{2.51}$$

Thus, the FE condition does not change even after the policy change.

2.5.2. Cutoff Productivities for Low Technology Adoption. As we have the new relations of φ_x^* with φ_l in (2.49) and φ_h^* with φ_l^* in (2.50), we can represent the FE condition of (2.51) with φ_l, φ_l^* as we did in (2.37).

$$(h-1)^{-\frac{1}{\chi}} \left\{ \left(\left[\frac{c_l^*(\tau_b^*)}{c_h^*(\tau_b^*)}\right]^{\sigma-1} - 1 \right) \left(\frac{c_l^*(\tau_b^*)}{c_l(\tau)} t\varphi_l \right)^{1-\sigma} + \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1 \right) \varphi_l^{*1-\sigma} \right\}^{\frac{1}{\kappa}} + \varphi_l^{*-\theta} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} \left[\frac{c_l^*(\tau_b^*)}{c_l(\tau)}\right]^{-\theta} (t\varphi_l)^{-\theta} = \frac{\delta f_e}{\chi f_l}, \tag{2.52}$$

where $\chi = \frac{\sigma-1}{\theta-\sigma+1} > 0$, $\kappa = \frac{\sigma-1}{\theta} > 0$. From the home country's perspective, we can use equation (2.36) because the BCA does not affect the home country's equilibrium conditions.

$$(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left(\varphi_l^{1-\sigma}+\left[\frac{c_l(\tau)}{c_l^*(\tau^*)}t\varphi_l^*\right]^{1-\sigma}\right)^{\frac{1}{\kappa}}+\varphi_l^{-\theta}+\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(\frac{c_l(\tau)}{c_l^*(\tau^*)}t\varphi_l^*\right)^{-\theta}=\frac{\delta f_e}{\chi f_l},$$

Thus, we can say that the above two equations (2.52) and (2.36) characterize the negative or inverse relationship between the domestic and foreign low-technology cutoff productivities. I will compare the equilibrium characterized by these two equations with the symmetric case and the case where the home country imposes only the unilaterally stricter environmental policy. The current policy mix assumes that emission tax of the home country is greater than that of the foreign country ($\tau > \tau^*$), and this assumption in the previous subsection still holds here too.

The imposition of BCA shifts the curve (2.37) very close to the original curve when the home country imposes the same level of emission tax.[13] In Figure 2.2, we will suppose that this shift results in the move to the original curve. Then, as we can see in Figure 2.2, the new equilibrium point is E'', thus lowering the home country's low-technology adoption cutoff ($\varphi_l^{e''}$) and raising the foreign country's low-technology adoption cutoff ($\varphi_l^{*e''}$) compared to those at the equilibrium of E' ($\varphi_l^{e'}$ and $\varphi_l^{*e'}$). However, at E'', the home country's low-technology adoption cutoff is lower and the foreign country's low-technology adoption cutoff is higher than those of the case of the symmetric equilibrium of E (φ_l^{e} and φ_l^{*e}). Thus, $\varphi_l^{e'} < \varphi_l^{e''} < \varphi_l^{e}$ and $\varphi_l^{*e} < \varphi_l^{*e''} < \varphi_l^{*e'}$. We can say that because of the BCA, the home country's competitiveness in the export market improves at the production using both low technology and high technology. Thus, their expected return increases, which raises the real wage. This acts to expel the less productive firms from the market. However, this is not enough to compensate for the home country's initial competitive loss, as its emission tax is still higher than that of the foreign country for its domestic use. On the contrary, the foreign country loses some of the relative competitiveness of its exports, so its expected return is lower, so the low-technology adoption cutoff decreases.

2.5.3. Cutoff Productivities for Exports. For the export cutoffs, we can compare the unilaterally stricter environmental policy and that policy with the BCA using the equations of

[13]The proof and details of the curve shifts are in the appendix.

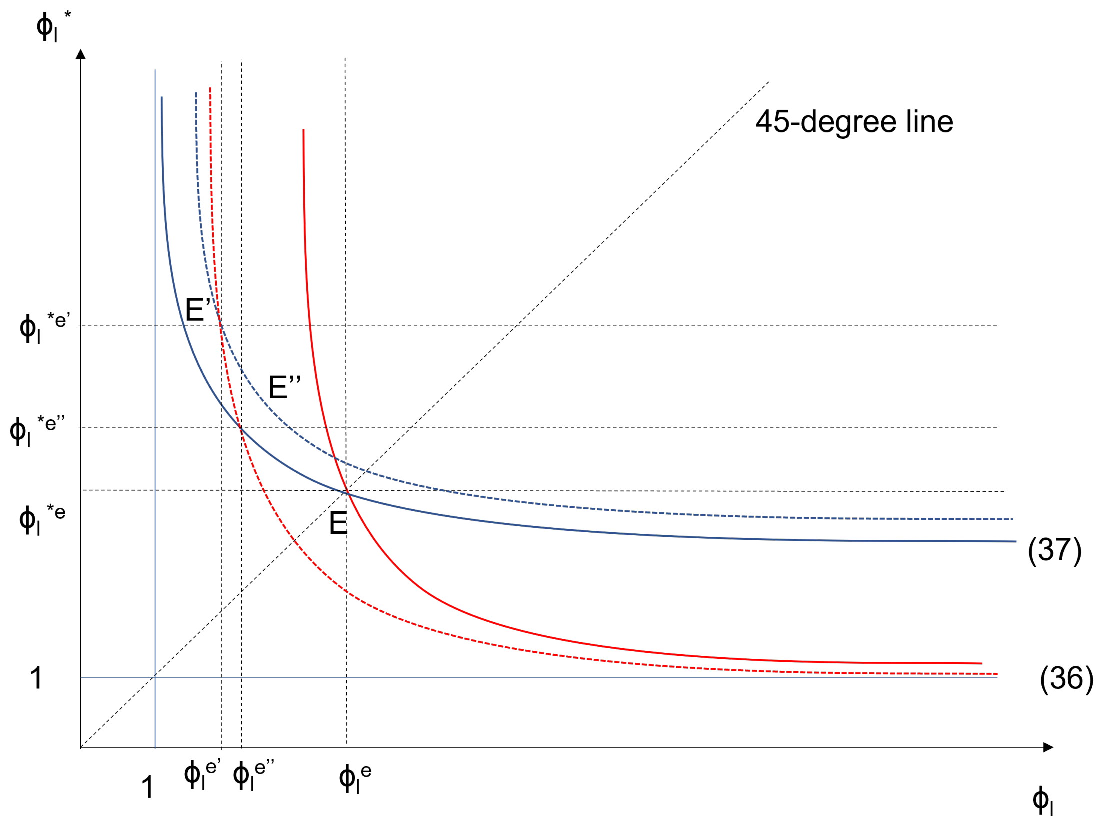


FIGURE 2.2. The Interactions of Low-Technology Adoption Cutoffs under Stricter Emission Tax with Border Carbon Adjustment

(2.49). Given $\varphi_l^{e'} < \varphi_l^{e''}$ and $\varphi_l^{*e''} < \varphi_l^{*e'}$, $\varphi_x^{*e'} < \varphi_x^{*e''}$ and $\varphi_x^{e''} < \varphi_x^{e'}$. If we first look at the right equation of (2.49), compared to the equilibrium E', $c_l(\tau)$ does not change at E'', so 'the relative competitiveness' of the home country does not change. However, as φ_l^* decreases ('less competition from the foreign market'), home exports can increase. In the left equation, the relative price ratio disappears with the imposition of the BCA, so only the effect of the change of φ_l exists. The increase of φ_l can be interpreted as 'more competition from the home market,' so foreign exports decrease.

For the comparison between the equilibria E'' and E, in case of the home export cutoff (φ_x), as $c_l(\tau)$ and φ_l^* are higher at E'' than at E, $\varphi_x^e < \varphi_x^{e''}$. However, we cannot compare them in case of the foreign export cutoff (φ_x^*) because the relationship has changed from (2.31) to (2.49). To check this, we will represent the FE condition of (2.26) with φ_x and φ_x^* and use another graphical approach like the one we used in the low-technology adoption cutoff analysis.

To check the change of the exporting cutoffs (φ_x and φ_x^*), this time, we will rewrite (2.21) and (2.22) as below.

$$\varphi_h = \left[\frac{f_x}{f_l}\right]^{\frac{1}{1-\sigma}} (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1} - 1\right)^{\frac{1}{1-\sigma}} \left(\left[\frac{c_l(\tau)}{c_l^*(\tau^*)t}\right]^{1-\sigma} {\varphi_x^*}^{1-\sigma} + {\varphi_x}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.53}$$

In the same way,

$$\varphi_h^* = \left[\frac{f_x}{f_l}\right]^{\frac{1}{1-\sigma}} (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1\right)^{\frac{1}{1-\sigma}} \left(\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\right]^{1-\sigma} {\varphi_x}^{1-\sigma} + {\varphi_x^*}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.54}$$

As we have the relations of φ_l with φ_x^* in (2.31) and φ_h with φ_x, φ_x^* in the above, we can represent the FE condition of (2.26) with φ_x, φ_x^*.

$$\begin{aligned} &\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\left[\frac{c_l(\tau)}{c_l^*(\tau^*)t}\right]^{1-\sigma} {\varphi_x^*}^{1-\sigma} + {\varphi_x}^{1-\sigma}\right)^{\frac{1}{\kappa}} \\ &\qquad + \frac{f_x}{f_l}\varphi_x^{-\theta} + \left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}} \left(\frac{c_l^*(\tau^*)}{c_l(\tau)}\frac{t}{\varphi_x^*}\right)^{\theta} = \frac{\delta f_e}{\chi f_l}. \end{aligned} \tag{2.55}$$

For the foreign country's perspective, we have the below equation.

$$\begin{aligned} &\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\right]^{1-\sigma} {\varphi_x}^{1-\sigma} + {\varphi_x^*}^{1-\sigma}\right)^{\frac{1}{\kappa}} \\ &\qquad + \frac{f_x}{f_l}{\varphi_x^*}^{-\theta} + \left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}} \left(\frac{c_l(\tau)}{c_l^*(\tau^*)}\frac{t}{\varphi_x}\right)^{\theta} = \frac{\delta f_e}{\chi f_l}. \end{aligned} \tag{2.56}$$

As we did in the case of the low-technology cutoffs in the previous subsection, the above two equations characterize the inverse relationship between the domestic and foreign exports' cutoff productivities. The exactly symmetric case equilibrium is $\varphi_x = \varphi_x^*$. Starting from this, if we draw the curves of equations (2.55) and (2.56) on the plane consisting of φ_x on the x-axis and φ_x^* on the y-axis, we get the intersection of these two curves at a 45-degree line. We check the slope of these two curves at the intersection by taking the total derivatives and using the property of the

45-degree intersection ($c_l(\tau) = c_l^*(\tau^*)$, $c_h(\tau) = c_h^*(\tau^*)$, and $\varphi_x = \varphi_x^*$). Then, (2.55) gives us

$$\left|\frac{d\varphi_x^*}{d\varphi_x}\right| = \frac{\lambda + \frac{f_k}{f_l}}{\lambda t^{\sigma-1} + \left[\frac{f_k}{f_l}\right]^{\frac{1}{\kappa}} t^{\theta}}. \tag{2.57}$$

where $\lambda = \left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(t^{\sigma-1}+1\right)^{\frac{1}{\chi}}$. Taking the total derivative of (2.56) gives us

$$\left|\frac{d\varphi_x^*}{d\varphi_x}\right| = \frac{\lambda^* t^{\sigma-1} + \left[\frac{f_k}{f_l}\right]^{\frac{1}{\kappa}} t^{\theta}}{\lambda^* + \frac{f_k}{f_l}}, \tag{2.58}$$

where $\lambda^* = \left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(t^{\sigma-1}+1\right)^{\frac{1}{\chi}}$. Because $t > 1$ and by (2.33), $\left|d\varphi_x^*/d\varphi_x\right| < 1$ for (2.57) and $\left|d\varphi_l^*/d\varphi_l\right| > 1$ for (2.58). Thus, if we draw a curve of φ_x on the horizontal axis and φ_x^* on the vertical axis, the slope of (2.56) is steeper than that of (2.55) at the 45-degree intersection point. Here, we need a condition like (2.40) for the complete description of the equilibrium. As in the case of the low-technology adoption cutoffs' interactions, in Figure 2.3, there exists an equilibrium only if the two curves intersect. Therefore, the range of τ should be within the range where these two curves intersect. For a given τ^*, denote $\varphi_x(\tau^*)$ as the solution to (2.56) when $\varphi_x^* = 1$, and denote $\varphi_x^*(\tau^*)$ as the solution to (2.56) when $\varphi_x = 1$. Further denote $\underline{\tau_x}(\tau^*)$ as the solution to (2.55) when $(\varphi_x, \varphi_x^*) = (\varphi_x(\tau^*), 1)$. Then, if $\tau < \underline{\tau_x}(\tau^*)$, the two curves of (2.55) and (2.56) do not intersect. In the same way, we can define $\overline{\tau_x}(\tau^*)$ as the solution to (2.55) when $(\varphi_x, \varphi_x^*) = (1, \varphi_x^*(\tau^*))$. Then, if $\tau > \overline{\tau_x}(\tau^*)$, the two curves of (2.55) and (2.56) do not intersect. Thus, the condition that there is an equilibrium from (2.55) and (2.56) is

$$\underline{\tau_x}(\tau^*) \leq \tau \leq \overline{\tau_x}(\tau^*). \tag{2.59}$$

As the interpretation of (2.40), we can interpret the above condition as the way to ensure that the difference of the emission taxes should not be too large. When the domestic emission tax is too high ($\tau > \overline{\tau_x}(\tau^*)$), the home country cannot export its manufacturing goods at all, and when the domestic emission tax is too low compared to the foreign country's ($\tau < \underline{\tau_x}(\tau^*)$), the foreign country cannot export its manufacturing goods. Thus, we exclude these extreme cases and assume that the above condition holds.

As usually assumed, $\varphi_l < \varphi_x$ is also assumed here too, so the upper bound part of (2.59) holds when (2.40) holds, and the lower bound part of (2.40) holds when (2.59) holds. Thus, the combined condition of equilibrium is

$$\underline{\tau_x}(\tau^*) \leq \tau \leq \overline{\tau_l}(\tau^*). \tag{2.60}$$

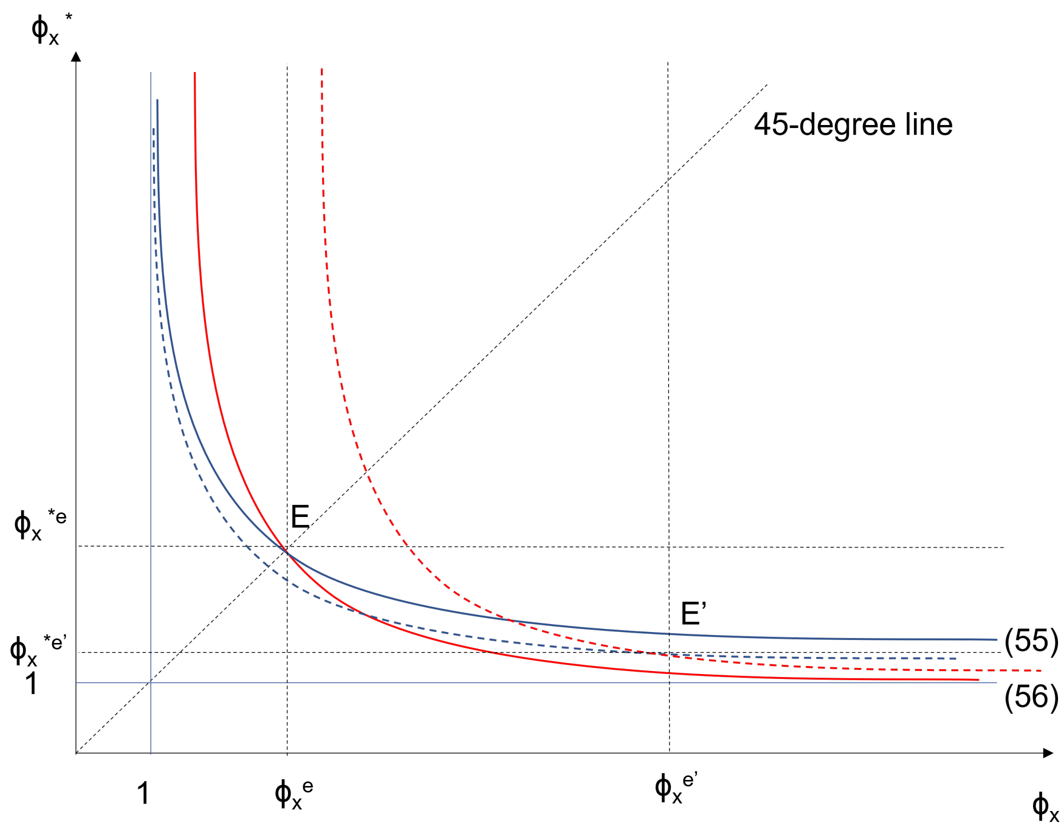


Figure 2.3. The Interactions of Export Cutoffs

We will explore the case of asymmetry in the emission prices ($\tau \neq \tau^*$), from here, then proceed to check the case of the higher emission tax with BCA. As we checked for the case of the low-technology adoption, the effects of the home adopting the stricter environmental policy ($\tau > \tau^*$) are the increase of $c_l(\tau)$, $c_h(\tau)$, and $c_l(\tau)/c_h(\tau)$ given the environmentally friendly technology advancement. Here, as there are no changes in τ^*, $c_l^*(\tau^*)$, and $c_h^*(\tau^*)$, $c_l^*(\tau^*)/c_h^*(\tau^*)$ remains the same. Given these changes, the effect of the increase in τ can be represented as the shift of the two curves as depicted in Figure 2.3. The initial equilibrium starts at E, where (2.55) and (2.56), the two solid lines, intersect. As a result of the increase of τ, (2.55) shifts to the left and (2.56) shifts to the right, as represented by the dotted lines.[14] The new equilibrium (E') shows that the domestic export cutoff (φ_x) increases, whereas the foreign export cutoff (φ_x^*) decreases. We interpreted these changes in the previous section.

Now, we will check what happens if the home country imposes a higher emission tax for domestic goods and applies the BCA to imports. Given the change of the relationship between φ_l and φ_x^* in (2.49), (2.53) can be now represented as below.

$$\varphi_h = \left[\frac{f_x}{f_l}\right]^{\frac{1}{1-\sigma}} (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1} - 1\right)^{\frac{1}{1-\sigma}} \left(\left[\frac{c_l^*(\tau_b^*)t}{c_l(\tau)}\right]^{\sigma-1} {\varphi_x^*}^{1-\sigma} + {\varphi_x}^{1-\sigma}\right)^{\frac{1}{1-\sigma}}. \tag{2.61}$$

Then, as we represent the FE condition of home using φ_x, φ_x^*, (2.55) changes as below.

$$\begin{aligned}&\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\left[\frac{c_l^*(\tau_b^*)t}{c_l(\tau)}\right]^{\sigma-1} {\varphi_x^*}^{1-\sigma} + {\varphi_x}^{1-\sigma}\right)^{\frac{1}{\kappa}} + \frac{f_x}{f_l}\varphi_x^{-\theta} \\ &+ \left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}} \left[\frac{c_l^*(\tau_b^*)t}{c_l(\tau)}\right]^{\theta} {\varphi_x^*}^{-\theta} = \frac{\delta f_e}{\chi f_l}.\end{aligned} \tag{2.62}$$

For the change of φ_h^*, we start from (2.50) and substitute φ_x and φ_x^* from (2.49).

(2.63)

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left[\frac{f_x}{f_l}\right]^{\frac{1}{1-\sigma}} \left\{\left(\left[\frac{c_l^*(\tau_b^*)}{c_h^*(\tau_b^*)}\right]^{\sigma-1} - 1\right) {\varphi_x^*}^{1-\sigma} + \left(\frac{c_l(\tau)t}{c_l^*(\tau^*)}\right)^{\sigma-1} \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1\right) {\varphi_x}^{1-\sigma}\right\}^{\frac{1}{1-\sigma}}.$$

[14] The proof and details of the curve shifts are in the appendix.

Then, as we represent the FE condition of the foreign country using φ_x, φ_x^*, (2.56) changes as below.

(2.64)

$$\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left\{\left(\left[\frac{c_l^*(\tau_b^*)}{c_h^*(\tau_b^*)}\right]^{\sigma-1}-1\right)\varphi_x^{*\,1-\sigma}+\left(\frac{c_l(\tau)t}{c_l^*(\tau^*)}\right)^{\sigma-1}\left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1}-1\right)\varphi_x{}^{1-\sigma}\right\}^{\frac{1}{\kappa}}$$

$$+\frac{f_x}{f_l}\varphi_x^{*\,-\theta}+\left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}}\left(\frac{c_l(\tau)}{c_l^*(\tau^*)}\frac{t}{\varphi_x}\right)^{\theta}=\frac{\delta f_e}{\chi f_l}.$$

Now, the above two equations (2.62) and (2.64) characterize the negative or inverse relationship

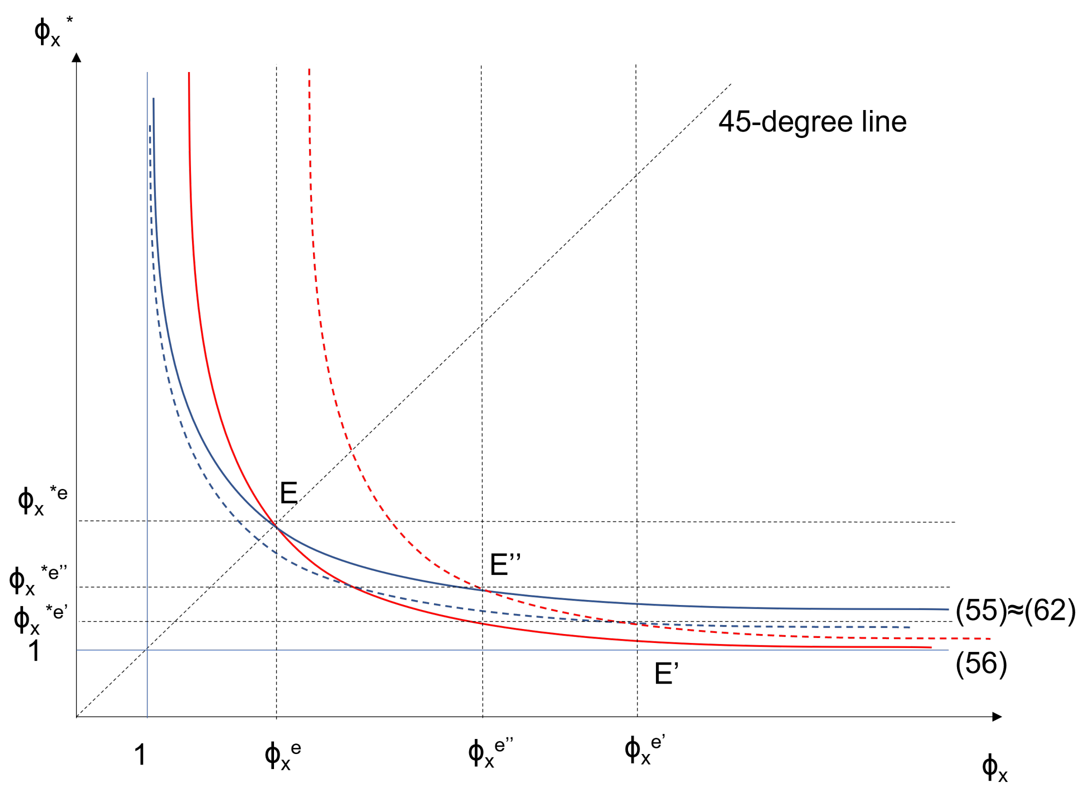


FIGURE 2.4. The Interactions of Export Cutoffs under Stricter Emission Tax with Border Carbon Adjustment

between the domestic and foreign export cutoff productivities, as we did in the low-technology cutoffs case. We can now compare the foreign export cutoffs of the symmetric case and the case where the home country imposes a unilaterally stricter environmental policy with the BCA. The imposition of BCA replaces the dotted curve of (2.55) with the curve (2.62), which is very close to the original curve (solid blue line) when the home country imposes the same level of emission tax.[15] In Figure 2.4, we suppose that this shift results in the move to the original curve (solid blue line). It also replaces the curve (2.56) with (2.64), which is to the right of the solid red line. The conclusion does not change whether the graph (2.64) is to the left or right of the dotted red line, so we suppose that (2.64) stays the same graph with the dotted red line. Then, as we can see, the new equilibrium point is E'', thus lowering the home country's export cutoff ($\varphi_x^{e''}$) and raising the foreign country's export cutoff ($\varphi_x^{*e''}$), compared to those at the equilibrium of E' ($\varphi_x^{e'}$ and $\varphi_x^{*e'}$), as we could also check without this graphical approach. However, the home country's export cutoff is still higher and the foreign country's export cutoff is lower than those of the case of the symmetric equilibrium of E (φ_x^e and φ_x^{*e}). Thus, $\varphi_x^e < \varphi_x^{e''} < \varphi_x^{e'}$ and $\varphi_x^{*e'} < \varphi_x^{*e''} < \varphi_x^{*e}$. We can say that because of the BCA, the foreign country has lost some of its 'relative competitiveness' because it should apply the higher emission tax to its exports like the home country. However, its export cutoff is lower than the initial E because it faces less competition from the home country. Meanwhile, the home country could recover some of its 'relative competitiveness,' as the foreign country firms also face the higher emission tax. However, its export cutoff is still higher than the initial equilibrium because it faces higher competition from the foreign country.

2.5.4. Cutoff Productivities for High-Technology Adoption. To check the change of φ_h, we can still use equation (2.46), as the imposition of the BCA does not affect the home country's ZCP condition or FE condition.

$$\left\{\left(\varphi_l^{1-\sigma} + \frac{f_x}{f_l}\varphi_x^{1-\sigma}\right) + (h-1)\frac{\varphi_x^{\theta+1-\sigma}}{\varphi_h^{\theta}}\right\}\frac{1}{\varphi_h}\frac{d\varphi_h}{d\tau} =$$
$$\underbrace{-\frac{1}{\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1}\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-2}\left(\varphi_l^{1-\sigma} + \frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)\frac{dc_l(\tau)/c_h(\tau)}{d\tau}}_{\text{technology upgrade incentive(-)}} + \underbrace{\left(\frac{\varphi_l^{\theta+1-\sigma} - \varphi_x^{\theta+1-\sigma}}{\varphi_l^{\theta+1}}\right)\frac{d\varphi_l}{d\tau}}_{\text{expected profit decrease(+)}}. \quad (2.43)$$

Among the terms in the second line, φ_l and φ_x are affected by the imposition of the BCA. φ_l increases and φ_x decreases compared to the unilateral higher emission tax, but the term $\left(\varphi_l^{1-\sigma} + \frac{f_x}{f_l}\varphi_x^{1-\sigma}\right)$ is still positive, so the 'technology upgrade incentive' still acts to lower the high-technology cutoff. For the second term, the absolute value of the term in front of $\frac{d\varphi_l}{d\tau}$ decreases. In

[15] The proof and details of the curve shifts are in the appendix.

the previous section, we checked that this term is related to the expected profit decrease. By the imposition of the BCA, the home firms' expected profit can be recovered, as it is more affordable for them to adopt the high technology than in the unilateral policy case. Therefore, the effect of the second term (expected profit decrease) decreases, so we can expect that the home country's high-technology adoption cutoff is lower than that under the unilateral policy.

To check the change of φ_h^*, we compare the determination of φ_h^* in (2.22) under the home country's unilateral policy and in (2.50) with the BCA.

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)} \right]^{\sigma-1} - 1 \right)^{\frac{1}{1-\sigma}} \left(\varphi_l^{*1-\sigma} + \frac{f_x}{f_l} \varphi_x^{*1-\sigma} \right)^{\frac{1}{1-\sigma}}. \quad (2.22)$$

$$\varphi_h^* = (h-1)^{\frac{1}{\sigma-1}} \left\{ \left(\left[\frac{c_l(\tau)}{c_h(\tau)} \right]^{\sigma-1} - 1 \right) \frac{f_x}{f_l} \varphi_x^{*1-\sigma} + \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)} \right]^{\sigma-1} - 1 \right) \varphi_l^{*1-\sigma} \right\}^{\frac{1}{1-\sigma}}. \quad (2.50)$$

The difference between these two equations is that the cost ratio term for exports has changed to $c_l(\tau)/c_h(\tau)$ in (2.50), as the foreign country applies the same cost as the home country. This term acts to lower φ_h^*, because adopting high technology is more beneficial for the foreign firms. However, the change of φ_l^* and φ_x^* acts to raise φ_h^* because the expected profit from exports now decreases compared to that under the home country's unilateral policy, so the cutoff productivity for the high-technology adoption will be determined by these competing forces.

To summarize, for the low-technology adoption cutoffs, we have $\varphi_l^{e'} < \varphi_l^{e''} < \varphi_l^{e}$ and $\varphi_l^{*e} < \varphi_l^{*e''} < \varphi_l^{*e'}$. For the export cutoffs, we have $\varphi_x^{e} < \varphi_x^{e''} < \varphi_x^{e'}$ and $\varphi_x^{*e'} < \varphi_x^{*e''} < \varphi_x^{*e}$. For the high-technology adoption cutoffs, $\varphi_h^{e''} < \varphi_h^{e'}$ and $\varphi_h^{*e'} < \varphi_h^{*e}$ are certain, but we cannot determine which one is bigger for φ_h^{e} or $\varphi_h^{*e''}$ with other equilibrium results. As we cannot get the analytical derivations of these, in the next section, we will explore the numerical simulation to get some sense of what will happen to these high-technology cutoffs.

2.6. Numerical Simulation

In the previous sections, we explored the analytical derivations of the asymmetric Melitz model using the graphical approach. We could recognize the shifts of the cutoff variables of low-technology adoption (φ_l) and exports (φ_x) and some of the high-technology adoption (φ_h). However, we could not get the direction of the high-technology cutoffs in some cases, as they depend on conflicting forces. In addition, there was another limitation to this graphical approach: it is hard to check the degree of the cutoff changes. We will see that these are needed to calculate the emissions in the following sections. To supplement these limitations, in this section, we will check these with the numerical simulation with some plausible parameters and calibrations. We will simulate three policy scenarios, as we did in the previous sections: the symmetric environmental policy($\tau = \tau^* = 1$), the home country imposing a higher emission tax ($\tau = 1.2 > \tau^* = 1$) without BCA, and the home country imposing a higher emission tax with BCA that makes the foreign export emission tax the same as that of the home country ($\tau_b^* = \tau = 1.2$). In addition to that, we will simulate one more scenario where both countries impose a higher emission tax ($\tau = \tau^* = 1.2$). This will serve as another baseline to compare the policy scenarios, as there will be no leakage, and this can be an ideal case if this price of emission is the same as the marginal damage of the emission ($\tau = \tau^* = 1.2 = \beta$, Pigouvian tax), as is well known by Baumol and Oates (1988).

2.6.1. Parameters. The assumed and calibrated parameters are in Table 2.1. As we assume

TABLE 2.1. Parameters for Numerical Simulation

Parameters	Symbols	Value
Abatement efficiency of low-technology	a_l	1.0
Abatement efficiency of high-technology	a_h	1.2
Elasticity of substitution between inputs	η	0.5
Elasticity of substitution across variety	σ	4.0
Pareto distribution parameter	θ	4.25
Fixed cost of entry	f_e	1.0
Fixed cost of low-technology adoption	f_l	1.0
Fixed cost of high-technology adoption	$f_h = hf_l$	4.1
Fixed cost of export	f_x	0.814
Iceberg trade cost	t	1.6
Market exit rate	δ	0.55
Non-agricultural production ratio	μ	0.935
Labor supply	$L_s = L_s^*$	222.63

that high technology is labor-biased, I chose elasticity of substitution between inputs less than 1 ($\eta = 0.5 < 1$). For the remaining parameters, I brought them from the previous research, following Cui (2017). The ratio of the abatement efficiency ($a_h/a_l = 1.2$) and elasticity of substitution across

Table 2.2. Simulation Results of the Cutoffs

Variables	Symbols	Policy scenarios: Symmetric Policy $\tau = \tau^* = 1$	Unilateral Policy($\tau = 1.2$) Without BCA	Unilateral Policy($\tau = 1.2$) With BCA	Symmetric Policy $\tau = \tau^* = 1.2$
Home country					
Cutoff productivity of low-tech adoption	φ_l	1.506	1.489	1.491	1.510
Cutoff productivity of export	φ_x	2.250	2.524	2.475	2.255
Cutoff productivity of high-tech adoption	φ_h	3.029	3.005	3.002	2.984
Fraction of the high-tech firms	$(\varphi_l/\varphi_h)^\theta$	0.051	0.051	0.051	0.055
Fraction of exporters	$(\varphi_l/\varphi_x)^\theta$	0.182	0.106	0.116	0.182
Fraction of the high-tech firms in export	$(\varphi_x/\varphi_h)^\theta$	0.283	0.476	0.441	0.304
Mass of the existing firms	M	11.711	10.170	11.440	11.603
Foreign country					
Cutoff productivity of low-tech adoption	φ_l^*	1.506	1.539	1.509	1.510
Cutoff productivity of export	φ_x^*	2.250	2.026	2.228	2.255
Cutoff productivity of high-tech adoption	φ_h^*	3.029	3.007	3.018	2.984
Fraction of the high-tech firms	$(\varphi_l^*/\varphi_h^*)^\theta$	0.051	0.058	0.053	0.055
Fraction of exporters	$(\varphi_l^*/\varphi_x^*)^\theta$	0.182	0.311	0.191	0.182
Fraction of the high-tech firms in export	$(\varphi_x^*/\varphi_h^*)^\theta$	0.283	0.187	0.276	0.304
Mass of the existing firms	M^*	11.711	12.538	12.341	11.603

variety ($\sigma = 4.0$) are from Cui (2017). The Pareto distribution parameter ($\theta = 4.25$) is from Melitz and Redding (2015). As in Cui (2017), the fixed costs of entry and low-technology adoption are normalized to 1 ($f_e = f_l = 1$). The fixed costs of export ($f_x = 0.814$), high-technology adoption ($f_h = 4.1$), and the iceberg trade cost ($t = 1.6$) are from the calibration by Cui (2017), which match the facts that around 18% of US manufacturing firms choose to export, around 11.6% of manufacturing firms use energy-saving technology, and export value's share of GDP is 14% (Bernard et al., 2007a; Cui, 2017). $\mu = 0.935$ is from the ratio of the non-agricultural goods production, and $L_s = L_s^* = 222.63$ (0.1 million) is the employment in the production sector in the US 2020 data from the US Bureau of Labor Statistics.

2.6.2. Simulation Results. Table 2.2 shows the numerical simulation results.[16] Even though these simulation results hold under the specific parameters above, we can get some implications that we could not get in the previous analytical derivation due to the conflicting forces.

In the analytical derivation, we have seen that when the home country's emission tax (τ) is increased, the cutoff for high-technology adoption for the home country (φ_h) is determined by the 'technology upgrade incentive,' which lowers φ_h, and 'decreased expected profit,' which raises φ_h.

[16]The graphical analysis results are attached in the appendix.

In the simulation, φ_h turns out to decrease as a result of the higher emission tax, so we can see that the effect of the 'technology upgrade incentive' is greater than that of 'decreased expected profit.' The imposition of the BCA recovers some part of the home country firms' expected profit, so it makes more home firms adopt the high technology while leaving the 'technology upgrade incentive' the same as before, so φ_h decreases further under the BCA. Now we get the result that $\varphi_h^{e''} < \varphi_h^{e'} < \varphi_h^{e}$.

In the previous section, we saw that the home country's higher emission tax lowers the foreign country's high-technology adoption cutoff ($\varphi_h^{*e'} < \varphi_h^{*e}$) because of the 'increased expected profit.' However, imposing the BCA created two competing forces: the first one raises the foreign country's high-technology adoption cutoff compared to the home country's unilateral policy, as the foreign firms' expected profit decreases, and the second one gives a higher incentive for the foreign firms to adopt higher technology because the cost ratio changes for their exports. From these simulation results, the high-technology adoption for the foreign firms under the BCA lies between those previous equilibrium results, that is, $\varphi_h^{*e'} < \varphi_h^{*e''} < \varphi_h^{*e}$, which implies that the 'decreased expected profit' effect is greater than the 'technology upgrade incentive' caused by the imposition of the BCA.

We also checked the ratios of the cutoffs because they are needed when calculating the emissions in the next section. $(\varphi_l/\varphi_h)^\theta$ is the ratio of the high-technology-adopting firms among the existing firms, because $(\varphi_l/\varphi_h)^\theta = [1 - G(\varphi_h)]/[1 - G(\varphi_l)]$. $(\varphi_l/\varphi_x)^\theta$ is the ratio of the exporters among the existing firms, as $(\varphi_l/\varphi_x)^\theta = [1 - G(\varphi_x)]/[1 - G(\varphi_l)]$. Lastly, $(\varphi_x/\varphi_h)^\theta$ is the ratio of the high-technology-adopting firms among the exporters, as $(\varphi_x/\varphi_h)^\theta = [1 - G(\varphi_h)]/[1 - G(\varphi_x)]$.

2.7. Equilibrium Results on Welfare

2.7.1. Utility from Consumption in the Home Country. With the results of the stricter environmental policy with and without the BCA on the cost and cost ratios for the individual firms and the cutoff productivities, here we examine the policy effects on the utility from consumption as in Unel (2013) and the total emissions and then overall welfare by balancing these two factors.

As we assume that the source of the expenditure is the labor wage, and the wage is normalized to 1, $X = X^* = \bar{L}$. Then, the expenditure on the non-polluting good in (2.5) is $(1-\mu)\bar{L}$, and the total expenditure on the manufacturing goods is $\mu\bar{L} = PQ$. Then, the welfare from the consumption of goods is

$$U_1 = \left[\frac{\mu}{P}\right]^{\mu} (1-\mu)^{1-\mu} \bar{L}, \tag{2.65}$$

where U_1 is the first part of the welfare, which is from the consumption. We will bring the derivation of the composite price index from the ZCP condition of (2.13), as $P = \left(\frac{\sigma f_l}{\mu \bar{L}}\right)^{\frac{1}{\sigma-1}} \frac{c_l(\tau)}{\rho \varphi_l}$. Then, the welfare is

$$U_1 = \left(\frac{\mu \bar{L}}{\sigma f_l}\right)^{\frac{\mu}{\sigma-1}} \left[\frac{\rho \varphi_l}{c_l(\tau)}\right]^{\mu} \mu^{\mu} (1-\mu)^{1-\mu} \bar{L}. \tag{2.66}$$

Now, the welfare is inversely related to $c_l(\tau)$ and positively related to φ_l. This makes sense, because the increase of $c_l(\tau)$ raises the price, thus decreasing the real wage. The increase of φ_l means that the least productive firms exit the manufacturing market and the remaining firms with higher productivity will gain higher profits. As we have seen in the previous subsection, the stricter environmental policy raises $c_l(\tau)$ and lowers φ_l; thus, the home country's utility from the consumption decreases in two ways. First, the increase of the variable cost is reflected in the consumer's price by the markup because the manufacturing goods market is a monopolistic competition. In addition, because the home firms lose competitiveness compared to the foreign firms, more inefficient firms are able to sneak into the market, and they take the role of making the goods with lower productivity than before. As a result, the welfare of the home country from the consumption deteriorates. If the home country imposes the BCA, the home country's low-technology cutoff recovers a little bit, so the welfare is improved compared to the unilateral environmental policy only. However, the recovery of φ_l is not complete compared to the initial equilibrium, and $c_l(\tau)$ is still higher than the initial point, so the welfare is still lower than the initial equilibrium, so $U_1^{e'} < U_1^{e''} < U_1^{e}$.

2.7.2. Utility from Consumption in the Foreign Country. From the perspective of the foreign country, the utility from consumption can be represented as

$$U_1^* = \left(\frac{\mu \bar{L}}{\sigma f_l}\right)^{\frac{\mu}{\sigma-1}} \left[\frac{\rho \varphi_l^*}{c_l^*(\tau^*)}\right]^{\mu} \mu^{\mu} (1-\mu)^{1-\mu} \bar{L}. \tag{2.67}$$

As we can see in the above equation, the foreign utility from consumption is also inversely related to $c_l^*(\tau^*)$ and positively related to φ_l^*. Although $c_l^*(\tau^*)$ is not affected by the home country's stricter environmental policy, φ_l^* increases due to the policy. This means that the foreign country takes the role of making the goods with higher productivity than before; thus, the expected profit of the foreign firms increases. As a result, the foreign country's overall utility from consumption increases. In addition, if emissions are reduced by the home country's policy, the foreign country can enjoy the additional benefit by free-riding on it too. After the imposition of the BCA, this utility improvement decreases as φ_l^* decreases, but as we checked in the previous section, it is still higher than the initial equilibrium, so the foreign country can enjoy the utility gain from the consumption, so $U_1^{*e} < U_1^{*e''} < U_1^{*e'}$.

2.7.3. Emissions from the Home Production. In this subsection, we will check the remaining part of the welfare, which is related to the disutility created by CO_2 emissions. We can get the demand for the factors for inputs by Shephard's lemma, so the demand for emissions is

$$E_{jd}(\varphi) = \frac{\partial C_j}{\partial \tau} = \frac{\partial c_j}{\partial \tau}\frac{q_{jd}}{\varphi} = \frac{q_{jd}}{\varphi}\frac{\tau^{-\eta}}{a_j^{1-\eta}}c_j^{\eta} = \frac{\mu X \rho^{\sigma}}{(P\varphi)^{1-\sigma}}c_j^{\eta-\sigma}\frac{\tau^{-\eta}}{a_j^{1-\eta}}, \tag{2.68}$$

$$E_{jx}(\varphi) = \frac{\partial C_j}{\partial \tau} = \frac{\partial c_j}{\partial \tau}\frac{q_{jx}}{\varphi} = \frac{q_{jx}}{\varphi}\frac{\tau^{-\eta}}{a_j^{1-\eta}}c_j^{\eta} = \frac{\mu X^* \rho^{\sigma}}{(P^*\varphi)^{1-\sigma}t^{\sigma}}c_j^{\eta-\sigma}\frac{\tau^{-\eta}}{a_j^{1-\eta}}, \tag{2.69}$$

where $j = l, h$. The last equalities in the above equations hold from the definitions of q_{jd}, q_{jx} and $r_{jd}(\varphi)$, $r_{jx}(\varphi)$. We can easily see that emissions are inversely related to the emission price τ, and if a firm adopts high technology (a_h), it emits less than a low-technology (a_l) firm. We can calculate the emission intensities by dividing the emission by the production.

$$e_{jd}(\varphi) = \frac{E_{jd}(\varphi)}{q_{jd}} = \frac{\partial C_j}{\partial \tau}\frac{1}{q_{jd}} = \frac{\partial c_j}{\partial \tau}\frac{1}{\varphi} = \frac{c_j^{\eta}}{\varphi}\frac{\tau^{-\eta}}{a_j^{1-\eta}}, \tag{2.70}$$

$$e_{jx}(\varphi) = \frac{E_{jx}(\varphi)}{q_{jx}} = \frac{\partial C_j}{\partial \tau}\frac{1}{q_{jx}} = \frac{\partial c_j}{\partial \tau}\frac{1}{\varphi} = \frac{c_j^{\eta}}{\varphi}\frac{\tau^{-\eta}}{a_j^{1-\eta}}, \tag{2.71}$$

where $j = l, h$. We can see that $e_{jd}(\varphi) = e_{jx}(\varphi) = e_j(\varphi)$, which means that as we divide the emission by the production, the emission intensity is the same between export goods and domestic consumption goods. We can also see that the emission intensity is inversely related to the emission price τ, and if a firm adopts high technology (a_h), its intensity is lower than that of a low-technology (a_l) firm. Given the results above, we can get the aggregate domestic demand for emissions.

$$E = \int_{\varphi_l}^{\varphi_h} E_{ld}(\varphi) M\gamma(\varphi) d\varphi + \int_{\varphi_x}^{\varphi_h} E_{lx}(\varphi) M\gamma(\varphi) d\varphi + \int_{\varphi_h}^{\infty} \big(E_{hd}(\varphi) + E_{hx}(\varphi)\big) M\gamma(\varphi) d\varphi, \tag{2.72}$$

where M is the mass of the existing firms. Using the demand for the emissions above and the Pareto distribution of $\gamma(\varphi)$,

$$\begin{aligned} E =& \mu M X P^{\sigma-1} \theta \rho^{\sigma} \varphi_l^{\theta} \tau^{-\eta} \left(\frac{c_l(\tau)^{\eta-\sigma}}{a_l^{1-\eta}} \int_{\varphi_l}^{\varphi_h} \varphi^{\sigma-\theta-2} d\varphi + \frac{c_h(\tau)^{\eta-\sigma}}{a_h^{1-\eta}} \int_{\varphi_h}^{\infty} \varphi^{\sigma-\theta-2} d\varphi \right) \\ & + \mu M X^* P^{*\sigma-1} \theta \left(\frac{\rho}{t}\right)^{\sigma} \varphi_l^{\theta} \tau^{-\eta} \left(\frac{c_l(\tau)^{\eta-\sigma}}{a_l^{1-\eta}} \int_{\varphi_x}^{\varphi_h} \varphi^{\sigma-\theta-2} d\varphi + \frac{c_h(\tau)^{\eta-\sigma}}{a_h^{1-\eta}} \int_{\varphi_h}^{\infty} \varphi^{\sigma-\theta-2} d\varphi \right) \end{aligned}$$

(2.73)

$$\begin{aligned} =& \mu M X P^{\sigma-1} \rho^{\sigma} \frac{\theta}{\theta-\sigma+1} \varphi_l^{\sigma-1} \tau^{-\eta} \frac{c_l(\tau)^{\eta-\sigma}}{a_l^{1-\eta}} \left\{ 1 + \left(\left[\frac{a_l}{a_h}\right]^{1-\eta} \left[\frac{c_h(\tau)}{c_l(\tau)}\right]^{\eta-\sigma} - 1 \right) \left(\frac{\varphi_l}{\varphi_h}\right)^{\theta-\sigma+1} \right\} \\ & + \mu M X^* P^{*\sigma-1} \left(\frac{\rho}{t}\right)^{\sigma} \left(\frac{\varphi_l}{\varphi_x}\right)^{\theta} \tau^{-\eta} \frac{\theta}{\theta-\sigma+1} \varphi_x^{\sigma-1} \frac{c_l(\tau)^{\eta-\sigma}}{a_l^{1-\eta}} \left\{ 1 + \left(\left[\frac{a_l}{a_h}\right]^{1-\eta} \left[\frac{c_h(\tau)}{c_l(\tau)}\right]^{\eta-\sigma} - 1 \right) \left(\frac{\varphi_x}{\varphi_h}\right)^{\theta-\sigma+1} \right\}. \end{aligned}$$

Using the ZCP conditions to get the price index again,

$$\begin{aligned} E =& \widetilde{M} f_l \left\{ \underbrace{\frac{1}{a_l^{1-\eta}} \left(1 - \left[\frac{\varphi_l}{\varphi_h}\right]^{\theta-\sigma+1} \right)}_{\text{emiss. low-tech production}} + \underbrace{\frac{1}{a_h^{1-\eta}} \left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-\eta} \left(\frac{\varphi_l}{\varphi_h}\right)^{\theta-\sigma+1}}_{\text{emiss. high-tech production}} \right\} \\ & + \widetilde{M} \frac{f_x}{t} \underbrace{\left(\frac{\varphi_l}{\varphi_x}\right)^{\theta}}_{\text{exporter ratio}} \left\{ \underbrace{\frac{1}{a_l^{1-\eta}} \left(1 - \left[\frac{\varphi_x}{\varphi_h}\right]^{\theta-\sigma+1} \right)}_{\text{emiss. low-tech production}} + \underbrace{\frac{1}{a_h^{1-\eta}} \left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-\eta} \left(\frac{\varphi_x}{\varphi_h}\right)^{\theta-\sigma+1}}_{\text{emiss. high-tech production}} \right\}, \end{aligned} \tag{2.74}$$

where $\widetilde{M} = \underbrace{M}_{\text{mass effect}} \sigma\rho \underbrace{\tau^{-\eta} c_l(\tau)^{\eta-1}}_{\text{price effect}} \frac{\theta}{\theta-\sigma+1}$, which affects the emission as the common factors. The stricter environmental policy reduces the mass of the firms and thus decreases the emissions ('mass effect'). $\tau^{-\eta}$ and $c_l(\tau)^{\eta-1}$ reflect the decreasing demand for emissions by each company as a result of the emission price increase; we checked this in the previous section. The stricter environmental policy (increase of τ) raises the cost $c_l(\tau)$, and given the condition that $0 < \eta < 1$, emissions are decreased by these two terms ('price effect').

Emissions from Production for the Domestic Market. The first line is the emissions from production for the domestic market. The first term in the curly brackets is from production for the domestic market using low technology, and the second term in the curly brackets is the emissions from production for the domestic market using high technology. As we saw in the previous section, the environmental policy affects the cutoff productivities. Therefore, the ratio of the high-technology-adopting firms among the existing firms, $(\varphi_l/\varphi_h)^\theta$, affects the composition of the emissions. If this ratio decreases, given the condition that $\theta - \sigma + 1 > 0$, the emissions from the production using low technology increase, whereas the emissions from the production using high technology decrease. This is like the 'scale effect' in Kreickemeier and Richter (2014) because the amount of the emissions is proportional to the quantity of the production.[17]

There is another effect from the change of the φ_l/φ_h ratio, which is from the emission efficiency (a_l and a_h). We know that $a_l < a_h$, thus production using high technology is better at reducing emissions ('abatement efficiency'). Thus, if the home country's production using high technology increases because of the higher emission tax, it can act to reduce the emissions.[18] If the home country government intends to decrease emissions via this channel ('technology converting effect'), it will want to lower φ_h. The cutoff productivity for high-technology adoption (φ_h) is determined by two forces, the 'technology upgrade incentive' and 'expected profit.' The 'technology upgrade incentive' is related to the difference of the costs using low and high technology. Thus, if the high-technology emission abatement efficiency is improved, which is possible through technological development, it can provide firms more incentive to upgrade their technology. For the 'expected profit,' the imposition of the unilaterally stricter environmental policy deteriorates the expected profit of the home country, making home firms more reluctant to upgrade their technology. The imposition of the BCA could offset part of the cutoff productivities of φ_l and φ_x, raising the expected profit of the home firms. Therefore, the BCA can be helpful to lower φ_h.

[17] In Kreickemeier and Richter (2014), the 'scale effect' appears as a result of trade liberalization.

[18] This is similar to the 'porter' hypothesis in the introduction. Faced with the higher emission tax, more home firms choose to adopt high technology, thus decreasing emissions.

Lastly, the term of the relative cost ratio $(c_l(\tau)/c_h(\tau))$ appears in the second term in the curly brackets. This term increases as the emission tax increases by the assumption in the previous section. However, the effect of that depends on the relative scale of the elasticities (η and σ). Given the assumption that $\eta < 1 < \sigma$, $\sigma - \eta$ is positive. Therefore, this term acts to raise emissions. This makes sense because if the production elasticity (η) is not that high, the producer cannot substitute the inputs freely even under an input price increase (here, the emission tax). Therefore, the increase of the production ratio using high technology accompanies these two conflicting effects.

Emissions from Production for the Export Market. The second line is the emissions from production for exports. As in the first line, 'mass effect' and 'price effect' act to reduce the demand for emission of each company as the price of emissions increases. The second line includes the trade cost(t), and it is inversely related to the emissions, as the trade cost is inversely related to the quantity of exports. It also includes the ratio of the exporters among the existing firms $(\varphi_l/\varphi_x)^\theta$. If this ratio increases, which means that there are more exporters, the emissions from exports increase.

The first and the second terms in the curly brackets represent the emissions from production for exports using low and high technology, respectively. Therefore, if the ratio φ_x/φ_h increases, the emissions from exports using low technology decrease, but the emissions from exports using high technology increase and vice versa.

2.7.4. The Effects of the Policies on the Home Emissions. The simulation results for the emissions under different policy scenarios are presented in Table 2.3.

2.7.4.1. *The Stricter Environmental Policy without the BCA.* The stricter environmental policy lowers the low-technology adoption cutoff (φ_l), and according to the numerical simulation, the high-technology adoption cutoff (φ_h) also decreases. As the low-technology adoption cutoff (φ_l) decreases more, the ratio $(\varphi_l/\varphi_h)^\theta$ turns out to decrease according to the simulation. Thus, the home country produces relatively more low-technology goods than high-technology goods for the domestic market. However, home emissions from the production using both technologies decrease overall, which is mainly due to the 'mass effect' and the 'price effect' as a result of the higher emission tax.

We know that as a result of the home country's higher emission tax, φ_x increases and φ_l decreases, resulting in the decrease of the exporter ratio $(\varphi_l/\varphi_x)^\theta$. Therefore, the emissions from

Table 2.3. Simulation Results of the Emissions

Variables	Symbols	Policy scenarios: Symmetric $\tau = \tau^* = 1$	Unilateral Policy($\tau = 1.2$) Without BCA	With BCA	Symmetric $\tau = \tau^* = 1.2$
Home country					
Emission from the domestic market	E_d	65.88	50.17	56.46	57.39
Low-tech. production	E_{dl}	34.79	26.42	29.63	29.56
High-tech. production	E_{dh}	31.10	23.76	26.83	27.83
Emission from the export market	E_x	6.46	2.95	3.63	5.65
Low-tech. production	E_{xl}	1.71	0.48	0.64	1.41
High-tech. production	E_{xh}	4.74	2.48	2.98	4.25
Home Total	E	72.34	53.13	60.08	63.04
Foreign country					
Emission from the domestic market	E^*_d	65.88	70.78	69.48	57.39
Low-tech. production	E^*_{dl}	34.79	36.26	36.46	29.56
High-tech. production	E^*_{dh}	31.10	34.52	33.02	27.83
Emission from the export market	E^*_x	6.46	11.65	6.30	5.65
Low-tech. production	E^*_{xl}	1.71	3.95	1.68	1.41
High-tech. production	E^*_{xh}	4.74	7.71	4.62	4.25
Foreign Total	E^*	72.34	82.43	75.78	63.043
Total emission	$E + E^*$	144.68	135.56	135.86	126.09

exports decrease as the home country's exports decrease. According to the simulation results, φ_h decreases; thus, combined with the increase of φ_x, the ratio $(\varphi_x/\varphi_h)^\theta$ increases. This means that the home country produces more high-technology goods than low-technology goods for the export market.

2.7.4.2. *The Effects of the Stricter Environmental Policy with the BCA.* The home country's imposition of the BCA raises φ_l and lowers φ_h compared to the higher emission tax only, thus raising the ratio $(\varphi_l/\varphi_h)^\theta$, too. Therefore, we can say that the BCA can alleviate the emissions from the production using low technology but raises the emissions from the production using high technology compared to the unilaterally stricter environmental policy. However, the overall emissions are mostly affected by the 'mass effect,' so they are greater than the case without the BCA and less than the baseline, so $E_d^{e'} < E_d^{e''} < E_d^{e}$.

On the contrary, the BCA can increase the emissions from exports because it raises the exporter ratio $(\varphi_l/\varphi_x)^\theta$ and the existing firm mass (M) compared to the unilaterally stricter environmental policy, but these are smaller than the initial equilibrium. As a result, the emissions from exports production also lie between the previous two cases, thus $E_x^{e'} < E_x^{e''} < E_x^e$. The imposition of the BCA lowers both φ_x and φ_h compared to the unilateral policy, and the ratio of high-technology adoption among exporters $(\varphi_x/\varphi_h)^\theta$ decreases from the simulation. Thus, the composition of the emissions from low-technology production increases among the export emissions accordingly.

2.7.5. Emissions from the Foreign Production. In a similar way to the home country, we can also get the emissions from foreign production.

$$E^* = \widetilde{M^*} f_l \left\{ \underbrace{\frac{1}{a_l^{1-\eta}} \left(1 - \left[\frac{\varphi_l^*}{\varphi_h^*} \right]^{\theta-\sigma+1} \right)}_{\text{emiss. low-tech production}} + \underbrace{\frac{1}{a_h^{1-\eta}} \left[\frac{c_l^*(\tau)^*}{c_h(\tau)^*} \right]^{\sigma-\eta} \left(\frac{\varphi_l^*}{\varphi_h^*} \right)^{\theta-\sigma+1}}_{\text{emiss. high-tech production}} \right\}$$

$$+ \widetilde{M^*} \frac{f_x}{t} \underbrace{\left(\frac{\varphi_l^*}{\varphi_x^*} \right)^\theta}_{\text{exporter ratio}} \left\{ \underbrace{a_l^{\eta-1} \left(1 - \left[\frac{\varphi_x^*}{\varphi_h^*} \right]^{\theta-\sigma+1} \right)}_{\text{emiss. low-tech production}} + \underbrace{a_h{}^{\eta-1} \left[\frac{c_h^*(\tau^*)}{c_l^*(\tau^*)} \right]^{\eta-\sigma} \left(\frac{\varphi_x^*}{\varphi_h^*} \right)^{\theta-\sigma+1}}_{\text{emiss. high-tech production}} \right\}, \tag{2.75}$$

where $\widetilde{M^*} = \underbrace{M^*}_{\text{mass effect}} \sigma\rho\tau^{*-\eta} c_l^*(\tau^*)^{\eta-1} \frac{\theta}{\theta-\sigma+1}$. The interpretation is very similar to the home country case, although the directions of the cutoff changes and existing firm mass (M^*) under the environmental policies can be different from those of the home country. Because the foreign emission tax (τ^*) does not change, the demand for emission at the company level does not change, so there is no individual firm-level effect. The changes of the cutoff ratios also apply to the foreign emissions in the same way as the case of the home emissions, including the 'abatement efficiency.'

2.7.6. The Effects of the Policies on Foreign Emissions.

2.7.6.1. *The Home Country's Stricter Environmental Policy without the BCA.* The home country's unilaterally stricter environmental policy raises the foreign low-technology adoption cutoff (φ_l^*) and lowers the high-technology adoption cutoff (φ_h^*); thus, $(\varphi_l^*/\varphi_h^*)^\theta$ increases. Therefore, the emissions from the production using low technology decrease because the production using low technology decreases, whereas the emissions from the production using high technology increase. According to the simulation, the overall emissions from foreign production for the domestic market increase because the mass of the existing firms (M^*) increases.

The home country's higher emission tax lowers φ_x^* and raises φ_l^*, resulting in the increase of the exporter ratio $(\varphi_l^*/\varphi_x^*)^\theta$. In addition, the mass of the existing firms (M^*) increases. Because of these two factors, the emissions from exports increase. As φ_x^* and φ_h^* decrease simultaneously, we rely on the simulation results for the change of the high-technology adoption ratio among the exporters, and it turns out that $(\varphi_x^*/\varphi_h^*)^\theta$ decreases. This means that the foreign country produces relatively more low-technology goods than high-technology goods for the export market.

2.7.6.2. *The Home Country's Stricter Environmental Policy with the BCA.* The imposition of the BCA offsets some part of the above effect. As a result of the BCA, $(\varphi_l^*/\varphi_h^*)^\theta$ decreases compared to the unilateral policy. Therefore, the emission from the production using low technology increases, whereas the emission from the production using high technology decreases. The overall emissions from the production for the domestic market decrease compared to the case without the BCA but are greater than the baseline; thus, $E_d^{*e} < E_d^{*e''} < E_d^{*e'}$.

The imposition of the BCA offsets the increase of the exporter ratio $((\varphi_l^*/\varphi_x^*)^\theta)$, and the emissions from exports decrease compared to the case without BCA. Combined with the decrease of the existing firm mass (M^*), the emissions from exports are less than in the symmetric policy case. Thus, the emissions from exports production are the lowest among the previous policy cases, hence $E_x^{*e''} < E_x^{*e} < E_x^{*e'}$. The imposition of the BCA raises φ_x^* and according to the simulation, φ_h^* increases compared to the unilateral policy, and the ratio of high-technology adoption among exporters $(\varphi_x^*/\varphi_h^*)^\theta$ increases from the simulation. Thus, the composition of the emissions from the high-technology production increase among the export emissions accordingly.

2.7.6.3. *Leakage in the Foreign Production and Total Emission.* To summarize, the effect of the higher emission tax in the home country affects not only the emissions at home but also the emissions in the foreign country in various ways. One difference is that there is no 'price effect' for the foreign production, and here, only the indirect effects through the changes of the cutoffs exist. We have seen that the increase of the emissions from foreign production comes mostly from the increase of the production of goods using high technology ('scale effect') for the domestic market and the increase of the exporter ratio. Therefore, we can say that the 'leakage problem' happens mainly in these fields.

Table 2.4. Simulation Results on the Welfare

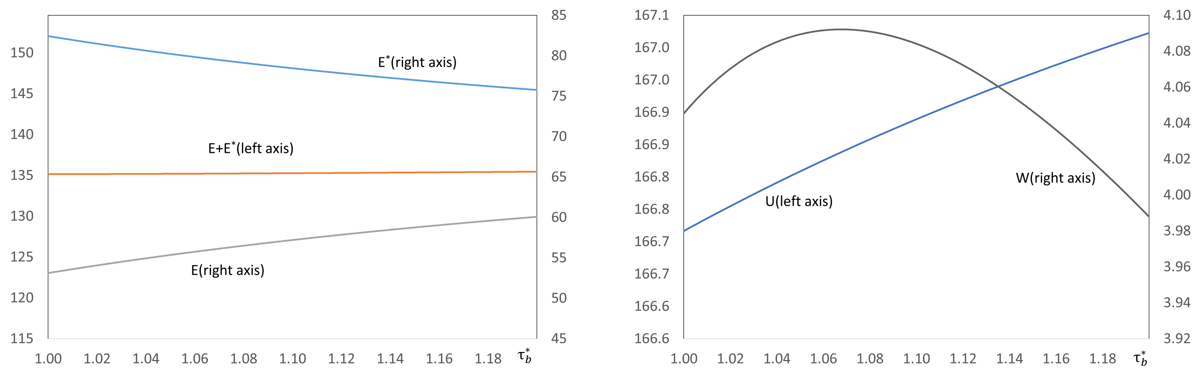
		Policy scenarios			
		Symmetric $\tau = \tau^* = 1$	Unilateral Policy($\tau = 1.2$) Without BCA	With BCA	Symmetric $\tau = \tau^* = 1.2$
Utility from consumption	Home (U)	183.9	166.7	167.0	168.9
	Foreign (U^*)	183.9	187.7	184.3	168.9
Emissions	Home (E)	72.3	53.1	60.1	63.0
	Foreign (E^*)	72.3	82.4	75.8	63.0
	Total	144.7	135.6	135.9	126.1
Welfare, $\beta = 0.8$	Home (W)	68.2	58.3	58.3	68.1
	Foreign (W^*)	68.2	79.3	75.6	68.1
Welfare, $\beta = 1.2$	Home (W)	10.3	4.0	4.0	17.6
	Foreign (W^*)	10.3	25.0	21.3	17.6
Welfare, $\beta = 3.0$	Home (W)	-250.1	-240.0	-240.6	-209.3
	Foreign (W^*)	-250.1	-219.0	-223.3	-209.3

The total emissions decrease under the unilateral policy, but the BCA is not effective in this regard. Rather, imposing the BCA raises the total emissions. This is because even though the BCA reduces the emissions from the foreign country's production of exporting goods, it recovers the mass of the home country. As a result, home country emissions increase a lot, especially from the production of domestic goods. If we suppose that there is asymmetry in abatement technology (the home country has a higher abatement efficiency), it turns out that the BCA can reduce the total emissions.[19] This is because increasing the production at home is advantageous for reducing emissions. However, the level of the emission reduction was not high, so we can say that even under the asymmetric technology, the BCA is not that good at reducing emissions.

2.7.7. The Welfare and Rationalization of the BCA. In this subsection, we will explore the overall welfare, considering both the utility from consumption and the damage from the total emissions. These simulation results are highly dependent on the marginal damage from emissions (β) and the amount of labor supply ($\bar{L}$). In Table 2.4, I simulate several cases by changing β, and

[19]The table which shows this result is in the appendix. Here, I supposed that the abatement efficiencies at home are $a_h = 1.5$, $a_l = 1.1$, keeping the foreign abatement efficiencies at $a_h^* = 1.2$, $a_l^* = 1.0$.

in the appendix, I include more cases with different parameters. Under the parameters which I have assumed so far, the home country does not have the incentive to impose the BCA at the same level as the emission tax at home. I trace the change of the home country's welfare by changing the level of the BCA in Figure 2.5. As we can see in that figure, the optimal level of the BCA to maximize the welfare is about $\tau_b^* \approx 1.068$. As we saw in the previous subsection, the total emissions increase slightly under the BCA; therefore, it is hard to find the logic behind the BCA from an environmental perspective. However, the home country has the incentive to impose the BCA because the BCA recovers part of its competitiveness and its utility from consumption.

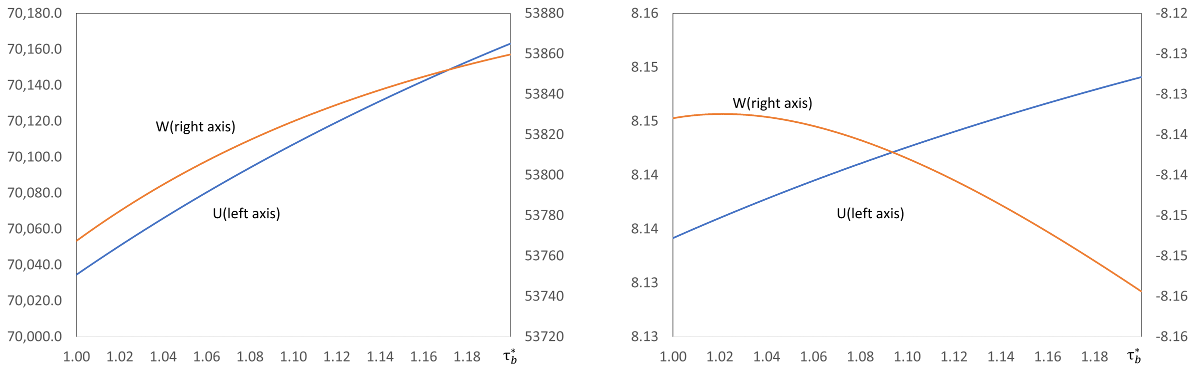


(a) Emissions (b) Utility and Total Welfare

Figure 2.5. Simulation Under the Symmetric Technology

In Figure 2.6, I conduct other simulations under the different levels of $\bar{L}$ to see how the results change. If we set a higher value of $\bar{L} = 22263$, the improvement in the utility from consumption dominates the disutility from emissions. Thus, the welfare-maximizing level of the BCA is the highest possible point, $\tau_b^* = 1.2$, whereas with the lower level of $\bar{L} = 22.263$, the disutility from emissions dominates the improvement in the utility from consumption. Thus, the welfare-maximizing level of the BCA is lower at $\tau_b^* \approx 1.02$. This is because the emissions are the multiple one of $\bar{L}$, whereas the utility of consumption is greater than one multiple of $\bar{L}$, as we can see in (2.66).

2.7.8. Strategic Decision of the Environmental Policy. In this subsection, as an extension of this calibration model, I check the possible strategic environmental policies at home and abroad. The parameters are assumed to be the same as the ones that I initially introduced. The order of the strategic decision is as follows. The foreign country strategically decides its level



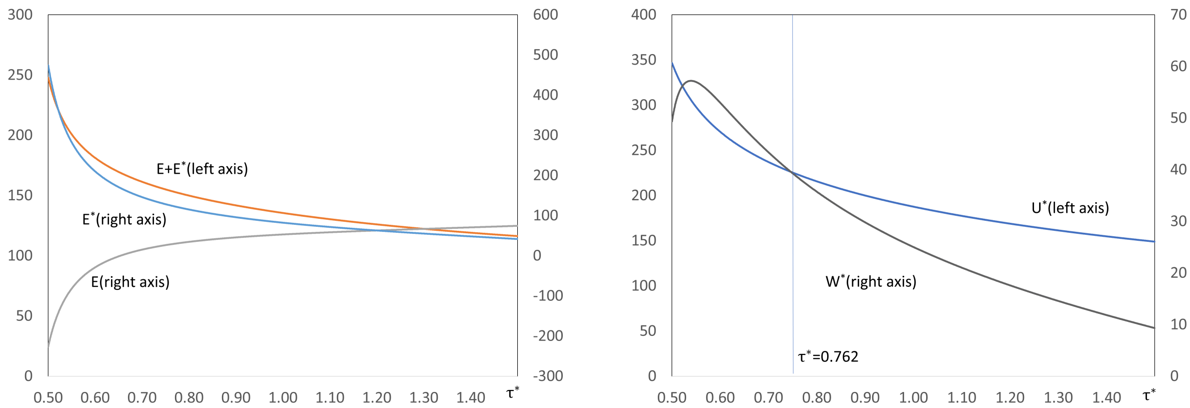
(a) $\bar{L} = 22263$ (b) $\bar{L} = 22.263$

FIGURE 2.6. Utility from Consumption and the Welfare under Different $\bar{L}$

of emission tax under the home country's unilateral policy without the BCA. Then, under this strategic emission tax, the home country decides its level of the BCA.

2.7.8.1. *Strategic Decision of the Emission Tax by the Foreign Country.* To check the strategic decision of the foreign country, I simulate the changes of the utility from consumption, emissions, and total welfare of the foreign country by changing τ^* to find the welfare-maximizing τ^*, the results of which are in Figure 2.7. For the emissions, as the foreign country raises its emission tax, foreign emissions decrease and home emissions increase. However, there are some points where home emissions are negative. This is because with a very low level of foreign emission tax, the home exporting cutoff is so high that it even exceeds the high-technology cutoff. The welfare-maximizing point is around $\tau^* \approx 0.54$, but at that point, the home emissions are still negative, and the reversal of the cutoffs still exists between the exporting cutoff and the high-technology adoption cutoff. The minimum value of the foreign emission tax, which does not create negative emissions or the reversal of the cutoffs, is around $\tau^* \approx 0.762$. A foreign emission tax which is above this level gives a lower level of welfare to the foreign country, so we will regard this as the foreign strategic emission tax, and in the next subsection, we will explore how the home country can react strategically by imposing the BCA.

2.7.9. Strategic Decision of the Level of the BCA by the Home Country. Here, we check how the home country can decide the level of the BCA (τ_b^*) strategically, given the strategic level of emission tax ($\tau^* \approx 0.762$) in the foreign country. The results are in Figure 2.8. For the



(a) Emissions (b) Utility and Total Welfare

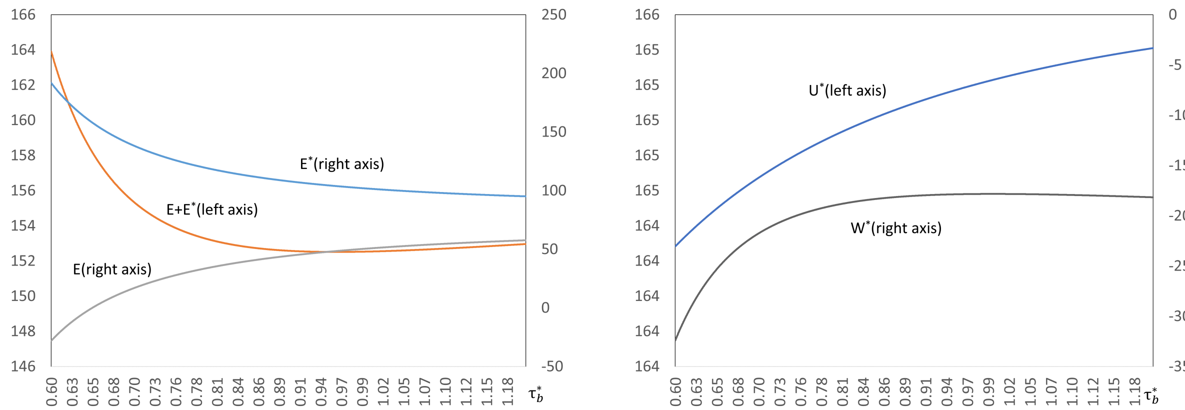
FIGURE 2.7. Simulation for the Foreign Strategic Policy

emissions, as the BCA increases, foreign emissions decrease, and home emissions increase. Here, there are some points where home emissions are negative and the cutoff reversal happens. The point where the negative emissions and cutoff reversal disappear is when the BCA is about the same level as the foreign strategic emission tax ($\tau^* \approx 0.762$). The point where total emissions are minimized is when the BCA is about $\tau_b^* \approx 0.96$. The welfare-maximizing point is around $\tau_b^* \approx 1.00$, which is slightly higher than the point where total emissions are minimized. As the home country raises the BCA, the utility from consumption increases, but the damage from emissions also increases. Until $\tau_b^* \approx 0.96$, the home country can benefit from the decreasing emissions and increasing utility from consumption. For values of τ_b^* between about 0.96 and 1.00, the increase of the utility from consumption is greater than the increase of the damage from emissions. Beyond the level $\tau_b^* \approx 1.00$, the damage turns out to be greater than the utility from consumption.

2.8. Conclusion

In this chapter, we explored the effect of the carbon tax and the BCA on the welfare and emissions under the heterogeneous trade model of Melitz (2003). Under a similar setup to that of Cui (2017), the carbon tax and the BCA bring about asymmetry in the variable costs, so I used the graphical analysis method from Unel (2013) to explore the changes of the productivity cutoffs.

From the analysis, we get several welfare and policy implications. First, as a result of the higher emission tax, the home country is worse off from consumption because of the lower real wage. On



(a) Emissions (b) Utility and Total Welfare

FIGURE 2.8. Simulation for the Foreign Strategic Policy

the contrary, the foreign country can enjoy higher welfare from consumption because the foreign country can gain 'relative competitiveness' from the increase of the cost in the home country. The imposition of the BCA can alleviate this by leveling the playing field, specifically making the foreign firms face the same cost in their export market.

According to the numerical simulation, the home country's unilateral higher emission tax turns out to reduce the home country's emission. First, faced with the higher variable cost, there are exits among the existing firms, thus reducing the emissions ('mass effect'). Second, faced with the higher cost of emissions, the individual firms in the home country reduce their emissions ('price effect'). It also affects emissions indirectly via the change of the cutoff ratios. Numerical simulation shows that the ratio of the high-technology-adopting firms among the existing firms does not change much. Thus, we can say that most of the emission reduction comes from the 'mass effect' and the 'price effect.'

However, part of the home country's emission reduction turns out to be offset by its imports. For the foreign country, there are no 'price effects,' but the indirect effects through the changes of the mass and the cutoff ratio affect emissions. If the home country imposes the unilateral policy only, there is entry by the firms in the foreign country with their competitiveness gain. Also, the ratio of the exporters among the existing firms increases a lot, resulting in an increase of the emissions from foreign exports. Overall emissions turn out to decrease, so the foreign country can enjoy the benefit of the decreased emissions by free-riding on the effort by the home country in addition to the higher utility from consumption.

The imposition of the BCA reverts part of the cutoffs for low-technology adoption and exports in both countries. Thus, it alleviates this 'leakage problem,' but it increases the emissions in the home country. The total emissions increase slightly compared to the unilateral policy by the home country, so we cannot say that the BCA can be rationalized by its effect on the environment. However, it recovers the home country's utility from consumption, so the home country can have enough incentive to impose the BCA.

These results are driven by the existence of the numeraire good and the assumption that the utility between the numeraire good and manufacturing goods is combined by the Cobb–Douglas function. Thus, the change of the environmental policies switches the production between the home and foreign countries. This might be the main reason that the imposition of the BCA could not decrease the overall emissions. The reality might be different; more people are aware of the importance of carbon neutrality, and many investors require firms to use ESG (environmental, social, and corporate governance) management. These changes and the social movement imply that the expenditure between the numeraire good and manufacturing goods might not be fixed as in the Cobb–Douglas function that I employed in this chapter. Reflecting the changing preference could be a possible future research topic.

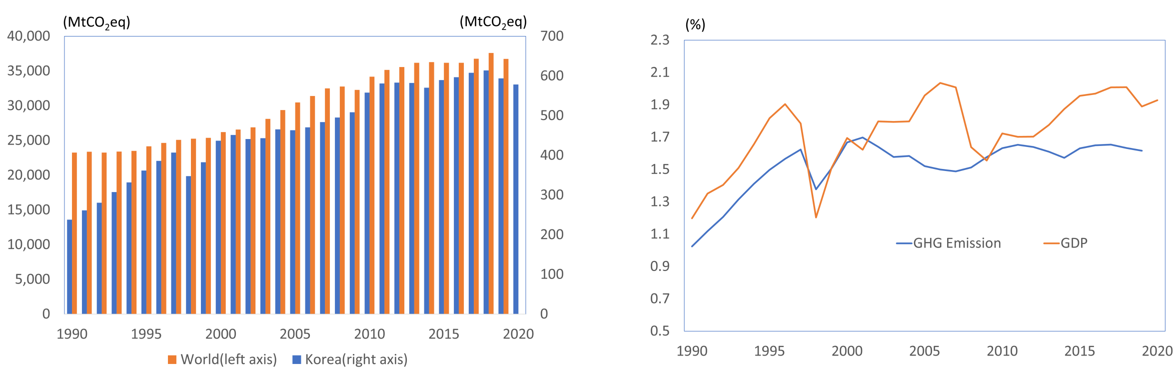
Another assumption of this model is that the emission tax and the BCA revenues evaporate after collection like the tariff revenue. If we relax this assumption, we might have a different result about the welfare in both countries. If we consider the revenue from the emission tax and the BCA, the policy implication might change to favor increasing the tax and imposing the BCA. The existence of the numeraire good is also used to derive the analytic solution. Therefore, deriving the analytic solution from relaxing this assumption and checking the effect would be possible future research direction. For example, Demidova and Rodríguez-Clare (2013) derived the analytical solution of the asymmetric country Melitz (2003) model without this numeraire good, so applying this approach could be a possible way to do this.

CHAPTER 3

The Effects of the Korean Emission Trading System on the GHG Emission and Economic Performance

3.1. Introduction

The first international commitment to reduce greenhouse gases (GHGs) was signed in 1997 (Kyoto Protocol). At that time, Korea was not included in the Annex I countries, which committed to target their reductions. However, Korea produces about 1.6% (1.5–1.7% during 2000–2019) of the world's GHG emissions from energy. Considering Korea's 1.8% share of the world economy (ranging from 1.6% to 2.0% between 2000 and 2019),[1] 1.6% is not especially high. Still, it is hard to neglect the absolute value of Korea's emissions because it ranked 7th (600 Mt CO_2) in CO_2 emissions from energy in 2017 (IEA). The high emissions in Korea mainly come from industry.



(a) GHG emissions from the energy (b) Proportion of Korea in the World

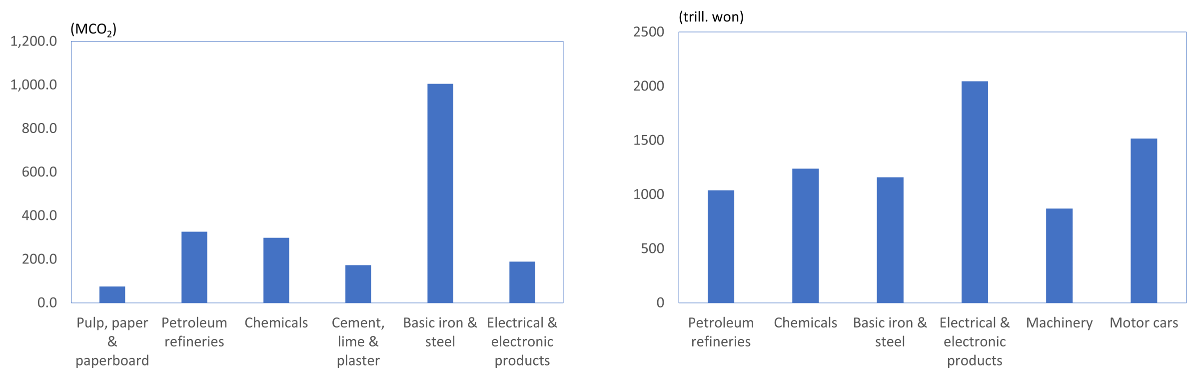
Source: IEA & IMF WEO

FIGURE 3.1. GHG emissions from the energy and the proportion of Korea

In 2018, the emissions from industry were 72% (Park and Lee (2021)), and among the industries, manufacturing occupied 65.9% and service occupied 29.9%, with transportation occupying the majority of the service (13.7%). If we look into the manufacturing sector's CO_2 emissions more

[1]Self-calculation, using the IMF WEO dataset.

deeply, during 2000–2019, the most emitting sector was the basic iron & steel, then petroleum refineries, followed by chemicals. These sectors also occupy the main industrial production, but the orders of the CO_2 emission and production are slightly different due to the industry characteristics, such as the energy use and the emission efficiency. My empirical analysis is based on the companies' emission reporting data, which is mandatory under the TMS, which I will explain below. This emission dataset represents the total emissions in Korea. For example, this dataset covers 95.3% (330,260 ktCO_2/346,540 ktCO_2 in 2019) of the GHG emission data from the "National Energy Consumption & GHG Emission Survey"[2] in the mining and manufacturing industries.



(a) CO_2 emissions from manufacturing

(b) Production of the manufacturing

Source: Korea Energy Agency & Statistics Korea

FIGURE 3.2. The emission and production of the manufacturing in Korea(2011 ∼ 2019)

3.1.1. Regulations to Reduce GHG Emissions.

Target Management System. Considering the high emissions by industries and the higher concerns about climate change, in 2007, Korea started its target management system (TMS), which is a type of command-and-control regulation to reduce GHG emissions. The Korean government legalized it in 2010,[3] expanding the system more broadly, and from 2012, they implemented the TMS at the national level based on that law and the following enforcement ordinances. The criteria for which companies are under this system have changed,[4] but from 2014, the companies which emit more than 50,000 t CO_2 annually or use more than 200 terajoules (TJ) of energy on three-year

[2] This can be regarded as a more thorough investigation, as it aims to calculate all GHG emissions.

[3] "Act on Low Carbon and Green Growth, Act No. 9931."

[4] In 2010, they were the same as the current criteria for the emissions trading system (ETS), but they were lowered afterwards when the ETS was adopted.

average are under this system. On the facility level, the individual facilities which emit more than 15,000 t CO_2 or use more than 80 terajoules (TJ) of energy on three-year average are under this system.

Although the TMS is a command-and-control regulation, the Korean government set the TMS as a preparatory stage for the ETS rather than applying the regulation strictly. According to Lee et al. (2017), TMS has a penalty for companies that do not meet the target, but the penalty was never imposed until when the paper was written. In addition, as emissions readjustment was possible in the middle of the system implementation, the coercion of the system was insignificant, and accordingly, the target companies lacked interest and effort in reduction activities.

Emissions Trading System. In 2012, the Korean government enacted another law which gives more specific grounds for setting up the Korea Emissions Trading System (K-ETS),[5] then started the trading by allotting the emission allowances from Jan. 2015.[6] Compared to the TMS, the ETS is more flexible, as the ETS is a type of regulation which is based on the market trading system and provides more incentive to reduce emissions, as a firm can sell its credits if it can decrease its emissions. The companies which emit more than 125,000 t CO_2 annually or facilities which emit more than 25,000 t CO_2 on three-year average are under the coverage of the K-ETS. The emissions from the companies under the K-ETS amount to more than 60% of the total emissions in Korea.

It has had three phases until now. The first phase lasted from 2015 to 2017 and the second phase from 2018 to 2020; currently, it is in the third phase (2021–2025); and it is scheduled to have new phases for each of the next five-year periods.[7] During the first phase, emission allowances were allocated 100% free, so only some adjustments between entities were traded and reflected in the allowance price. The free allocation ratio decreased to 97% in the second phase and is expected to decrease further to 90% in the third phase. Also, in the first phase, most of the allowances were allocated by grandfathering, under which allowances are allocated based on the firms' past emission records. Only in three sectors, cement, oil refining, and aviation, was benchmark allocation used,

[5]Act on the allocation and trading of greenhouse-gas emissions permits, Act No. 11419

[6]The explanation about the Korea ETS in this paper is mainly from the paper by Son and Jeon (2018), the report by Ministry of Environment (Korea) (2015), and the information at the webpage of the Greenhouse Gas Inventory & Research Center of Korea under the Korean Ministry of Environment and Korea Environmental Corporation.

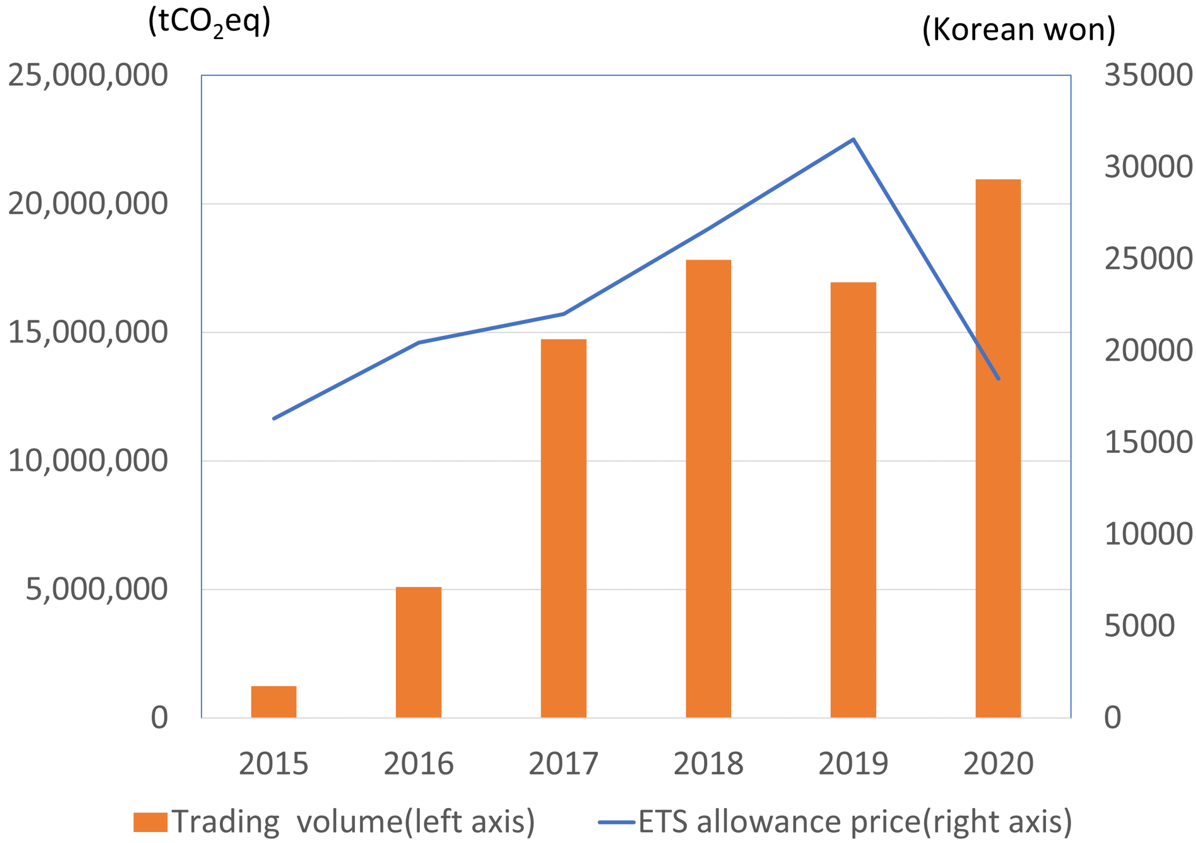
[7]The first and second phases lasted three years so firms could accumulate experience and to securely establish the system.

under which allowances are allocated based on the firm's activity, like production, and considering its emission efficiency. In Phase 2, the benchmarking method of allocation was expanded to four more sectors, power generation, integrated energy supply (residential and industrial), and waste. Based on the fact of the shrinkage of the free allowances and the expanding of the benchmark allocation method, we can expect that firms would have felt more binding effects in the second phase and will do so in the new phases.

3.1.2. Korean ETS Market. There are three types of allowances which are mainly traded in the Korea Exchange (KRX) market. The basic allowance is KAU (Korean Allowance Unit), which is allocated by the government and which the firms are obliged to submit. Compliance years are attached after 'KAU.' For example, the allowance for the 2021 compliance year is 'KAU21.' In addition to KAU, KCU (Korean Credit Unit) and KOC (Korean Offset Credit) are also traded for the regulation flexibility. KCU (Korean Credit Unit) is an emission permit converted from the credits for external carbon-offsetting activities. KOC (Korean Offset Credit) is also an emission permit, similar to KCU, but KOC is converted from the credits for external carbon-offsetting activities which are conducted by firms that are not obliged to submit their allowances.

Since the introduction of the ETS in 2015, the Korean emission trading market has grown. By 2020, total trading volume had increased by 16 times since 2015, and the price of the KAU increased steadily until 2019. The price fell in 2020 due to the effect of the economic recession from the pandemic. In the earlier period of the system, the trading was concentrated on the period near when the submission of the permits was due (late June after the compliance year). As the system gets stabilized, transactions continue during the whole period. According to Korea Exchange (year), two factors are pointed out for this continued transaction. First, the market-makers other than the compliance firms started to participate in the allowance transaction from the Phase II period. Second, more firms came to realize that it is more beneficial to guarantee the permits earlier rather than rushing to the market near the submission period. These two factors contributed to the steady increase of trade volume even under the recession in 2020.

3.1.3. Plan for this Chapter. In this chapter, I will evaluate several propositions that we saw in the previous chapter. These propositions are also tested a lot in the environmental economics



Source: Korea Exchange market data system

Note: Yearly price is the trading volume weighted average price for each year's KAU

FIGURE 3.3. Price of KAU and the emission permit trading volume

literature. Although the main focus of the previous chapter was the effect of the BCA on the economy, the application of the BCA in the real world is very limited, as we have seen that the recent attempt of the EU is being regarded as a new milestone. Thus, in this chapter, I will mainly focus on evaluating the economic effects of the unilaterally stricter environmental policy in the home country. The previous chapter's main findings that I want to test here are as follows:[8]

[8]Dechezleprêtre and Sato (2017) classifies the competitiveness effects of the stricter environmental policy into three categories. The first-order effect is the increase of the cost, and the second-order is how the firms react to the first-order effect, so the changes of the production volume, prices, and investments are the examples of the second-order effect. Lastly, the third-order effects are the combining effects from the first- and second-order effects. Profitability, employment, innovation, trade flows, and pollution level can be the third-order effects. Thus, according to this classification, testing propositions 1, 2, and 4 belong to the third-order effect, and 3 belongs to the second-order effect.

1. Stricter environmental policy reduces the emissions and emission intensity from home production at the firm level ($E_j(\varphi)$ and $e_j(\varphi)$ decrease).
2. Stricter environmental policy makes it harder for the home country to export (φ_x increases).
3. Stricter environmental policy makes the home country firms adopt high technology (φ_h decreases).
4. Stricter environmental policy reduces the home country firms' expected revenue and profit (φ_l decreases).

Although I will try to test all of the above hypotheses, the main focus will be the first one, as the framework and the explanatory variables that I will use in this chapter are apt to test the first hypothesis. As the dataset includes two phases of Korean ETS (I: 2015–2017, II: 2018–2020), I will try to test whether the effects on the emission differ according to the phases. In addition, I will also test how the effects on emissions vary according to the way the allowance is allocated. To do that, I estimate a separate regression for the industries which are under the benchmark allocation (cement, oil refining, aviation, power generation, integrated energy supply (residential and industrial), and waste). According to the 'Coase theorem,' the allocation mechanism does not affect the abatement choices, but due to the transaction costs, imperfect competition in the market, and the endowment effect, the theorem sometimes does not hold. For the EU ETS market, this is also debatable, and Dechezleprêtre et al. (2018) find that a lower free allocation ratio induces higher emission reduction. Therefore, in our case, I suspect that the allocation mechanism can affect GHG emissions. Thus, by estimating the average treatment effect on the treated (ATET) for only those industries and comparing it with that for all the industries, we can investigate whether the benchmark allocation is a more effective way to reduce GHG emissions.

3.2. Literature Review

The research which analyzes the effect of the Korean ETS usually focuses on the effect of that policy on GHG emission reduction. Yu et al. (2017) analyzes the effect of the introduction of the ETS in Korea on GHG emission reduction for the Korean ETS Phase I period. They find a significant reduction in GHG emissions in the industries which are covered by the ETS, whereas there did not exist such an effect in the industries which are not covered by the ETS and in the power generation which can pass through their burden to the price. They use panel regression to compare the emission reduction effect of the ETS with the counterfactual of case where it was not introduced.

Lee et al. (2017) compare the GHG emission reduction performances under the TMS and ETS for the top 10% of GHG-emitting firms in Korea. They transform the emission data using 'z-normalization' and find that among 73 companies, 32 firms showed better performance in reducing their emissions. If classified by the industry, the firms in electricity generation and electronics reduced emissions more under the ETS, the firms in cement and oil refineries showed a higher emission reduction under the TMS, and steel industry firms did not show any difference according to the regulation change.

Dechezleprêtre et al. (2018) is the research about the impact of the EU ETS. They analyze the effect of the EU-ETS on carbon emissions and the economic performance of regulated firms. They use installation-level data from France, the Netherlands, Norway, and the UK and employ the matching methodology and difference-in-differences estimation. They find a decrease of emissions among the regulated firms.

Another research area of the environmental policy effect is about the effects of environmental policies on economic performance. Dechezleprêtre et al. (2018) also checks this effect and cannot find negative economic performance for the regulated firms. Dechezleprêtre and Sato (2017) reviews several recent empirical analyses, especially how cross-country differences in environmental policies affect the economic competitiveness of those countries. They find that environmental regulations had relatively small adverse effects on trade, employment, productivity, and so on compared to other traditional competitiveness factors such as transport costs, availability of labor and raw materials, capital costs, and so on. They also find that there exists enough evidence that environmental regulations induce innovation of clean technology.

Among many areas of economic performance, the effects of environmental policies on trade get higher attention; this area has the name of the 'pollution haven hypothesis,' and this is a debatable issue. The 'pollution haven effect' means that stringent environmental regulation in a country weakens its competitive advantage. According to the survey by Cherniwchan et al. (2017), it is a settled question that this effect exists. However, it seems that this effect is not large enough to change the flow of trade. The 'pollution haven hypothesis' asserts that environmental regulation changes the competitive advantage, so the country with the higher environmental regulation tends to reduce the production of pollution-intensive goods, and the country with the lower environmental regulation tends to increase the production of dirtier goods. According to Cherniwchan et al. (2017), there is little evidence that trade liberalization shifted the production of dirtier goods to the countries with lower environmental regulations.

Fowlie (2009) addresses interstate emission leakage. As we saw in the literature review from the previous chapter, it is hard to observe strong evidence of emission leakage at the international level. However, Fowlie (2009) finds that there can exist a substantial emission leakage of carbon dioxide in California's electricity industry, as the neighboring states are not regulated by the emission trading system. Using a numerical model, she finds that if the regulation included out-of-state firms, the GHG emission would decrease by 8.5–11%, and cost per GHG emission reduction would be lower under the complete regulation than under the incomplete regulation which is applied currently.

Fowlie (2010) analyzes the effect of the emission trading program (NO_x Budget Program) in the electricity industry. To comply with this program, the plant managers can choose either to invest in capital-intensive technology which reduces NO_x emissions or to buy emissions allowances. The choices were different across the states, and the generators that were subject to rate regulation or were publicly owned were more likely to adopt the technology than the deregulated plants. This supports the Averch–Johnson effect that regulated companies, especially under rate regulation, tend to increase their capital to get more profit. She also finds that if there is no heterogeneity of the rate regulation, some of the permitted emissions can be shifted to the states where the pollution is less vulnerable, so the damage from the pollution can be reduced.

Cicala (2015) examines the change of the electricity-generating firms' procurement of coal and gas depending on whether the firm was divested or deregulated. He finds that the deregulated firms could lower the price paid for coal. Faced with the cap-and-trade regulation of sulfur oxides by the Clean Air Act, deregulated firms opted to use lower-sulfur coal rather than invest in capital-intensive technology to reduce sulfur emissions, so the Averch–Johnson effect is supported again. However, this price drop was not observed for gas procurement. This is because gas is traded more in the transparent market, whereas coal is often sold via bilateral contracts. Therefore, Cicala (2015) concludes that asymmetric information can result in regulatory distortion.

Levinson (2009) decomposes the sources of pollution change into three effects using the simple accounting method. The 'scale effect' captures the change of the pollution due to the change of the total output, and this effect usually increases pollution emissions because the economy grows in most countries and industries. Next, the 'composition effect' explains how pollution changes as a result of industry composition changes. Lastly, the 'technique effect' explains the change of the pollution from the change of the pollution intensity. Levinson (2009) finds that the decrease of US air pollution in manufacturing came mostly from the 'technique effect,' and the imports of polluting goods from other countries played only a small part (around 10%). Although his analysis focuses on air pollution other than GHG, such as SO_2, NO_2, CO, and VOC, his paper gives an implication that the most crucial factor of emission reduction is technological development.

3.3. Data

From the "Act on Low Carbon and Green Growth, Act No. 9931," the companies under the TMS and later the companies under the ETS are required to submit annual GHG emission reports to the government. These reports should be verified by an independent and certified institution to guarantee their accuracy. In addition, this information is open to the public in principle,[9] so the dataset includes the amount of GHG emissions and the energy use of each firm or facility.

There are some cases where I had to drop or adjust data. If there were emission and energy use data for both the business and the facility, I used the business-level data, as it represents the firm's emissions more extensively. If there was data for several facilities under the same business, I added them if possible. For example, if there are several factories and they have the same time range, summing them can represent the total emissions of that firm better. If the factory sizes were different substantially across the facilities and the time ranges were different, I chose a bigger one, as it could represent the firm's status better. If the time ranges were different and the factory sizes were similar, I chose a factory which had a longer time period.

[9]The firms can request to hide their reports, but according to the survey in Ministry of Environment (Korea) (2021), only 11.3% of 252 answering firms said that they had made that request.

For the other firm characteristics or economic performance, I used the firms' financial statements from the 'KIS-VALUE' database and 'DART' (Data Analysis, Retrieval and Transfer System) from the Financial Supervisory Service.

3.3.1. Summary Statistics. Table 3.1 displays summary statistics for the emissions and energy use among this dataset by year. As time passes, the criteria for reporting the annual GHG emissions and energy use are getting stricter,[10] so more reports are being observed. As a result, the emission and energy use per report is getting smaller and the standard deviations are smaller from 2014, as there are more smaller firms which emit less GHG and use less energy. During this period, more firms were included in the dataset, especially in electric power generation and energy, basic iron and steel, chemicals, electrical and electronic products, semiconductors, display, and motor cars. This contributed to the decrease of the standard deviation of the sample in 2014. Table 3.2 displays summary statistics by industry category. As we already know, the electric power generation, petroleum refineries, cement, lime and plaster, and iron and steel industries show high levels of average GHG emissions.

TABLE 3.1. Summary Statistics (Yearly)

Year	obs.	Energy usage(kTJ)			GHG emission($ktCO_2eq$)		
		Total	Mean	SD	Total	Mean	SD
2011	449	7,043.8	15.7	70.5	543,856.3	1,211.3	5,801.0
2012	544	7,401.2	13.6	65.3	564,695.9	1,038.0	5,334.4
2013	596	7,477.1	12.5	61.9	576,865.7	967.9	5,106.3
2014	843	7,193.5	8.5	44.6	600,459.0	712.3	4,296.8
2015	845	7,293.4	8.6	43.4	593,354.2	702.2	4,183.7
2016	886	7,403.5	8.4	43.2	600,116.4	677.3	4,116.3
2017	950	7,542.7	7.9	41.0	631,796.1	665.0	4,058.4
2018	993	8,081.7	8.1	41.6	649,503.2	654.1	4,024.1
2019	1,033	7,566.1	7.3	37.9	625,856.4	605.9	3,972.9
2020	1,048	7,355.8	7.0	34.2	585,753.7	558.9	3,569.1
Total	8,187	74,358.6	9.1	46.7	5,972,256.9	729.5	4,324.8

Source: Greenhouse Gas Inventory & Research Center of Korea, own calculation

[10]During 2010–2011, firms emitting more than 125 kt CO_2 eq or using more than 500 TJ of energy firms (for a facility, 25 kt CO_2 eq or 100 TJ) were under the TMS, but the criteria were tightened to more than 87.5 kt CO_2 eq emission or 350 TJ energy use (for a facility, 20 kt CO_2 eq or 90 TJ) for 2012–2013. From 2014, it has been more than 50 kt CO_2 eq emission or more than 200 TJ energy use (for a facility, 15 kt CO_2 eq or 80 TJ).

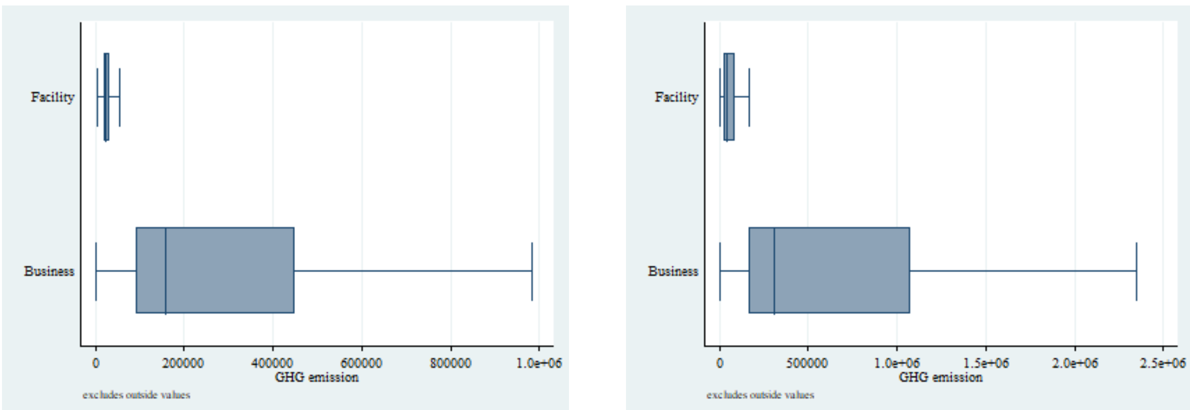
TABLE 3.2. Summary Statistics (Industry)

Industry	obs.	Energy usage(kTJ) Total	Mean	SD	GHG emission($ktCO_2eq$) Total	Mean	SD
Building of ships & boats	128	411.4	3.2	4.2	23,750	186	239
Communication & Data center	103	707.0	6.9	8.8	34,617	336	432
Construction	36	57.8	1.6	0.5	2,9745	83	25
Electric power generation & energy	510	33,949.7	66.6	146.3	2,650,512	5,197	12,084
Basic iron & steel	616	9,231.1	15.0	77.1	1,059,782	1,720	9,762
Batteries & accumulators	35	84.7	2.4	1.9	4,163	119	91
Cement, lime & plaster	281	2,447.9	8.7	15.3	427,952	1,523	2,773
Chemicals	1,140	9,817.7	8.6	21.7	531,319	466	1,097
Electrical & electronic products*	611	4,503.2	7.4	23.0	290,923	476	1,511
Food, beverage & tobacco	417	706.3	1.7	2.0	35,287	85	98
Glass & ceramic products	339	777.4	2.3	4.1	61,863	182	436
Insulated wires & cables	20	36.6	1.8	1.1	1,857	93	55
Machinery	293	277.0	0.9	1.0	14,321	49	55
Medicinal chemicals & antibiotics	33	73.8	2.2	5.8	3,724	113	294
Motor cars	493	963.8	2.0	4.8	48,204	98	239
Non-ferrous metal	325	1,186.4	3.7	8.5	78,757	242	615
Pulp, paper & paperboard	443	1,195.4	2.7	3.4	71,922	162	172
Textiles	245	824.2	3.4	6.1	45,049	184	332
Wood	67	108.4	1.6	1.2	3,758	56	32
Mining	50	25.6	0.5	0.2	7,038	141	85
Petroleum refineries	54	3,736.0	69.2	39.9	296,915	5,498	3,196
Public service & Others	740	1,080.3	1.5	2.3	55,022	74	118
Sewage & waste treatment	655	981.1	1.5	4.7	154,387	236	395
Transport	529	1,035.0	2.0	4.5	61,261	116	244
Water Supply Service	24	140.7	5.9	5.9	6,897	287	287
Total	8,187	74,358.6	9.1	46.7	5,972,257	729	4,325

Note: * includes semiconductor and display
Source: Greenhouse Gas Inventory & Research Center of Korea, own calculation

3.3.2. Comparison of Emissions by the Reporting Units and under Different Regulations. The figures below show the different distributions of GHG emissions under the TMS regulation and ETS regulation. As the criteria for applying the ETS have two dimensions (business level and facility level), there are two groups of observations. As the criteria for TMS and ETS are higher at the business level, higher emissions are observed more at the business level, and the observations from facilities are more concentrated at the lower level of emissions. Next, if we look at the emission distribution under the same reporting unit, what is common between the two graphs is that the firms under the ETS show higher emissions than the firms under the TMS. This is due to the design of the ETS per se. The ETS-regulated firms were under the TMS before 2015, and they were reclassified as being under the ETS from 2015. Therefore, the mean or median GHG emissions of the TMS firms decreased in 2015. This explains why we can see a higher median of the ETS-regulated firms, even though they are under the stricter regulation.[11]

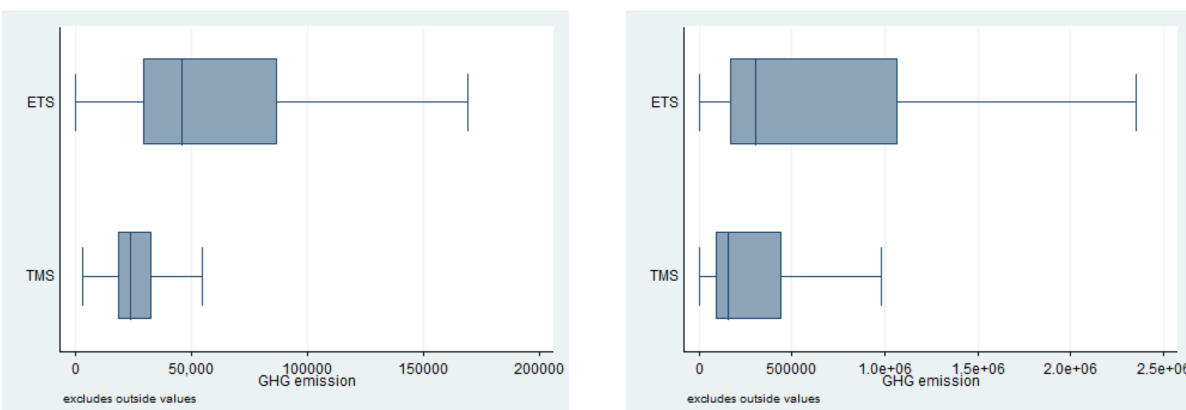
As there seems to be enough overlap between the firms under the TMS and ETS, applying a matching method based on the reporting unit seems plausible.



(a) TMS

(b) ETS

FIGURE 3.4. Distribution of GHG emissions across the regulations



(a) Facility

(b) Business

FIGURE 3.5. Distribution of GHG emissions across the reporting units

[11]The trends of the mean and median emissions are in the appendix.

3.4. Empirical Analysis of the ETS Effects on GHG Emissions

3.4.1. Difference in Differences Estimation. One of the previous chapter's propositions that we discovered is that 'Stricter environmental policy reduces the emissions ($E_j(\varphi)$) from home production at the firm level,' and this fits with common sense. As we have seen in the previous graphs, according to the type of the reporting entity, the emission patterns are quite different, so here, I segregate the sample to the reporting entity and conduct the analysis separately. In 2020, the Korean economy also suffered from the economic depression due to the pandemic, and as you can see in the price change of the emission allowances, the firms' behavior in 2020 might be different from other years, so I exclude 2020 data.

To get the policy effect[12], we compare the treated dependent variables before $(y_{1b}|x, D = 1)$ and after the treatment $(y_{1a}|x, D = 1)$ under the treatment, where a represents 'after the treatment' and b represents 'before the treatment.' However, there can exist a time trend in the dependent variables. Then, this difference does not capture the true policy effects. Thus, we need to remove this trend, which is the difference of the dependent variables before $(y_{1b}|x, D = 0)$ and after the treatment $(y_{1a}|x, D = 0)$ under the untreated condition. However, we cannot observe this counterfactual; thus, we replace it with the control group difference $(y_{0b}|x, D = 1)$ and $(y_{0a}|x, D = 1)$ under the treatment. This is the idea of the difference in differences (DID) model, so we calculate the average treatment effect on the treated (ATET).

$$\begin{aligned} ATET &= E((y_{1a} - y_{1b}) - (y_{0b} - y_{0a})|x, D = 1) \\ &= E(y_{1a} - y_{1b}|x, D = 1) - E(y_{0a} - y_{0b}|x, D = 1), \end{aligned} \tag{3.1}$$

The regression equation reflecting this idea from Angrist and Pischke (2009) is as follows.

$$E_{it} = \beta_t t + \delta \cdot reg_{it} + \Theta X_{it} + \alpha_i + \epsilon_{it}, \tag{3.2}$$

where i is the firm index, t represents the years from 2011 to 2019, E_{it} is the GHG emissions of firm i at time t, reg_{it} is the regulation dummy (0 if the reporting entity i is under the TMS in year t, 1 if the reporting entity is under the ETS in year t), and X_{it} is other explanatory variables which can affect the GHG emission of each firms. Following Yu et al. (2017), I put the

[12] The explanation about the difference in differences model is from Katchova (2020) and Angrist and Pischke (2009).

following as explanatory variables: Dubai crude oil price to represent the energy price and real GDP to represent the domestic demand. The ratio of renewable energy is the proxy variable which represents the government's effort to reduce GHG emissions. It is calculated by dividing renewable energy production by the total primary energy supply. Dubai crude oil price and real GDP data are from the Bank of Korea, and the renewable energy ratio is from the Yearbook of the Energy Statistics published by the Korea Energy Economics Institute. These data are not firm-specific. I also conducted the DID estimation controlling the industry-specific trends using the interaction dummy of the industry sector that the reporting entity belongs to and the time. α_i captures the firm characteristics, and ϵ_{it} is the error term. For GHG emissions, real GDP, and oil price, I took the natural log. I estimated the ATET represented by δ in the above equation using the panel DID estimation.

One caveat for the DID analysis and matching method in the following sections is that these methods depend on the assumption that the control group is not affected by the treatment. However, this assumption is hard to hold because strict regulations can cause firms to move production between factories. For example, the facility-reporting firm can adjust the production from facilities under the ETS regulation to the facilities under the TMS regulation if capacity allows. If this is the case, our policy effects can be overestimated. For the business-reporting firms, this possibility is lower than for the facility-reporting firms, but it can happen if the regulation affects the competitiveness between the ETS-regulated firms and the TMS-regulated firms. Thus, we need to take this possibility into consideration when we interpret the results.

Results – Business. The results when the reporting unit is the business are in Table 3.3. In the first and second columns, the average treatment effect of the ETS regulation on the treated (ATET) turns out to decrease emissions by 10.2–11.4%. In the second column, I control the industry-specific trends using the interaction dummy of industry sector and time. As a result, the statistical significance of the ATET decreases, but the absolute value of the effect turns out to be larger. The increase of the oil price also acted to reduce emissions with statistical significance, whereas the signs of renewable energy ratio and the real GDP were opposite to our expectations.

In the third and fourth columns, I estimate the ATET for the industries which are under the benchmark allocation only. The degree of the ATET ranges from 16.7% to 17.4%, which is greater than in the whole sample. However, due to the lack of samples, these figures are not statistically significant. Thus, we can see weak evidence that the ETS regulation using the benchmark allocation turns out to reduce emissions more than the ETS regulation under the grandfathering allocation.

In the last column, to check the effect of the capital intensity, I estimate the ATET and the interaction of the regulation dummy and capital intensity. Thus, the estimation equation is now

$$E_{it} = \beta_t t + \delta_1 \cdot reg_{it} + \delta_2 \cdot reg_{it} \cdot capint_{it} + \Theta X_{it} + \alpha_i + \epsilon_{it}, \tag{3.3}$$

where $capint_{it}$ is the capital intensity. I calculate capital intensity for each industry by dividing the capital assets by the revenue in each industry. I use the data from the 'Financial Statement Analysis' by the Bank of Korea. I get the expected negative ATET and interaction coefficient, but the degree of ATET is smaller as we consider the interaction term, and they are not statistically significant.

Table 3.3. Effects on GHG Emission (Business)

	GHG emission				
	Total		Benchmark alloc.		Capital intensity
ATET	−0.102**	−0.114	−0.167	−0.174	−0.020
	(0.051)	(0.079)	(0.108)	(0.108)	(0.078)
ATET × Cap inten.					−0.002
					(0.001)
log(oil price)	−0.417***	−0.502**	−0.818***	-0.152	−0.415***
	(0.108)	(0.209)	(0.281)	(0.112)	(0.107)
log(gdp)	-4.190	-11.54	-9.410	-1.761	-4.193
	(2.742)	(7.225)	(6.969)	(4.599)	(2.731)
renewable	0.211	0.919*	0.504	0.176	0.209
	(0.176)	(0.475)	(0.428)	(0.286)	(0.175)
Industry-time trend control	no	yes	no	yes	no
Firm level & time control	yes	yes	yes	yes	yes
Observations	3,334	3,334	964	964	3,334

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level.

Results – Facility. The results when the reporting unit is the facility are in Table 3.4. With the total sample in the first and second columns, we get surprising results. First, the average treatment effect on the treated (ATET) turns out to increase emissions by 7.5–7.8%. The increase of the oil price acts to reduce emissions, but with statistical significance only for two cases. The other explanatory variables are statistically insignificant, and the sign of the GDP coefficient is opposite to our intuition.

In the third and fourth columns, I estimate the ATET for the industries which are under the benchmark allocation. The degree of the ATET increases to 9.7–13.8%, although these figures are not statistically significant. Again, we can see that the ATET of the ETS regulation turns out to be bigger for the firms under the benchmark allocation than the total, but as the observation is smaller, they are not statistically significant. In the next subsection, we will check the possible reasons for this surprising result of the positive effect of the ETS on GHG emissions.

In the last column, I check the effect of the capital intensity. The ATET is now negative because the positive interaction term offsets the ATET. Again, the terms are not statistically significant.

TABLE 3.4. Effects on GHG Emission (Facility)

	log(GHG emission)				
	Total		Benchmark alloc.		Capital intensity
ATET	0.078***	0.075***	0.097	0.138	-0.019
	(0.027)	(0.027)	(0.135)	(0.121)	(0.067)
ATET × Cap inten.					0.002
					(0.003)
log(oil price)	−0.093***	0.029	-0.255	0.175**	−0.097***
	(0.036)	(0.152)	(0.189)	(0.070)	(0.035)
log(gdp)	-0.177	-1.427	−18.28**	3.220*	−0.298
	(1.354)	(3.626)	(7.924)	(1.800)	(1.387)
renewable	-0.045	0.109	1.238**	-0.180	-0.037
	(0.093)	(0.230)	(0.550)	(0.130)	(0.096)
Industry-time trend control	no	yes	no	yes	no
Firm level control	yes	yes	yes	yes	yes
Observations	3,805	3,805	389	389	3,805

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level.

3.4.2. Difference in Differences Estimation Using Continuous Treatment. In the previous analysis, I used a 'common treatment dummy' across all industries. This misses the fact that industries vary with respect to pollution intensity and the degree to which the regulation impacts operations. Here, I consider a continuous treatment that reflects industry-level pollution intensity to separate industries that use a relatively small amount of pollution (or have low pollution intensity) from those for which energy use and pollution are fundamental to their production process.

First I construct the industry-level emission intensity using the emission data from the 'National Energy Consumption & GHG Emission Survey' and the revenue data from the 'Economy Census' in 2010. This is one year from the start of the firm-level data we used. The 'National Energy Consumption & GHG Emission Survey' includes all the emissions from manufacturing and mining. The census gives us all the revenue data across all industries. Because the first one gives us the emissions from manufacturing and mining, I can construct the emission intensity for each industry in manufacturing and mining. I use this intensity as a continuous treatment and get the results below.

Results – Business & Facility. The results when the reporting unit is the business are in Table 3.5. The first and second columns show the expected signs of the ATET, but they are not statistically significant. In the third and fourth columns, there are ATETs for the industries which are under the benchmark allocation. The signs are positive, and the coefficients are insignificant.

The results when the reporting unit is the facility are also in Table 3.5. We get the same surprising results that ATET is positive, although again the figures lack statistical significance. The lack of statistical significance may be the result of the smaller observations because here, I only include the manufacturing and mining industries, as the industry-level emission data was available for only these two industries. Otherwise, considering the fact that the continuous treatment is a more realistic representation of the regulation, there is a possibility that the previous DID exaggerates the ATET.

3.4.3. Staggered Difference in Differences Estimation. In the previous analysis, I used the usual DID analysis, but the dataset deviates from the usual DID format. The timing of the first treatment varies in this dataset. Many treated firms were first under the ETS in 2015, but some were not. For some extreme cases, the following example can exist: the firm appears in the dataset in 2013, then is under the ETS in 2017, then disappears from the dataset in 2019. Callaway and Sant'Anna (2021) deal with this heterogeneous first treatment timing and suggest the staggered DID setup that can give us the causal effect parameters for the different groups of the

Table 3.5. Effects on GHG Emission

	log(GHG emission)(Business)				log(GHG emission)(Facility)			
	Total		Benchmark alloc.		Total		Benchmark alloc.	
ATET	-0.004	-0.025	0.001	0.007	0.008	0.013*	0.008	0.008
	(0.008)	(0.029)	(0.006)	(0.006)	(0.007)	(0.008)	(0.019)	(0.019)
log(oil price)	−0.260**	−0.509**	-0.080	-0.152	−0.093**	0.036	-0.147	-0.147
	(0.108)	(0.208)	(0.093)	(0.116)	(0.042)	(0.152)	(0.317)	(0.317)
log(gdp)	-1.924	-11.44	0.014	-1.761	0.079	-1.400	−18.19*	−18.19*
	(2.503)	(7.222)	(2.631)	(4.762)	(1.468)	(3.603)	(10.39)	(10.39)
renewable	0.059	0.917	0.008	0.176	-0.052	0.110	1.263*	1.263*
	(0.164)	(0.475)	(0.173)	(0.296)	(0.101)	(0.230)	(0.663)	(0.663)
Industry-time trend control	no	yes	no	yes	no	yes	no	yes
Firm level	yes	yes	yes	yes	yes	yes	yes	yes
Observations	2125	2125	202	202	2793	2793	93	93

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level.

first treatment and for each year. Rios-Avila et al. (2021) provide the Stata coding to do Callaway and Sant'Anna (2021)'s 'csdid' estimation. Thus, here, I use Rios-Avila et al. (2021)'s coding and report the results.

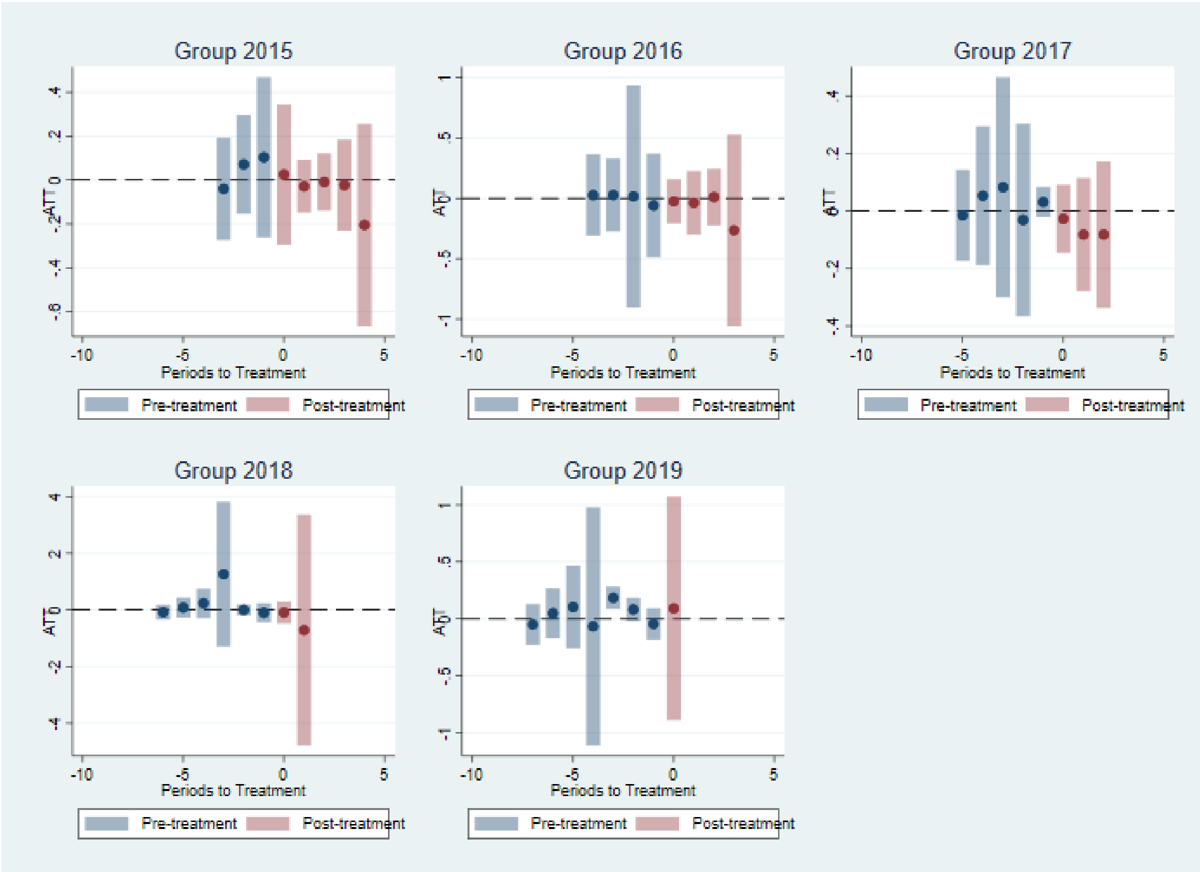
In this method, it is possible to get the $ATET(g,t)$ for each groups g which got the treatment first in the g period at a particular time period g defined as below.

$$ATET(g,t) = E[Y_t(g) - Y_t(0)|G_g = 1], \tag{3.4}$$

where G_g is a binary variable that is equal to 1 if a unit is first treated in g, otherwise 0. This estimation is possible for the pair-balanced observations, so some observations which are not balanced are missing.

Results – Business. The estimation results of the $ATET(g,t)$ for the business-reporting firms are in Figure 3.6. Given these $ATET(g,t)$, we can have the heterogeneous ATET for each group by averaging $ATET(g,t)$ over t:

$$\theta(\tilde{g}) = \frac{1}{T - \tilde{g} + 1} \sum_{t=\tilde{g}}^{T} ATET(\tilde{g},t), \tag{3.5}$$



Note: Shades are uniform 95 % confidence bands.

FIGURE 3.6. Average Treatment Effects on the Treated

where $T = 9$ is the total period. The summary is in Table 3.6. Except for the 2019 group (9.1% increase), all the groups show negative $ATET(g)$, ranging from -4.6% to -40.7%, and were significant in 2016 and 2017. The average weighted by the group size is 5.7% lower emissions due to the ETS regulation, which is significant at a 5% p-value.

TABLE 3.6. ATET on log(GHG emissions) across the first treated time(Business)

	Average	2015	2016	2017	2018	2019
ATET	-0.057^{**}	-0.046	-0.078^{*}	-0.059^{*}	-0.407	0.091
	(0.027)	(0.029)	(0.046)	(0.030)	(0.329)	(0.143)
N			3,029			

Similarly, we can also have the ATET in the specific time period t by averaging $ATET(g,t)$ over g:

$$\theta_c(\tilde{t}) = \sum_{g \in G} \mathbf{1}[\tilde{t} \geq g] P(G = g | G \leq \tilde{t}) ATET(g,t), \tag{3.6}$$

The summary is in Table 3.7. Except for the first year of the regulation (2015, 2.5% increase), all the years show negative $ATET(t)$, ranging from -1.3% to -21.8%, which was significant in 2019. The average weighted by the time period size is 5.1% lower emissions due to the ETS regulation, which is significant at a 10% p-value.

TABLE 3.7. ATET on log(GHG emissions) across the calendar time(Business)

	Average	2015	2016	2017	2018	2019
ATET	-0.051^{*}	0.025	-0.028	-0.013	-0.023	-0.218^{***}
	(0.027)	(0.052)	(0.020)	(0.023)	(0.033)	(0.071)
N			3,029			

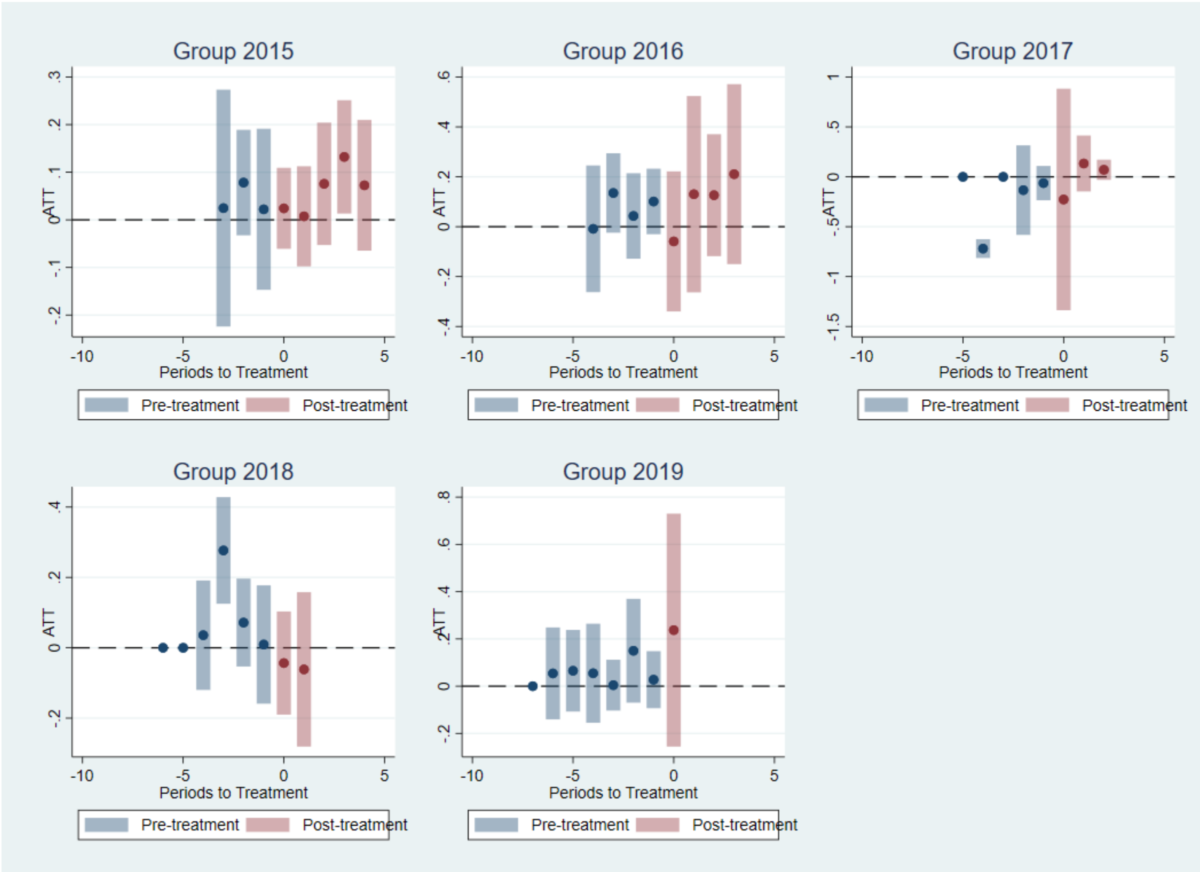
Results – Facility. The estimation results of the $ATET(g,t)$ for the facility-reporting firms are in Figure 3.7.

Given these $ATET(g,t)$, we can have the heterogeneous ATET for each group by averaging $ATET(g,t)$ over t, and the summary is in Table 3.8. Although the ATET was negative in 2017 and 2018, it was positive in other years, ranging from a 5.8% to a 23.7% increase, and was significant in 2015 and 2019. The average weighted by the group size is 5.8% higher emissions due to the ETS regulation, which is significant at a 5% p-value.

TABLE 3.8. ATET on log(GHG emissions) across the first treated time(Facility)

	Average	2015	2016	2017	2018	2019
ATET	0.058^{**}	0.058^{**}	0.083	-0.066	-0.052	0.237^{*}
	(0.023)	(0.026)	(0.055)	(0.151)	(0.050)	(0.135)
N			3,059			

Similarly, we can also have the ATET in the specific time period t by averaging $ATET(g,t)$ over g, and the summary is in Table 3.8. Except for 2016 (1.0% decrease), all the years show a positive $ATET(t)$, ranging from a 2.4% to a 10.8% increase, which was significant in 2018 and 2019.



Note: Shades are uniform 95 % confidence bands.

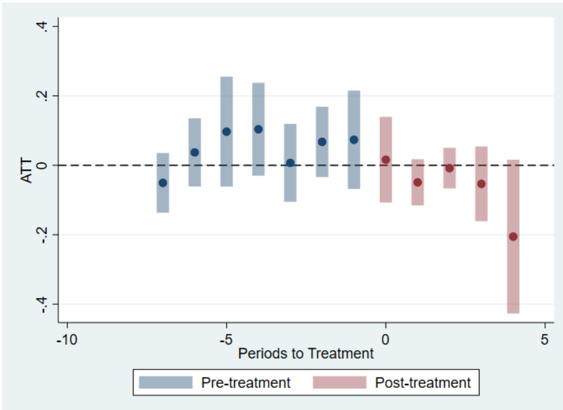
FIGURE 3.7. Average Treatment Effects on the Treated

The average weighted by the time period size is 5.6% higher emissions due to the ETS regulation, which is significant at a 5% p-value.

TABLE 3.9. ATET on log(GHG emissions) across the calendar time(Facility)

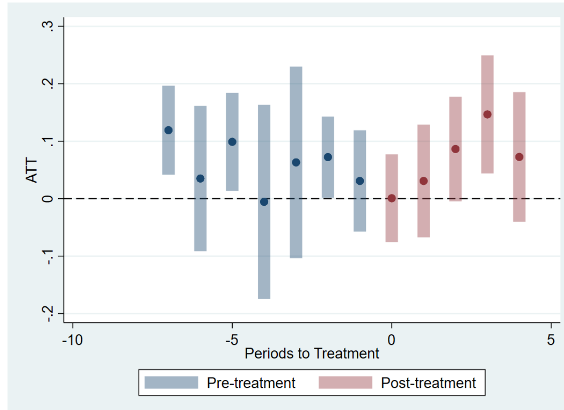
	Average	2015	2016	2017	2018	2019
ATET	0.056**	0.024	-0.010	0.072	0.108***	0.087**
	(0.023)	(0.025)	(0.031)	(0.045)	(0.030)	(0.037)
N				3,059		

Event Study and Checking the Parallel Shifts of the Trends. Under this staggered DID, event study analysis is also possible, and we can check the pretrend with the graph and perform a chi-square test. We can see that it is hard to say that the pretrends are parallel in either case, and a chi-square test rejects in both cases the null hypothesis that H_0: 'All pre-treatments are equal to 0' (Business: $\chi^2(30) = 38,997.0$, $p = 0.00$, Facility: $\chi^2(27) = 164.059$, $p = 0.00$).



Note: Shades are uniform 95 % confidence bands.

(a) Business



Note: Shades are uniform 95 % confidence bands.

(b) Facility

FIGURE 3.8. Average Treatment Effects on the Treated (Event Study Analysis)

3.4.4. The Background of the Anomaly in the Facility Results. The DID estimation results when the reporting unit is the facility are quite surprising. Usually, we expect that the introduction of the ETS regulation would lower the emission, but we get a positive ATET, which means that the firms under the ETS raised their emissions after the regulation.

In the previous research, the increase of GHG emissions after the introduction of the ETS was observed in some specific industries. According to Dechezleprêtre et al. (2018), the electricity and heat industries could benefit from the EU ETS, as they can pass through the increase of the production cost. Yu et al. (2017) also find that the electricity and cement industries showed no emission reductions after the introduction of the Korean ETS Phase I, because electricity can pass through the cost and cement does not have any room to decrease emissions, but rather, they chose to buy the allowances.

Another finding in Dechezleprêtre et al. (2018) is that GHG emission reduction is related to firm size. They estimate the treatment effect by splitting the matched sample according to the installation size, and in their first quartile analysis, they get a positive treatment effect, and the fourth-quartile firms showed a negative treatment effect. They explain this result with the fact that pollution control is capital-intensive and involves high fixed cost, so larger firms are more reactive to carbon pricing. Similar reasoning can be found in the survey in Ministry of Environment (Korea) (2021). The criterion of the ETS for facilities (25,000 t CO_2) is lower than that for businesses (125,000 t CO_2). Therefore, in most cases, the scale of the firm was smaller for facility-reporting than for business-reporting firms. We can see this by comparing the revenues of the business-reporting and facility-reporting firms in Figure 3.9. From the survey in Ministry of Environment

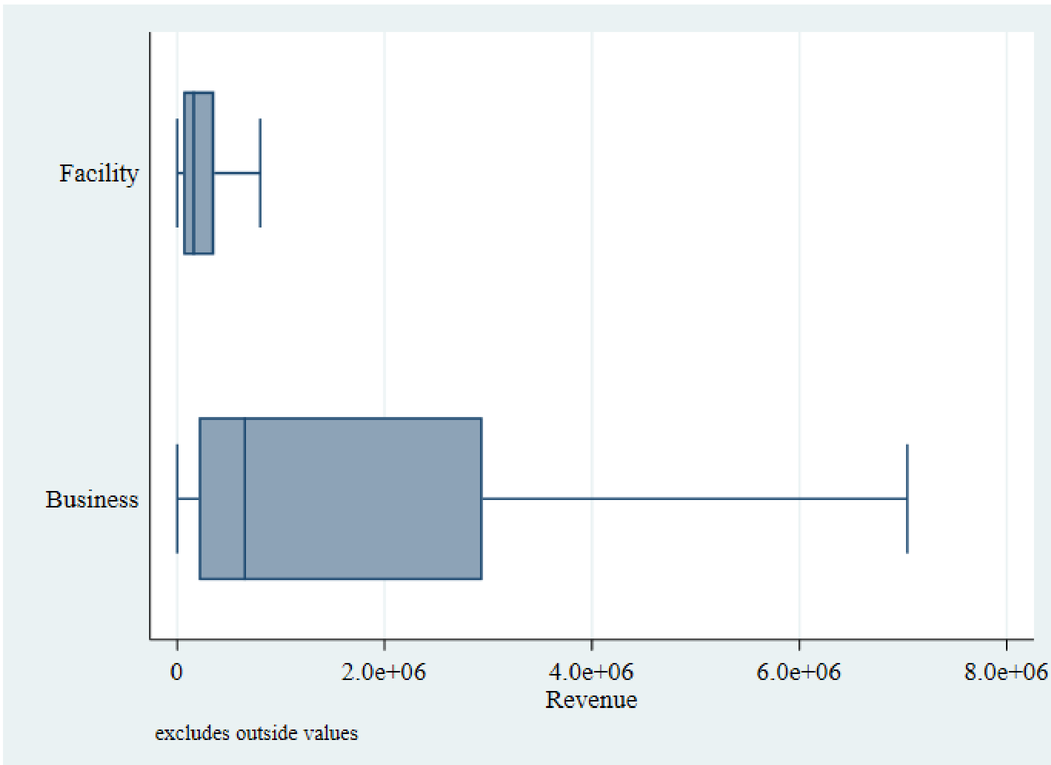
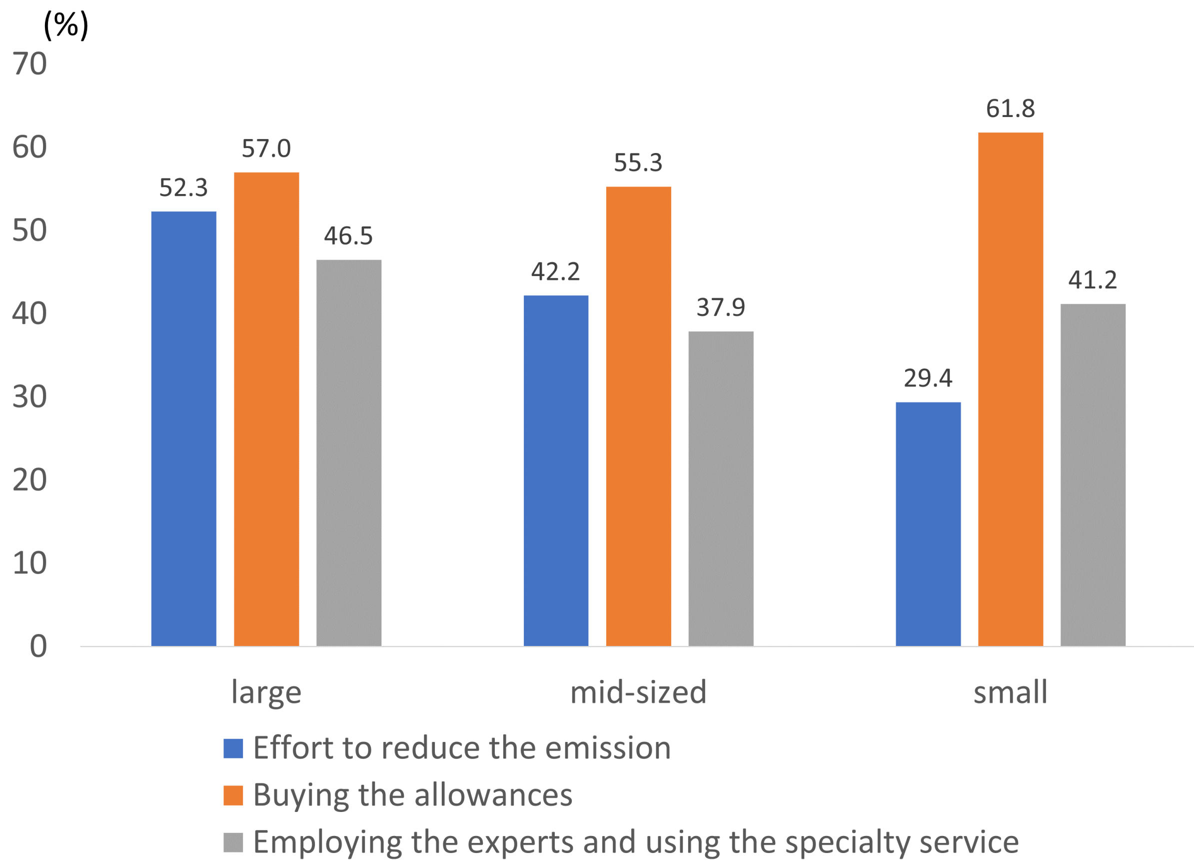


FIGURE 3.9. Distribution of Revenues

(Korea) (2021), small companies tended to rely on purchasing allowances to cope with the ETS but spent less on the effort to reduce their emissions. On the contrary, although large companies also spent a lot on purchasing allowances, they spent a much higher portion on the effort to reduce their emissions. This survey result is also consistent with the finding in the previous chapter that the highly productive firms choose to adopt high technology if we assume that the scale of the company can proxy its productivity. Considering that most reporting facilities belong to a small company, and many reporting businesses belong to a large company, this survey explains some of our anomalies in the facility estimation. The reporting facilities, which are mostly small businesses, tended to buy the allowances rather than trying to reduce their emissions when faced with the ETS.



Source: Ministry of Environment (Korea) (2021)
Note: Multiple choices are possible up to 2 choices

FIGURE 3.10. Expenditure to cope with the ETS by the scale of the company

3.4.5. Propensity Score Matching Estimation. In this section, we will analyze the effect of the introduction of the ETS by employing the propensity score matching method. The matching method as an econometric evaluation estimator has been used in much economic literature to judge the policy effect after Heckman et al. (1998). In addition, Abadie (2005) proposes propensity score matching as an alternative to the usual DID methods when the parallel trend assumption is not met. As we have seen that a pretrend exists in our data, employing this propensity score matching is quite appropriate.

To get the policy effect correctly, we need to get the average treatment effect on the treated as in the DID model.[13]

$$ATET = E(\Delta y|D = 1) = E(\delta y_1|x, D = 1) - E(\delta y_0|x, D = 1), \tag{3.7}$$

where δy_1 is the change of the dependent variable treated before and after the treatment and δy_0 is the change of the dependent variable control before and after the treatment. As $E(\delta y_0|x, D = 1)$ is the counterfactual, we need to estimate it, and we replace it with the matched control observation, which is obtained by the matching method. So, the above is now

$$ATET = E(\Delta y|p(x), D = 1) = E(\delta y_1|p(x), D = 1) - E(\delta y_0|p(x), D = 0), \tag{3.8}$$

where $p(x)$ is the propensity score, or the probability given x as the explanatory variable based on the probit model. In our case, the treatment is the introduction of the ETS, and the criteria for the ETS are based on the average of the past three years' GHG emissions. Thus, to get the propensity score, I used only the average of the past three years' GHG emissions as the independent variable x. As in the DID analysis, I segregated the sample to the reporting entity and conducted the analysis separately because the emission pattern is quite different according to the type of the reporting entity. I followed the matching method package by Becker (2002) and allowed full matching, which means that one treated entity can be matched to several control entities and vice versa, and to calculate the propensity score, I used the 'Probit' model. For matching, I used the nearest neighbor matching method, which matches the treated firm with the control firm which has the closest propensity score.

One of the drawbacks of the matching method is that we lose some observations which do not get a counterpart in the process of the matching. First, we lose some entities which is out of common support. Thus, if the propensity score is at an extreme, we exclude those cases. In the process of the nearest neighbor match, we lose more data. The total number of entities and the number of the entities without common support in the first year of the ETS (2015) is in Table 3.10. Another reason that we lose data is that we restrict the match to the firms which have data before

[13] The explanation about propensity score matching is from Katchova (2020).

and after the introduction of the ETS. I mainly focus my analysis on these matches and expand them to the remaining periods.

TABLE 3.10. Number of entities in the common support(CS) (2015)

	In CS		Out CS		Total	
	TMS	ETS	TMS	ETS	TMS	ETS
Business	85	223	16	2	101	225
Facility	204	133	63	119	267	252

First, I tested the proposition that 'Stricter environmental policy reduces the emissions ($E_j(\varphi)$) from home production at the firm level.' Thus, I estimated the average treatment effect on the treated for GHG emissions first. I still can use the Dubai crude oil price, real GDP, and the ratio of renewable energy as explanatory variables. I took the log for oil price and real GDP, but not for GHG emissions, as the criterion for the regulation is the average emissions for the past three years, not the log of the average. Instead, I adjusted the scale by using the kt CO_2 level of GHG emissions, which means that I divided the original data (t CO_2) by 1,000.

Results – Business. The results when the reporting unit is the business are in Table 3.11. In the first column, I find the ATET for the whole period of the treatment (2015–2020); in the second column, I do the same for the Phase I period of the ETS as the treatment era (2015–2017). In the third column, I do that for the Phase II period of the ETS as the treatment era (2018–2020), and in the fourth column, I do that for the firms under the benchmark allocation. The average treatment effect of the ETS regulation on the treated (ATET) for the whole period is −335.51, which means that the firm under the ETS emits on average 335.5 kt CO_2 less GHG than the TMS-only firms, which have a similar probability of being regulated. Considering the average of 2,762.7 kt CO_2 for the firms which were matched after being treated, this 335.5 kt CO_2 is about a 12.1% reduction.

The ATET turns out to be bigger in absolute terms for the Phase II period than for the Phase I period. Therefore, we can say that the emission reduction effect seems to be greater in the Phase II period. The ATET for the industries which are under the benchmark allocation turns out to be greater than that for all the industries, but as the sample which could be matched was small (71), this was not statistically significant.

Table 3.11. Effects on GHG Emission (Business)

	GHG emission ($ktCO_2$)			
	Total	Phase I	Phase II	BM
ATET	-335.5^{**}	-263.6^{**}	-356.1^{**}	-348.6
	(155.7)	(120.3)	(177.0)	(563.3)
Proportion of the ATET (%)	-12.1	-9.5	-12.9	-12.6
no. of matched firms treated	223	223	233	71

Notes: Standard errors are in parentheses
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level.

Results – Facility. The results when the reporting unit is the facility are in Table 3.12. As in the case of the business-reporting forms, the ATET for the whole period of the treatment is in the first column, the ATET for the Phase I period of the ETS is in the second column, and the ATET for the Phase II period of the ETS is in the third column. Although the ATET for the whole period shows a negative sign, it is not statistically significant, and the ATET for Phase I is positive and statistically insignificant. The only statistically significant ATET is the one for Phase II, so we can say that the firm under the ETS emits on average 10.34 kt CO_2 (29.3%) less GHG than the TMS-only firms, which have a similar propensity to be regulated during the Phase II ETS regulation. I could not get the ATET for the industries which are under the benchmark allocation because only 12 treated firms could be matched. Therefore, with the matching method estimation, we cannot say whether the benchmark allocation is more effective at reducing GHG emissions than the grandfathering allocation for the facility-level reporting.

Table 3.12. Effects on GHG Emission (Facility)

	GHG emission ($ktCO_2$)			
	Total	Phase I	Phase II	BM
ATET	-8.407	7.201	-10.34^{*}	-
	(5.948)	(6.496)	(6.304)	(-)
Proportion of the ATET (%)	-23.8	20.4	-29.3	-
no. of matched firms treated	133	133	133	12

Notes: Standard errors are in parentheses
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level.

3.5. Empirical Analysis of the ETS Effects on Emission Intensity

3.5.1. Difference in Differences Estimation. In this section, we test the ETS effects on emission intensity. To do that, we need to calculate the emission intensity and need to have data for the production. Although it is hard to get the product data at the firm level, we have data for revenue from the firms' income statements, so we use revenue as a proxy for products and regard the GHG emissions per revenue as emission intensity. The GHG emissions per revenue ratio can be dissected as the GHG emission per energy ratio and energy per revenue ratio, GHG emission/Revenue = GHG emission/Energy × Energy/Revenue. The decrease of the GHG emissions per energy ratio represents the shift to low-emission energy use, and the decrease of the energy per revenue ratio represents the improvement of energy-use efficiency.[14] Here, I test not only the GHG emissions per revenue ratio but also the GHG emission per energy ratio and energy per revenue ratio. The regression equation is the same as in the previous section. The only difference is that we have replaced the dependent variables with the emission intensities. I use the same macroeconomic variables as explanatory variables, such as the Dubai oil price, real GDP, and the renewable energy ratio.

Results – Business & Facility. The results for the business-reporting firms are in Table 3.13, and those for facility-reporting firms are in Table 3.14. Regardless of the reporting type and whether we controlled the industry time trend or not, there was no case that showed statistical significance in ATET for the ETS regulation. Therefore, we can say that it is hard to find evidence that the introduction of the Korean ETS affected the emission intensity.

3.5.2. Propensity Score Matching Estimation. As we did in the previous section, here, we apply the propensity matching approach to test the proposition that 'Stricter environmental policy reduces the emission intensity ($e_j(\varphi)$) from home production at the firm level.' We use revenue as a proxy for products and test the effect of the introduction on the GHG emissions per energy ratio and energy per revenue ratio as well as the GHG emissions per revenue ratio.

Results – Business. The results for the business-reporting firms are in Table 3.12. The statistically significant cases are the emission/revenue ratio and energy/revenue ratio. The ATETs are all positive. Thus, we get the result that the emission intensity increased as a result of the ETS

[14] Park and Lee (2021)

Table 3.13. Effects on Emission Intensity (Business)

	Emission/Revenue (tCO_2eq/million Won)		Emission/Energy (tCO_2eq/TJ)		Energy/Revenue (TJ/million Won)	
ATET	-1.008	-1.456	-2.556	1.409	-0.010	-0.016
	(0.776)	(1.076)	(3.830)	(5.145)	(0.009)	(0.012)
log(oil price)	-1.451	0.098	-14.92**	25.93	-0.029	-0.002
	(1.868)	(0.226)	(7.499)	(26.75)	(0.037)	(0.004)
log(gdp)	-37.96	-4.073	-583.2***	-533.4	-0.430	-0.069
	(28.91)	(3.134)	(222.8)	(390.3)	(0.577)	(0.048)
renewable	2.505	0.189	33.82**	38.42	0.026	0.004
	(2.139)	(0.206)	(14.62)	(29.35)	(0.042)	(0.004)
Industry-time trend control	no	yes	no	yes	no	yes
Firm level control	yes	yes	yes	yes	yes	yes
Observations	2,670	2,670	3,333	3,333	2,670	2,670

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

Table 3.14. Effects on Emission Intensity (Facility)

	Emission/Revenue (tCO_2eq/million Won)		Emission/Energy (tCO_2eq/TJ)		Energy/Revenue (TJ/million Won)	
ATET	-0.824	-0.926	0.347	0.106	-0.015	-0.018
	(0.706)	(0.874)	(3.645)	(3.021)	(0.014)	(0.018)
log(oil price)	-0.160	0.008	-8.133	1.716	-0.003	0.0001
	(0.141)	(0.076)	(6.231)	(1.950)	(0.003)	(0.001)
log(gdp)	-75.76	1.854	-169.0	43.34	-1.484	0.037
	(72.75)	(2.818)	(198.9)	(52.53)	(1.459)	(0.054)
renewable	5.140	-0.080	8.883	-2.689	0.101	-0.002
	(4.949)	(0.173)	(13.10)	(3.394)	(0.099)	(0.003)
Industry-time trend control	no	yes	no	yes	no	yes
Firm level control	yes	yes	yes	yes	yes	yes
Observations	3,057	3,057	3,805	3,805	3,057	3,057

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

introduction, which is contradictory to our expectation. In the DID analysis, we got a negative

ATET, although it was not statistically significant. Therefore, it is hard to conclude whether this proposition fits the data or not.

Table 3.15. Effects on Emission Intensity (Business)

	Emission/Revenue (tCO_2eq/million Won)			Emission/Energy (tCO_2eq/TJ)			Energy/Revenue (TJ/million Won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	0.526*	0.619*	0.578	13.884	14.507	11.149	0.009*	0.011*	0.011*
	(0.315)	(0.339)	(0.359)	(13.769)	(10.979)	(14.181)	(0.005)	(0.006)	(0.006)
no. of matched firms treated	223								

Notes: Standard errors are in parentheses
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

Results – Facility. The results for the facility-reporting firms are in Table 3.13. There was no case which showed statistical significance in ATET for the ETS regulation. This is the same as in the DID analysis, so we can say that it is hard to find evidence that the introduction of the Korean ETS affected the emission intensity for the facility-reporting firms.

Table 3.16. Effects on Emission Intensity (Facility)

	Emission/Revenue (tCO_2eq/million Won)			Emission/Energy (tCO_2eq/TJ)			Energy/Revenue (TJ/million Won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	0.001	0.002	-0.004	2.60	2.554	6.111	0.000	0.000	0.000
	(0.033)	(0.021)	(0.052)	(1.937)	(2.512)	(4.698)	(0.001)	(0.000)	(0.001)
no. of matched firms treated	133								

Notes: Standard errors are in parentheses and are calculated by bootstrapping for emission/revenue and energy/revenue ratio
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

3.6. Empirical Analysis of the ETS Effects on Firms' Performance

The last propositions that will be tested are related to the firms' performance, that 'Stricter environmental policy reduces the average revenue of the firms at home, then the profit as well' and that 'Stricter environmental policy makes it harder for the firms at home to export (φ_x increases) and makes the firms at home adopt the high technology (φ_h decreases).' These also fit with our common sense and are tested in several studies. We have these firm performance data from the firms' income statements. To check the high-technology adoption, I used the level of R&D expenditure, which is the sum of the research and development expense (R&D), and depreciation of R&D investments and amortization of intellectual property. The problem is that these items include not only the emission-reducing technology investments but also all other R&D expenditure, so they are broader than the range of our analysis, because in the previous chapter, we only focused on the emission-reducing technology. However, such a specific R&D expenditure item is not available under the current accounting system, so I used this broader item instead. Another problem is that the quantity of available export data in the database was small, so the observation of the exports is less than the other dependent variables.

3.6.1. Difference in Differences Estimation. For DID analysis, I used the same regression equation as in the previous section. However, the dependent variables changed to the log of revenue, log of export, log of R&D investment, and net profit of firm i at time t. Due to the large scale of the variables, I took the log, but profit and R&D can have negative values.[15] As in the previous subsection, I estimated the average treatment effect on the treated (ATET) using the panel difference in differences (DID) estimation.

Results – Business. The estimation results for the business-level reporting firms are in Table 3.17. For the revenue, the ATET effect was consistent with our expectation that the ETS effect is negative, although it was not statistically significant after controlling the industry trends. For exports and R&D expenditure, the signs of the ATET fit our expectations, although we could not get statistical significance. Exports decreased under the effect of the ETS regulation, while R&D expenditure increased. For the profit, the sign of ATET changed before and after controlling the industry trends. Therefore, we can say that the ETS regulation has reduced revenue and exports and stimulated R&D expenditure slightly, but it is hard to say that those effects are meaningful, and it is hard to say that the ETS regulation has a meaningful relationship with the firm's profit.

[15]Negative net profit can be observed because firms can have a loss; negative R&D expenditure is quite rare, but a few examples were observed. Those firms had a negative amortization, but as this is quite rare, I excluded these observations from the analysis and took the log on R&D investment.

Table 3.17. Effects on Firms' Economic Performances(Business)

	log(Revenue)		log(Export)		log(R&D)		Profit (bn won)	
ATET	-0.122^{*}	-0.110	-0.112	-1.253	0.260	0.022	-51.25	17.33
	(0.0734)	(0.0996)	(0.653)	(0.790)	(0.196)	(0.120)	(62.22)	(69.87)
log(oil price)	-0.240	-0.576^{*}	-0.275	-0.792	-0.116	-1.067	-431.5	-7298.1
	(0.146)	(0.300)	(0.271)	(0.937)	(0.147)	(0.746)	(286.6)	(5072.6)
log(gdp)	7.849^{**}	-8.856	15.78	-25.64	-1.723	-41.55	$-10,740.5^{***}$	-257,842.3
	(3.371)	(8.618)	(12.25)	(23.47)	(4.179)	(27.55)	(3,811.0)	(153,766.3)
renewable	-0.515^{**}	0.807	-1.131	2.040	0.068	3.047	646.3^{***}	18,696.4
	(0.235)	(0.583)	(0.935)	(1.527)	(0.311)	(1.938)	(229.1)	(11,408.5)
Industry-time trend control	no	yes	no	yes	no	yes	no	yes
Firm level control	yes	yes	yes	yes	yes	yes	yes	yes
Observations	2,670	2,670	559	559	2,039	2,039	2,674	2,674

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

Results – Facility. The estimation results for the facility-level reporting firms are in Table 3.18. In the revenue, exports, and R&D, the ATET was statistically significant, although the signs need some careful interpretation. The ATET of the ETS regulation on revenue and export turned out to be positive, and that on R&D was negative. This is in contrast to our expectation but can be understood in the context of the background of the anomaly in the emission analysis. If we interpret the results in the context of that explanation, the facility-level reporting firms, which tend to be small businesses, may have chosen to react by buying allowances rather than taking effort to reduce their emissions (negative ATET on R&D expenditure). We can think of this as the decrease of the low-technology cutoff in the previous chapter (decrease of φ_l as a result of the unilateral environmental policy). This might affect the firms' profitability (negative ATET on profit, although it is not statistically significant), but they might not have changed their production plan, as we could see in the positive ATET on GHG emissions in the first DID analysis. Thus, the positive ATET on revenue can be related to the positive ATET on GHG emission. However, the positive ATET on exports is hard to understand. It could be just the result of the increase of production (positive ATET on revenue), but if we accept the general fact that the export cutoff is higher than the low-technology cutoff or market entry cutoff, we need another explanation for this. The explanation could be that there exist other factors than the environmental policy which determine the exports. If this is the case, this result could be a counterexample of the 'pollution haven hypothesis.'

TABLE 3.18. Effects on Firms' Economic Performances(Facility)

	log(Revenue)		log(Export)		log(R&D)		Profit (bn won)	
ATET	0.110***	0.080**	0.389**	0.403***	−0.225**	−0.236**	-12.37	-7.640
	(0.036)	(0.034)	(0.170)	(0.149)	(0.095)	(0.091)	(12.23)	(7.932)
log(oil price)	0.046	0.108	0.338	0.313	0.307*	0.737	6.357	-6.407
	(0.052)	(0.185)	(0.351)	(1.368)	(0.163)	(0.820)	(11.64)	(19.20)
log(gdp)	2.772*	−7.769*	6.718	33.45	2.617	5.572	-201.3	−1,581.7**
	(1.580)	(4.168)	(9.676)	(34.29)	(5.409)	(14.07)	(379.7)	(615.9)
renewable	−0.202**	0.614**	-0.447	-1.951	-0.070	-0.405	13.40	112.0***
	(0.107)	(0.277)	(0.700)	(2.350)	(0.377)	(0.898)	(26.64)	(42.10)
Industry time trend control	no	yes	no	yes	no	yes	no	yes
Firm level control	yes	yes	yes	yes	yes	yes	yes	yes
Observations	3,057	3,057	583	583	2,114	2,114	3,056	3,056

Notes: Standard errors are in parentheses and are clustered at the company level
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

3.6.2. Propensity Score Matching Estimation. Here, we test the propositions related to the firms' economic performance using propensity score matching estimation. Instead of taking the log, I adjusted the scale by dividing the data by 10,000, which means that the dependent variables are measured in 10 billion Korean won.

Results – Business. The estimation results for the business-level reporting firms are in Table 3.19. For the revenue, as in the DID analysis, we got a negative ATET, which is consistent with our expectation. The scale of ATET is greater in ETS Phase II, so we can say that the negative effect of the ETS played a bigger role in Phase II. For the profit, we got a negative ATET, but it was not statistically significant. For the R&D expenditure, the sign of the ATET was consistent with our expectations, but it was not statistically significant. For the exports, the ATETs had a positive sign, which is contradictory to our expectation, and were not statistically significant. Combining the results from the DID, we find evidence that the ETS regulation has reduced the revenue, but it is hard to say that the ETS regulation had a meaningful effect on other economic performance.

TABLE 3.19. Effects on Firms' Economic Performances(Business)

	Revenue (10bn won)			Profit (10bn won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	−137.1***	−100.0***	−162.0**	-18.83	-18.12	-14.03
	(45.68)	(31.02)	(69.16)	(23.42)	(21.39)	(20.44)
Proportion of the ATET (%)	−23.4	−17.1	−27.7	-59.4	-57.2	-44.3
	R&D (10bn won)			Export (10bn won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	2.427	-0.109	5.631	36.93	2.505	89.10
	(12.20)	(8.078)	(12.03)	(123.8)	(79.09)	(166.8)
Proportion of the ATET (%)	11.3	−0.5	26.2	7.2	0.5	17.3
no. of matched firms treated			223			

Notes: Standard errors are in parentheses
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

Results – Facility. The estimation results for the facility-level reporting firms are in Table 3.20. There was no case that showed a statistically significant result. In addition, the nearest matching method could not find the proper matches between the treated group and the control group for R&D and exports, so I used the kernel matching method for those cases. Contrary to the DID analysis, the sign of the ATET on the revenue was consistent with our expectation (negative), but the signs of the ATET on other economic performance variables were contrary to our expectations, and as they were not statistically significant, we can say that we do not find any meaningful impact of the ETS on economic performance for the facility-level reporting firms.

3.7. Conclusion

In this chapter, I tested the several propositions related to the unilaterally stricter environmental policy that I found in the previous chapter with the firm-level data in Korea before and after the introduction of the ETS. Using the DID estimation and matching method, what is commonly observed is that GHG emissions and revenue decreased for the business-reporting firms after the introduction of the ETS. The event study analysis revealed the existence of a pretrend in the DID

Table 3.20. Effects on Firms' Economic Performances(Facility)

	Revenue (10bn won)			Profit(10bn won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	-21.73	-14.38	-25.85	0.406	0.624	0.086
	(17.82)	(13.56)	(19.37)	(0.601)	(0.697)	(0.791)
Proportion of the ATET (%)	−39.5	−26.2	−47.0	80.7	124.1	17.1
	R&D (10bn won)			Export (10bn won)		
	Total	Phase I	Phase II	Total	Phase I	Phase II
ATET	-0.095	-0.069	-0.119	0.854	0.921	0.788
	(0.352)	(0.150)	(0.625)	(1.128)	(0.959)	(1.099)
Proportion of the ATET (%)	−29.2	−13.7	−23.6	4.0	4.3	3.7
no. of matched firms treated			133			

Notes: Standard errors are in parentheses and are calculated by bootstrapping
*** Significant at the 1 percent level,
** Significant at the 5 percent level,
* Significant at the 10 percent level

analysis, so the estimates in the propensity score matching are regarded as more reliable, as this method does not depend on the non-existence of a pretrend. The decreasing effect of the ETS is consistent with our expectation. This effect turned out to be greater for the Phase II period, and for the industries in which the benchmark allocation was used. For the other propositions, the results were not sufficient to draw a conclusion or were mixed and sometimes in contrast to our expectations. For example, the GHG emissions and revenue of the facility-reporting firms did not decrease or increase after the introduction of the ETS in the DID analysis. Considering the existing research and the survey from the firms, this might be related to the smaller scale of the facility-reporting firms and the frequent changes of the samples,[16] but further investigation is needed. For the exports, the results were insignificant or in contrast to our expectation, so it is hard to observe evidence of the 'pollution haven hypothesis' in Korea due to the ETS regulation. As pointed out in the existing literature, there seem to be many factors which affect Korean exports other than environmental regulations such as the ETS.

[16] The facility-reporting firms' entry and exit are more frequent than those of the business-reporting firms. In Appendix B.2, the changes of the firms are described in more detail.

Currently, the GHG emission data is available yearly. As is pointed out in Yu et al. (2017), if more frequent data such as quarterly data were available, further research could be possible. For example, we could trace the relationship between GHG emissions and the allowance price, as the allowance price data is available in real time. The Korean government has announced that it will decrease the number of allowances as needed to meet the Paris agreement,[17] so the regulation will be tightened. In addition, as they are planning to expand the way of benchmark allowance allocation to more industries and reduce the free allocation, the firms will experience more binding regulation. Thus, tracing the changing effects due to those policy movements will be important in the future. Also, as the EU is expected to impose a 'border carbon adjustment' in the near future, investigating the effect of the BCA based on the findings in the previous chapter or another theoretical framework could be not only an interesting future research topic but also important to counter the climate crisis.

[17]The Korean government plans to reduce GHG emissions gradually to 37% below the business as usual (BAU) level by 2030 (Ministry of Environment (Korea) (2019)).

CHAPTER 4

Domestic Externalities and Regulations in the 'Protection for Sale' Model

4.1. Introduction

It is debatable whether it is good to impose tariffs for any reason except the optimal tariff argument.[1] Here, the 'optimal tariff' means the tariff which corrects the distortions in the international trade market from the national point of view (i.e., discrepancies between the marginal rate of substitution and marginal rate of transformation in foreign and domestic markets).[2] In this chapter, I find a proper level of tariffs when the factors other than optimal tariff argument affect the tariff determination. I propose an extended version of Grossman and Helpman (1994)'s 'Protection for Sale' model to allow for externalities in consumption and product standards in production. As this model assumes that the externalities occur in domestic consumption, and we do not consider it from a global perspective, this can be local pollution, such as the emission of SO_x from fossil fuel consumption.

I obtain the result that political factors can influence the level of domestic regulation, and as a consequence, tariffs can be higher than the optimal tariff argument because of the existence of externalities. In the sense of an indirect approach to the distortions, the policies here are not the first best, as they do not address the distortions directly. This result can provide some implications for tariff determination because tariffs can also be used when distortion and its remedy exist in different economic activities.

This chapter consists of the following sections. After a literature review, I include the domestic regulations in the 'Protection for Sale' model of a small open economy from Grossman and Helpman

[1]The survey paper of Ederington (2010) addresses the question, *"Should trade agreements include environmental policy?"* and concludes that as environmental policy can affect trade flows significantly, it is desirable to consider environmental policy in trade issues, but more research is needed to judge whether it would be good to include these issues in the current GATT rules.
[2]Johnson (1963)

(1994) in Section 4.3. I obtain a similar extension in the large country model in Section 4.4 (uncooperative) and Section 4.5 (cooperative) from the model of Grossman and Helpman (1995). In Section 4.6, I summarize my findings and conclude.

4.2. Literature Review

Many of the analyses about domestic regulations tend to be based on the tariff model framework and expand the model by adding domestic regulation to the policy consideration in that framework. For example, Bagwell and Staiger (2001) extend the model of Bagwell and Staiger (1999). These studies view that tariff and domestic policies act as substitutes, although the degree of the substitution is not perfect. If a government imposes a consumption tax differently depending on whether the product is produced domestically or imported, then the effects of the consumption tax are very similar to those of a tariff. The mechanism of how domestic regulation can act as a tariff substitute needs more explanation. This can be explained using the famous beef-hormones case example which is introduced in Staiger and Sykes (2011).[3]

Here, it is assumed that the importing country is the 'large' country and the consumers do not care about whether the beef is hormone-treated or not. Foreign exporters want to use the hormone because using the hormone can increase the foreign production of beef. Now, suppose that the importing country imposes restrictions on the usage of hormones in beef production to almost zero. Then, the foreign exporters will move from the production of hormone-treated beef to the production of hormone-free beef as long as the price of hormone-free beef is higher than the price of the hormone-treated beef plus the compliance cost. The world price of the hormone-treated beef falls because the demand for it decreases as a result of the home country's regulation. Then, the price of the hormone-free beef imported to the home country, which is the sum of hormone-treated beef and the regulation compliance cost, will rise by less than the regulation compliance cost. Then, the home country can get the benefit from the regulation by shifting the regulation compliance cost to the foreign exporters. Thus, the domestic regulation has created the same 'terms of trade' gain as the tariffs in standard tariff models.[4] Under these circumstances, the

[3]WTO Appellate Body opinion report (WT/DS26 and DS48/AB/R) adopted February 13, 1998, "EC Measures Concerning Meat and Meat Products (Hormones)."

[4]Some studies such as Krugman (1997) and Ossa (2011) point out the limitations of this 'terms of trade' argument in that it is hard to observe this terms-of-trade manipulation issues in real-world trade negotiations.

research on domestic regulations evaluates whether the related articles in the trade agreements or WTO (GATT) can work to prevent governments from pursuing this terms-of-trade gain in domestic regulation imposition.

For example, Ederington (2001) models that tariff and domestic policies can be partially substitutable, so facing the decrease of a tariff, governments have an incentive to distort their domestic policies to protect their domestic industries. In his model, a negative externality occurs in the domestic production, so using domestic taxes to counter these externalities can be rationalized, but the domestic tax can also be used for 'protectionist' purposes. But it is not a good idea to use domestic taxes for 'protectionist' purposes because the first-best policy to correct distortions is the policy that addresses the sources of the distortions directly. Thus, Ederington (2001) argues that the best policy is to use tariffs to counter the trade distortions from the terms-of-trade incentive and domestic regulations to tackle the domestic production distortions.

Staiger and Sykes (2011) show how a 'large' nation can have an incentive to use product standards to discriminate against importing goods when the use of tariffs is restrained by trade agreements. They further show that if product standards discrimination is prohibited, an inefficient level of stringent standards can emerge. Based on this framework, they argue that the current WTO legal system is good at policing regulatory discrimination but does little for excessive nondiscriminatory regulations.

Bagwell and Staiger (2001) examine the interaction between tariff negotiations and the decision to impose domestic standards, and they assess whether current WTO rules are proper to handle labor and environmental standards problems. Based on a two-goods, two-countries general equilibrium framework that was established in Bagwell and Staiger (1999), they add domestic standards into the governments' decision. Under this framework, even though governments agree to decrease tariff rates, there still exists an incentive to distort domestic policies to seek terms of trade gains. They focus on the 'non-violation' complaints in GATT articles. When a country's market access is impeded by a change of its trading partner's domestic policies, this complaint provision enables the country to request that its trading partner guarantee its market access by offering compensation policies. Thus, they formally show that the possibility of this 'non-violation' complaint allows governments to reach an efficient level of tariffs and domestic policies.

However, Bagwell and Staiger (2001) admit the practical difficulties of the 'non-violation' complaints. These difficulties stem from the burden of the complaining country to prove that the partner violated the agreement's spirit. Horn (2006) instead focuses on the role of the 'National Treatment (NT)' provision in the GATT system. 'National Treatment' requires that imported goods should be treated at least as favorably in treatment as 'like' domestic products. According to him, even NT also has a limitation because it cannot eradicate the problem of high taxation for both 'home' and 'foreign' goods (even though they are treated equally under NT, he shows that high taxation is likely to be imposed on both kinds of goods). According to him, even with this limitation, NT can be welfare-improving because it at least prevents discriminatory taxes.

As we have seen in Bagwell and Staiger (2001), it is natural to consider domestic regulations in the context of the tariff model framework. The political economy argument is one of the central parts of how trade policies are determined. Therefore, it is meaningful to consider domestic regulation in the political economy trade model. There have been many political economy approaches to the determination of trade policy. Among them, Grossman and Helpman (1994) is one of the most renowned works, which has been applied and tested in various ways. They suggest how a government decides the level of protection after comparing the contributions of producer lobbies and consumer welfare. This is a small open economy model, so it is assumed that the world price is given. The large country version of this model is Grossman and Helpman (1995). They consider the political economy in a two-country model where the trade policy can affect the world price. They first consider the tariff determination in an uncooperative way, then in a cooperative situation. Among the empirical investigations of this model, Gawande and Bandyopadhyay (2000) reformulate Grossman and Helpman's (1994) 'Protection for Sale' model to include intermediate goods trade. Using the 242 US industries dataset, they find that the US considers consumer welfare more than political contributions when setting the NTMs.

Schleich (1999) and Schleich and Orden (2000) use the 'Protection for Sale' model framework to analyze the environmental policy. Schleich (1999) considers environmental quality and trade and domestic taxes in a small open economy, and Schleich and Orden (2000) does a similar analysis in a large country case. They categorize the situations according to the cases when the externality is on the production side or on the consumption side. Based on this, Schleich (1999) derives the production and trade policies when domestic and trade policies are both available, and when only trade policy is available. He compares the results and which policy regime leads to higher environmental quality. Schleich and Orden (2000) conducts a similar analysis in a large country case, especially classifying the cases when the home and foreign governments cooperate or do not cooperate based on the policy availabilities.

Holland et al. (2015) examines the possibility that political consideration can affect the environmental policy decision and finds some evidence which supports this. The Waxman–Markey (WM) Cap and Trade (CAT) bill proposes the introduction of a CAT system to reduce CO_2 emissions. Holland et al. (2015) calculates the costs of the CO_2 emission reductions across the policies of CAT, ethanol subsidies, a renewable fuel standard (RFS), and a low-carbon fuel standard. Among them, CAT turns out to be the most cost-efficient, but the US representatives from the states which gain from the alternative ways of reduction, such as RFS, were more likely to vote against this bill. On the contrary, representatives from the states which would gain from the CAT tended to vote for this bill.

This paper is similar to Schleich (1999) and Schleich and Orden (2000) in that this paper also analyzes the trade policy and domestic regulation in Grossman and Helpman's 'Protection for Sale' model framework. However, Schleich (1999) and Schleich and Orden (2000) use the ad-valorem tax as a tool to counter the externalities in production or consumption. This paper does not specify the regulation as the ad-valorem tax, instead following Staiger and Sykes (2011) to use a more general form of domestic regulation and externality.

4.3. Protection for Sale Model Considering Domestic Externalities and Regulations in a Small Open Economy

Grossman and Helpman (1994)'s 'Protection for Sale' model explains that policies are determined by how politicians value lobbies' contributions versus the social welfare costs from protections. Here, I add externalities such as the pollution problem and domestic regulations to this model. I further assume that the level of externalities is determined by total consumption, so the existence of externalities does not affect an individual's choice of consumption. However, externalities harm social welfare, so the government cares about them. Therefore, the externalities appear not in the individual's utility function but in the social welfare function. Because we add one more policy goal to pursue, which is to deal with the externalities, we need one more policy tool, following a theorem by Jan Tinbergen. Thus, the government is supposed to use domestic regulation to manage the externalities.

As in the original model by Grossman and Helpman (1994), I assume a small economy and that consumers have identical preferences with the quasi-linear utility function, but now with the additional component of externality. Thus, the utility function is $u = x_0 + \sum_{i=1}^{n} u_i(x_i) + \theta_i(\rho_i, x_i)$, where x_0 is a numeraire good and x_is are consumptions of non-numeraire goods i, $i = 1, 2, ..., n$. Here, as in Staiger and Sykes (2011), I introduce the domestic standard level ρ_i and denote $\theta_i(x_i, \rho_i)$ as the level of the externality generated by consumption of the goods x_i under the standard ρ_i. The world price of good i (p_i^w) is exogenous to this country, and p_i denotes the domestic price of good i. The level of externality is determined by total consumption; thus, an individual's consumption does not affect the level of externality. Conversely, the existence of this component of externality does not affect an individual's choice of consumption either. Therefore, the optimization result of this quasi-linear utility is that the per-capita consumption of a non-numeraire good depends on its price, $x_i = d_i(p_i)$, $i = 1, \ldots, n$, and the consumption of the numeraire good is the remaining income after the consumption of the non-numeraire goods, $x_0 = I - \sum_{i=1}^{n} p_i d_i(p_i)$. Then, the indirect utility function is as follows.

$$V(\boldsymbol{p}, \boldsymbol{I}, \boldsymbol{\rho}) = I + s(\boldsymbol{p}) + \theta(\boldsymbol{\rho}, \boldsymbol{d}), \tag{4.1}$$

where $\boldsymbol{p} = (p_1, p_2, ..., p_n)$ is the domestic prices vector of the non-numeraire goods and $s(\boldsymbol{p}) \equiv \sum_{i=1}^{n} u_i[d_i(p_i)] - p_i d_i(p_i)$ is the consumer surplus from each good's consumption. $\theta(\boldsymbol{\rho}, \boldsymbol{d})$ is the per-capita externalities which individuals face from all over the industries; thus, we can define it as $\theta(\boldsymbol{\rho}, \boldsymbol{d}) = \sum_{i=1}^{n} \theta_i(\rho_i, d_i)/N$. Finally, $\boldsymbol{\rho} = (\rho_1, \rho_2, \ldots, \rho_n)$ is the domestic standards vector of the non-numeraire goods, and $\boldsymbol{d} = (d_1, d_2, ..., d_n)$ is the per-capita consumption vector of the non-numeraire goods.

The numeraire good is produced with one unit of labor only, and its labor requirement is 1, so wages are equal to 1. In addition, there exists a cost for a firm to comply with the standard $\phi_i(\rho_i)$, which is dependent on ρ_i. This is the cost that a company should pay or invest. For example, in the automobile industry, companies are required to reduce their carbon emissions, so they need to invest to develop technology to do so.[5],[6] In addition, 'carbon offset projects' such as reforestation, developing renewable energy, or other greenhouse gas capturing, can be examples of the regulation compliance cost, even though as 'carbon offsets' do not affect the product quality, they are different from the product standard. I further assume that this cost function $\phi_i(\rho_i)$ is convex. Then, the profit of the non-numeraire good is

$$R_i(p_i, \rho_i) = p_i f_i(L_i, K_i) - L_i - \phi_i(\rho_i). \tag{4.2}$$

The compliance cost does not affect the domestic price. This is because, as this country is a small open economy, the world price is given; thus, the domestic firms cannot affect the price. Tariffs only affect the domestic price, as the world price is given. The tariff revenue is assumed to be redistributed per person, so $r(\boldsymbol{p}) = \sum_{i=1}^{n}(p_i - p_i^w)[d_i(p_i) - \frac{1}{N}y_i(p_i)]$, where N is the total population.

The total income of an individual is composed of their profit from industry, their wage, and the redistributed tariff revenue. Some of the population ℓ_i owns industry-specific capital K_i; thus, they take the profit, $R_i(p_i, \rho_i)$. If I represent the group of the capital owners as $\ell = \sum_{i=1}^{n} \ell_i$, there are $N - \ell > 0$ people who do not own any capital. As I assume that externalities harm social welfare, I need to consider this in a social welfare function. The externality in industry i is a function of the consumption of that good and the standard on that good. It creates a negative utility to society, $\theta_i(\rho_i, d_i) < 0$. Specifically, this negative utility is assumed to increase (decrease the welfare) with higher consumption of that good, $\frac{\partial \theta_i(\rho_i, d_i)}{\partial d_i} < 0$, and decrease (increase the welfare) with a higher standard of the regulation, $\frac{\partial \theta_i(\rho_i)}{\partial \rho_i} > 0$. In addition, this component of the utility function is assumed to be concave, as is common. I further assume that these externalities enter into the

[5] As we stated in the introduction of this chapter, global warming is a different issue from the local pollution that we are dealing with in this chapter in that global warming deteriorates globally, but the damage of local pollution is focused locally, so it does not create the cooperation issue that I mentioned in the introduction chapter. The point of this example is that firms need to invest to reduce their pollution emissions.

[6] In 2017, the average CO_2 emission per car in the EU was $118.5g/km$. In 2018, the EU adopted limits on CO_2 emissions to $95g/km$ by 2021. They require companies to reduce the emissions further by 15% from 2025 and 30% from 2030 (https://www.europarl.europa.eu/news/en/headlines/society/20180920STO14027/reducing-car-emissions-new-co2-targets-for-cars-explained, visited on May 18, 2020).

social welfare additively and affect all the population. Thus, the social welfare from industry i is

$$W_i(\boldsymbol{p}, \boldsymbol{\rho}) = R_i(p_i, \rho_i) + \ell_i[1 + r(\boldsymbol{p}) + s(\boldsymbol{p}) + \theta(\boldsymbol{\rho}, \boldsymbol{d})], \tag{4.3}$$

where $\theta(\boldsymbol{\rho}, \boldsymbol{d})$ is the per-capita externalities which individuals face from all over the industries; thus, we can define it as $\theta(\boldsymbol{\rho}, \boldsymbol{d}) = \sum_{i=1}^{n} \theta_i(\rho_i, d_i)/N$. $\boldsymbol{\rho} = (\rho_1, \rho_2, ..., \rho_n)$ is the domestic standards vector of the non-numeraire goods, and $\boldsymbol{d} = (d_1, d_2, ..., d_n)$ is per-capita consumption vector of the non-numeraire goods.

The overall social welfare is the sum of the above equation over the industries $i = 1, ..., n$, plus the welfare of the persons who do not own capital:

$$W(\boldsymbol{p}, \boldsymbol{\rho}) = \sum_{i=1}^{n} R_i(p_i, \rho_i) + N[1 + r(\boldsymbol{p}) + s(\boldsymbol{p}) + \theta(\boldsymbol{\rho}, \boldsymbol{d})]. \tag{4.4}$$

For the political aspects, we assume that some industries are organized to lobby, $j \in J_o$, and the remainder are not organized, $j \in J_u$; that means $J_o \cup J_u = [1, ..., n]$. Lobby groups propose their schedule of contributions $C_j(p, \rho)$ depending on the combination of tariffs and domestic standards. The tariffs will affect the domestic consumer prices, thus affecting tariff revenue. The domestic standards, ρ, affect the compliance costs and eventually affect revenue too. Then, the government compares these contributions with the deadweight loss to the total social welfare caused by the tariffs or subsidies and the welfare gain from the prevention of the externalities. I further assume that this comparison is linear; then, the objective function of the government is

$$G(p, \rho) = \sum_{j \in J_o} C_j(\boldsymbol{p}, \boldsymbol{\rho}) + aW(\boldsymbol{p}, \boldsymbol{\rho}), \quad a \geq 0, \tag{4.5}$$

where a is the weight of the social welfare. The lobby groups are assumed to choose their contribution schedule based on Bernheim and Whinston (1986)'s 'truthful contributions schedule,' which means that they choose their schedule taking other groups' schedules as given. This 'truthful contributions schedule' takes the following form:

$$C_j(\boldsymbol{p}, \boldsymbol{\rho}) = \max[0, W_j - B_j], \quad j \in J_o, \tag{4.6}$$

for some constant value of B_j. Now, we can substitute this into (4.5) to obtain

$$G(\boldsymbol{p},\boldsymbol{\rho}) = \sum_{j\in J_o}[(1+a)W_j(\boldsymbol{p},\boldsymbol{\rho}) - B_j] + \sum_{j\notin J_o} aW_j(\boldsymbol{p},\boldsymbol{\rho}). \tag{4.7}$$

4.3.1. Determining the Trade Policy. We solve for the optimal tariff policy as in Feenstra (2015), extended here to allow for the externality and product standard. The workers with no capital would not form a lobby group, so they belong to a unorganized group. As we can see in the above, the welfare of organized lobby groups receives a higher weight $(1+a)$ than that of the unorganized group (a). To get the first-order condition of a tariff, we calculate the differentiation of welfare with respect to p_j, $j \in J_o$ for capital owners of that good $(\frac{\partial W_j}{\partial p_j})$, that for capital owners of other goods $(\frac{\partial W_i}{\partial p_j}, i \neq j)$, and that for workers without capital $(\frac{\partial W_0}{\partial p_j})$:

$$\frac{\partial W_j}{\partial p_j} = y_j - \ell_j d_j + \frac{\ell_j}{N}\left[M_j + (p_j - p_j^w)\frac{dM_j}{dp_j} + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right], \tag{4.8}$$

$$\frac{\partial W_i}{\partial p_j} = -\ell_i d_j + \frac{\ell_i}{N}\left[M_j + (p_j - p_j^w)\frac{dM_j}{dp_j} + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right], i \neq j, \tag{4.9}$$

$$\frac{\partial W_0}{\partial p_j} = -(N-\ell)d_j + \frac{N-\ell}{N}\left[M_j + (p_j - p_j^w)\frac{dM_j}{dp_j} + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right], \tag{4.10}$$

where $M_j = d_j(p_j)N - y_j$ is the import of good j. By giving weights of $(1+a)$ to (4.8) and (4.9) for $i \in J_o$, (a) to (4.9) for $i \in J_u$ and (4.10), then aggregating, we have the first-order condition for (4.7):

$$\frac{\partial G}{\partial p_j} = (1+a)y_j + (a+\alpha_L)(M_j - Nd_j) + (a+\alpha_L)\left[(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right] = 0, \tag{4.11}$$

where $\alpha_L = \sum_{i\in J_o}\frac{\ell_i}{N}$ is the ratio of the people who have the capital in the organized lobbying group. Using the definition of imports $(M_j = Nd_j - y_j)$, we have

$$\frac{\partial G}{\partial p_j} = (1-\alpha_L)y_j + (a+\alpha_L)\left[(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right] = 0. \tag{4.12}$$

If we calculate the differentiation of welfare with respect to p_j, $j \in J_u$, then the form is

$$\frac{\partial G}{\partial p_j} = -\alpha_L y_j + (a+\alpha_L)\left[(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right] = 0. \tag{4.13}$$

Thus, the complete form is

$$\frac{\partial G}{\partial p_j} = (\delta_j - \alpha_L)y_j + (a+\alpha_L)\left[(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}\right] = 0, \tag{4.14}$$

where δ_j is an indicator variable that equals 1 if industry j is organized and 0 otherwise. By calculations, we can get the equilibrium policies, which are defined by $\tau_i \equiv (p_i - p_i^w)p_i^w$:

$$\frac{\tau_i}{1+\tau_i} = \frac{\delta_i - \alpha_L}{(a+\alpha_L)}\frac{z_i}{e_i} + \frac{\partial \theta_i}{\partial d_i}\frac{\partial d_i}{\partial p_i}\frac{1}{e_i M_i} \quad \text{for i=1,2,...n,} \tag{4.15}$$

where $z_i = y_i/M_i$ is the equilibrium domestic output to imports ratio (if it is negative, domestic output to exports ratio) and $e_i = -\frac{dM_i}{dp_i}\frac{p_i}{M_i} > 0$ is the elasticity of import demand (positive) or the elasticity of export supply (negative).

The result of the first term is the same as in the original model. The tariff or subsidy is inversely related to the import or export elasticity because the higher absolute value of elasticity means higher welfare loss as a result of the tariff or subsidy. In addition, in the case of importing goods, if an industry is organized, the tariff is positively related to the domestic output to imports ratio. This is because it is more beneficial to protect such industries, which means that the revenue of the organized industry is higher when the production (y_i) is higher and the social cost is lower when the imports (M_i) are lower.

To check the sign of the second term, first $\frac{\partial \theta_i}{\partial d_i} < 0$ because more consumption increases the externality (negative welfare) and $\frac{\partial d_i}{\partial p_i} < 0$ as a result of the law of demand. If a country imports in industry i, $e_i > 0$ and $M_i > 0$. Thus, the tariff τ_i is higher than in the original model when we consider externality. In addition, the degree of that depends on the marginal externality that additional consumption creates and marginal change of consumption with respect to price. This makes sense because when a good creates externality, it is better to tax it, thus reducing the demand for that good. In addition, it is inversely related to the absolute value of import elasticities and the amount of the imports for the same reason as the first term (higher elasticity and imports mean higher social welfare cost).

4.3.2. Is This Trade Policy the First Best? We have seen that the existence of domestic externality can affect the determinations of the tariffs. In the next sections, domestic externalities combined with regulations affect the determinations of the tariffs in different ways. These results are notable as they seem to contradict the propositions of Johnson (1963).

Proposition of Johnson (1963) 1. *The correction of domestic distortions does not require intervention in the form of taxes on international trade*

Proposition of Johnson (1963) 2. *Taxes or subsidies on international trade designed to offset domestic distortions will not necessarily increase welfare by comparison with the free trade situation*

The first proposition of Johnson (1963) holds from the marginal 'Pareto optimality' conditions. Under these conditions, the marginal rate of substitution in consumption needs to be equal to the marginal rate of transformation, including the international exchange in the open economy. We can use the tariffs to correct the domestic distortions by equating the domestic price ratio to the marginal rate of substitution. However, this brings about a discrepancy between the domestic price ratio and the international price ratio. Thus, the first-best policy is to regulate the domestic market where the distortion happens and not to use tariffs.

We can confirm this from Johnson (1963)'s further combinations of the above two propositions that *"The only valid argument for protection as a means of maximizing economic welfare is the optimum tariff argument; . . . and lead to the recommendation of protection only when supported both by practical considerations that render the appropriate form of intervention unfeasible and empirical evidence that protection will in fact increase economic welfare."* Here, I could not provide the empirical evidence that the use of trade protection in reducing the domestic externalities can increase economic welfare. However, I could find that the trade protection is affected by the domestic externalities when the appropriate form of intervention on the domestic externalities is not possible.

Even though the results in this paper only apply to this specific circumstance, this case is not rare in reality. For example, we can witness this in fossil fuels. Polluting gases are discharged during the consumption of fossil fuels. Regulations are levied on production, so producers are required to reduce the polluting materials in fossil fuels. For example, International Maritime Organization (IMO) regulations require shipping companies to reduce the emission of sulfur oxides (SO_x), which are known to be harmful to human health and the environment, such as forests, crops, and so on. Even though the regulations are imposed on the consumption of 'bunker oil,' the oil companies are required to provide low-sulfur oil. Oil companies may charge higher prices on low-sulfur oil, but what is important is that the agents of externalities and the agents under the regulations are different.

4.3.3. Determining the Domestic Regulation. To get the first-order condition for domestic regulation, we differentiate welfare with respect to ρ_j, $j \in J_o$ for capital owners of that good ($\frac{\partial W_j}{\partial \rho_j}$), for capital owners of other goods ($\frac{\partial W_i}{\partial \rho_j}, i \neq j$), and for workers without capital ($\frac{\partial W_0}{\partial \rho_j}$):

$$\frac{\partial W_j}{\partial \rho_j} = -\phi_j'(\rho_j) + \frac{\ell_j}{N}\frac{\partial \theta(\rho_j, d_j)}{\partial \rho_j}, \tag{4.16}$$

$$\frac{\partial W_i}{\partial \rho_j} = \frac{\ell_i}{N}\frac{\partial \theta(\rho_j, d_j)}{\partial \rho_j}, \tag{4.17}$$

$$\frac{\partial W_0}{\partial \rho_j} = \frac{N-\ell}{N}\frac{\partial \theta(\rho_j, d_j)}{\partial \rho_j}. \tag{4.18}$$

By giving weights of $(1+a)$ to (4.16) and (4.17) for $i \in J_o$ and (a) to (4.17) for $i \in J_u$ and (4.18), then aggregating and using the definitions above, we can have the first-order condition for (4.7):

$$\frac{\partial G}{\partial \rho_j} = -(\delta_j + a)\phi_j'(\rho_j) + (a + \alpha_L)\frac{\partial \theta(\rho_j, d_j)}{\partial \rho_j}. \tag{4.19}$$

By setting this first-order condition equal to 0, we can get the equilibrium condition for the domestic standard:

$$\frac{\partial \theta(\rho_i, d_i)}{\partial \rho_i} = \frac{a + \delta_i}{a + \alpha_L}\phi_i'(\rho_i). \tag{4.20}$$

We can think of $\frac{\partial\theta(\rho_i,d_i)}{\partial\rho_i}$ as the marginal welfare benefit which we can get by increasing the standard, and $\phi_i'(\rho_i)$ as the marginal cost to abide by that standard. In case of the ideal government, which gives very high weight to the society's overall welfare ($a = \infty$), ρ_i is determined efficiently, which means that the standard's marginal benefit and marginal cost are the same ($\frac{\partial\theta(\rho_i,d_i)}{\partial\rho_i} = \phi_i'(\rho_i)$). Another condition for this efficient regulation happens when all the industries are unorganized ($\delta_i = 0$, $\alpha_L = 0$) or all industries are organized ($\delta_i = 1$, $\alpha_L = 1$). That is, no industry tries to lobby, or all industries try to lobby, thus offsetting lobby effects against each other. We can see that these cases coincide with the case where free trade (no trade protection) was implied in the original model.

However, cases are more realistic when a is not that high, $\alpha_L \neq 0$, and $\alpha_L \neq 1$. In that case, $0 < \alpha_L < 1$, as a decreases, thus having a finite number, the influence of δ_i increases. If industry i is not organized ($\delta_i = 0$), then $\frac{\partial\theta(\rho_i,d_i)}{\partial\rho_i} < \phi_i'(\rho_i)$, which means that the standard's marginal cost is higher than the marginal benefit. As we assumed a convex cost function and a concave utility function, the above inequality means that unorganized industries are over-regulated. When industry i is organized ($\delta_i = 1$), then $\frac{\partial\theta(\rho_i,d_i)}{\partial\rho_i} > \phi_i'(\rho_i)$, which means that the standard's marginal cost is lower than the marginal benefit. Using the same logic, this means that organized industries are under-regulated. These results fit our intuition that industries want to be less regulated, but lobbying industries are more likely to succeed in making the government comply with their wishes.

4.4. Trade Wars

In the previous section, we saw how political economy factors affect domestic regulation and how considering domestic externalities and regulation can affect trade policy. However, in the previous section, we did not consider the domestic regulation's influence on the world price, as we assumed a small open economy. In this section, I will consider domestic regulation in Grossman and Helpman (1995)'s two-country model. As in Bagwell and Staiger (2001), I will assume that the countries can address domestic externalities by manipulating the world price using trade policies and domestic regulations. Bagwell and Staiger (2001) excluded the non-pecuniary effect of the externalities, not because it is unimportant, but because the issue of the non-pecuniary effect is out of bounds in WTO and economic analysis. Following them, I also exclude the non-pecuniary effect of the externalities.

Here, I analyze a two-country trade model that includes political factors. The format of the model is almost the same as that of the small economy model that I described in the previous section, except for the world price determination. Thus, I use the same representation as in the previous section for the home country and add asterisks "*" to the foreign country. Nominal ad-valorem trade taxes create the discrepancy between domestic prices and world prices ($p_j = p_j^w t_j$). $t_j > 1$ means a tariff for imports and subsidy for exports; similarly, $t_j < 1$ is a subsidy for imports and tax for exports. The world price is not given; rather, it is determined by the world product market clearing conditions between the home and foreign countries. The home country's net imports are determined by the domestic price p_j, which reflects the nominal trade tax t_j. Thus, the market clearing condition for good j is that the sum of the net imports of these two countries is equal to 0.

$$M_j(p_j^w t_j) + M_j^*(p_j^w t_j^*) = 0, \quad \text{for} \quad j = 1, 2, ...n. \tag{4.21}$$

With this condition, we can get the market clearing world price of good i as a function of the tariffs or subsidies of the two countries, $p_i^w(t_i, t_i^*)$. Then, domestic prices at home and abroad are determined by this equilibrium world price along with the countries' trade taxes. Thus, the trade taxes imply the domestic and world prices, then domestic consumption, production, and imports or exports, and so on.

A trade war is a case where the governments decide the level of tariffs unilaterally without considering their impacts on the other country's economy. Thus, it is expected that the equilibrium argument will be similar to the small country case in the previous section except for the terms of trade gain consideration, as the world price $p_i^w(t_i, t_i^*)$ is endogenous.

The profit of the non-numeraire good is $R_j(p_j^w, t_j, \rho_j) = p_j^w t_j f_j(L_j, K_j) - L_j - \phi_j(\rho_j)$, and the tariff revenue per capita is $r(\boldsymbol{p^w, t}) = \sum_{i=1}^n p_i^w(t_i - 1)[d_i(p_i^w t_i) - \frac{1}{N} y_i(p_i^w t_i)]$, where N is the total population, $\boldsymbol{t} = (t_1, t_2, ..., t_n)$ is the nominal tariff rate vector, $\boldsymbol{\rho} = (\rho_1, \rho_2, ..., \rho_n)$ is the domestic standard vector, and $\boldsymbol{p^w} = (p_1^w, p_2^w, ..., p_n^w)$ is the world price vector for the non-numeraire goods.

Like in the "small" country model, individuals earn three types of income: wages, redistributed tariff revenue, and the profits of any industry in which they have capital. To that I add the externalities, which have the same properties as in the previous section. Thus, the welfare from industry i can be represented by

$$W_i(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}) = R_i(p_i^w, t_i, \rho_i) + \ell_i[1 + r(\boldsymbol{p^w}, \boldsymbol{t}) + s(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}) + \theta(\boldsymbol{\rho}, \boldsymbol{d}(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}))]. \tag{4.22}$$

The overall social welfare is the sum of the above welfare equation over the industries $i = 1, ..., n$, plus the welfare of the persons who do not own capital.

$$W(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}) = \sum_{i=1}^{n} R_i(p_i^w, t_i, \rho_i) + N[1 + r(\boldsymbol{p^w}, \boldsymbol{t}) + s(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}) + \theta(\boldsymbol{\rho}, \boldsymbol{d}(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}))]. \tag{4.23}$$

The political aspects are also the same as in the "small country case": some industries are organized to lobby, $j \in J_o$, and the remaining are not organized, $j \in J_u$, which means $J_o \cup J_u = [1, ..., n]$. Lobby groups propose their schedule of contributions $C_j(\boldsymbol{t}, \boldsymbol{\rho})$ contingent on the tariff and standard schedule, which will affect the domestic consumer prices. Then the government compares this combination with the total social welfare, with a linear relationship; thus, the objective function of the government is

$$G = \sum_{j \in J_o} C_j(\boldsymbol{t}, \boldsymbol{\rho}) + aW(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}), \quad a \geq 0. \tag{4.24}$$

The lobby groups are assumed to choose their contribution schedule based on Bernheim and Whinston (1986)'s 'truthful contributions schedule,' which means that they choose their schedule taking other groups' schedules as given. This 'truthful contributions schedule' takes the following form.

$$C_j(\boldsymbol{t}, \boldsymbol{\rho}) = \max[0, W_j - B_j], \quad j \in J_o, \tag{4.25}$$

for some constant value of B_j. Now, we can substitute this into (4.24) to obtain

$$G = \sum_{j \in J_o} [(1 + a)W_j(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}) - B_j] + \sum_{j \notin J_o} aW_j(\boldsymbol{p^w}, \boldsymbol{t}, \boldsymbol{\rho}). \tag{4.26}$$

4.4.1. Determining the Trade Policy. Here, I only consider the trade policy. As we assume that the domestic regulation does not affect the world price, the domestic regulation determination is the same as that under the small country case.

The workers with no capital would not form a lobby group, so they belong to an unorganized group. As we can see in the above, the welfare of an organized lobby group receives a higher weight $(1+a)$ than that of the unorganized group (a). To get the first-order condition of a tariff, we calculate the differentiation of welfare with respect to t_j, $j \in J_o$ for the capital owners of that good $(\frac{\partial W_j}{\partial t_j})$, that for the capital owners of other goods $(\frac{\partial W_i}{\partial t_j}, i \neq j)$, and that for workers without capital $(\frac{\partial W_0}{\partial t_j})$:

$$\begin{aligned}\frac{\partial W_j}{\partial t_j} =&(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) y_j - \ell_j d_j (p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) + \frac{\ell_j}{N}[(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j - \frac{\partial p_j^w}{\partial t_j}) M_j \\ &+ p_j^w (t_j - 1)(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) M_j' + \frac{\partial \theta_j}{\partial d_j}(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) \frac{\partial d_j}{\partial p_j}],\end{aligned} \tag{4.27}$$

$$\begin{aligned}\frac{\partial W_i}{\partial t_j} =& - \ell_i d_j (p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) + \frac{\ell_i}{N}[(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j - \frac{\partial p_j^w}{\partial t_j}) M_j \\ &+ p_j^w (t_j - 1)(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) M_j' + \frac{\partial \theta_j}{\partial d_j}(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) \frac{\partial d_j}{\partial p_j}],\end{aligned} \tag{4.28}$$

$$\begin{aligned}\frac{\partial W_0}{\partial t_j} =& - (N - \ell) d_j (p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) + \frac{N - \ell}{N}[(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j - \frac{\partial p_j^w}{\partial t_j}) M_j \\ &+ p_j^w (t_j - 1)(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) M_j' + \frac{\partial \theta_j}{\partial d_j}(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) \frac{\partial d_j}{\partial p_j}].\end{aligned} \tag{4.29}$$

By giving weights of $(1+a)$ to (4.27) and (4.28) for $i \in J_o$, (a) to (4.28) for $i \in J_u$ and (4.29), then aggregating using the definition of imports $(M_j = d_j N - y_j)$, we can have the first-order condition for (4.26):

$$\begin{aligned}\frac{\partial G}{\partial t_j} =&(1 - \alpha_L)(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) y_j \\ &+ (a + \alpha_L) \left[p_j^w (t_j - 1)(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) M_j' - \frac{\partial p_j^w}{\partial t_j} M_j + \frac{\partial \theta_j}{\partial d_j}(p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) \frac{\partial d_j}{\partial p_j} \right] = 0.\end{aligned} \tag{4.30}$$

If we calculate the differentiation of welfare with respect to t_j, $j \in J_u$, the only difference is that the first term on the right-hand side of (4.30) is $-\alpha_L(p_j^w + \frac{\partial p_j^w}{\partial t_j}t_j)y_j$. Thus, the complete form is

$$\begin{aligned}\frac{\partial G}{\partial t_j} =&(\delta_j - \alpha_L)(p_j^w + \frac{\partial p_j^w}{\partial t_j}t_j)y_j \\ &+ (a+\alpha_L)\left[p_j^w(t_j-1)(p_j^w + \frac{\partial p_j^w}{\partial t_j}t_j)M_j' - \frac{\partial p_j^w}{\partial t_j}M_j + \frac{\partial \theta_j}{\partial d_j}(p_j^w + \frac{\partial p_j^w}{\partial t_j}t_j)\frac{\partial d_j}{\partial p_j}\right] = 0.\end{aligned} \tag{4.31}$$

When we take the derivatives of (4.21) with respect to t_j, we have

$$\frac{\partial p_j^w}{\partial t_j}\frac{1}{p_j^w} = -\frac{M_j'}{t_j M_j' + t_j^* M_j^{*\prime}}. \tag{4.32}$$

Using this, we have the optimal trade tax for the home country:

$$t_i - 1 = -\frac{\delta_i - \alpha_L}{a+\alpha_L}\frac{y_i}{p_i^w M_i'} + \frac{1}{e_i^*} - \frac{\partial \theta_i}{\partial d_i}\frac{\partial d_i}{\partial p_i}\frac{1}{p_i^w M_i'} \quad \text{for i=1,2,...n.} \tag{4.33}$$

Similarly, the optimal tariff for the foreign country is

$$t_i^* - 1 = -\frac{\delta_i^* - \alpha_L^*}{a^*+\alpha_L^*}\frac{y_i^*}{p_i^w M_i^{*\prime}} + \frac{1}{e_i} - \frac{\partial \theta_i^*}{\partial d_i}\frac{\partial d_i^*}{\partial p_i^*}\frac{1}{p_i^w M_i^{*\prime}} \quad \text{for i=1,2,...n,} \tag{4.34}$$

where $e_i^* = t_i^* p_i^w M_i^{*\prime}/M_i^*$ is the foreign country's import demand elasticity (if $M_i^* > 0$) or export supply elasticity (if $M_i^* < 0$) and $e_i = t_i p_i^w M_i'/M_i$ is the home country's import demand elasticity (if $M_i > 0$) or export supply elasticity (if $M_i < 0$).

The first two terms are the same as the results of the original model of Grossman and Helpman (1995). The first term reflects the political economy explanation of the trade policy and is the same as in the small open economy case. The second term reflects the trade policy's terms of trade gain motivation. In this section, we assume a large country, so governments can affect the world price to benefit their countries' welfare. If an industry is organized and import-competing, this second term reinforces the protection, whereas if an industry is unorganized and exporting, the second term increases the export tax, and this is supported by the organized industries, as they are the consumers of that good. If an industry is organized and exporting or unorganized and importing, this second term acts in the opposite direction. The inverse of absolute value of foreign import elasticity $|e_i^*|$ represents the market power of the home country. Thus, as this value declines, the home country can expect more gains from trade policy.

As in the small open economy in the previous section, we have externality-related terms. As we saw in the previous section, $\frac{\partial \theta_i}{\partial d_i} < 0$, $\frac{\partial d_i}{\partial p_i} < 0$, and $M_i' < 0$ regardless of whether industry i is importing or exporting; thus, the third term is positive. We can see that the third term is related to the marginal welfare benefit by taxing that good more. The third term increases, as the deadweight loss associated with the trade tax is small ($|M'|$). We can conclude that we have higher tariffs as we consider the externalities.

This result is related to the argument in Section 4.3.2. In this model, the externalities occur in the consumption of non-numeraire goods, but the regulations to cure the externalities are on the firms that produce the goods. The first-best policy is to correct the distortions directly. However, because this is not possible in this model, we get the second-best policy that domestic externalities affect the trade policy.

4.5. Trade Talks

In the previous section, we saw how governments impose trade protections and domestic regulations with externalities when they pursue their selfish domestic welfare. Although we observed there are conflicting forces as we consider the externalities and regulations, government officials tend to impose trade taxes, thus imposing a deadweight loss on consumers, because they can collect contributions. This political motivation could be observed in domestic regulations too. The level of standard could be set inefficiently in exchange for contributions. These trade taxes and domestic regulations also act as implied avoidable costs to the other country. For example, tariffs include the other country's inverse elasticities, which reflect market power. If the government officials realize this, they may try to cooperate by trade negotiations and could enter into trade agreements. Here, I will consider that the two countries negotiate over their tariffs as in Grossman and Helpman (1995).

The two governments negotiate their tariff rates t and t^*, and we need a transfer of R (can be positive or negative) that the foreign government gives to the home country. The remaining settings are almost the same as in the 'trade war.' Before the governments negotiate, the organized lobbies provide their contribution schedule contingent on domestic and foreign tariffs and domestic regulation standards. Given these schedules, the governments try to maximize their weighted social welfare.

$$G = \sum_{j \in J_o} C_j(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}); \boldsymbol{t}^*) + a[W(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + R], \quad a \geq 0, \tag{4.35}$$

$$G^* = \sum_{j \in J_o^*} C_j^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*); \boldsymbol{t}) + a^*[W^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t}) - R], \quad a^* \geq 0. \tag{4.36}$$

According to Grossman and Helpman (1995), in 'trade talks,' it is possible to pursue efficient policies, which means that G cannot be raised without lowering G^*. As in their work, I use the Nash bargaining solution because it has this efficiency property. Under the Nash bargaining solution, governments choose the trade policy vectors to maximize the weighted sum of their objective functions:

$$\begin{aligned} a^*G + aG^* = a^* \sum_{j \in J_o} C_j(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}); \boldsymbol{t}^*) + a \sum_{j \in J_o^*} C_j^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*); \boldsymbol{t}) \\ + aa^*[W(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + W^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t})]. \end{aligned} \tag{4.37}$$

This is the weighted average of G and G^* after R is canceled out. After this sum is maximized, the governments can pursue any utility points (G, G^*) using the transfers. Using the assumption of Bernheim and Whinston (1986)'s 'truthful contributions schedule' ($C_j(\boldsymbol{t}; \boldsymbol{t}^*) = \max[0, W_j - B_j], j \in J_o$ for some constant value of B_j), we can substitute this into (4.37) to obtain

$$\begin{aligned} a^*G + aG^* = a^* \sum_{j \in J_o} [W_j(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) - B_j] + a \sum_{j \in J_o^*} [W_j^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t}) - B_j^*] \\ + aa^*[W(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + W^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t})]. \end{aligned} \tag{4.38}$$

Then, the first-order conditions are the partial derivatives of the sum with respect to t and t^*, which are equal to 0.

$$\begin{aligned} a^* \sum_{j \in J_o} \nabla_t W_j(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + a \sum_{j \in J_o^*} \nabla_t W_j^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t}) \\ + aa^*[\nabla_t W(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + \nabla_t W^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t})] = 0, \end{aligned} \tag{4.39}$$

$$a^* \sum_{j\in J_o} \nabla_{t^*} W_j(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + a \sum_{j\in J_o^*} \nabla_{t^*} W_j^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t}) + aa^*[\nabla_{t^*} W(\boldsymbol{t}, \boldsymbol{\phi}(\boldsymbol{\rho}), \boldsymbol{t}^*) + \nabla_{t^*} W^*(\boldsymbol{t}^*, \boldsymbol{\phi}^*(\boldsymbol{\rho}^*), \boldsymbol{t})] = 0. \tag{4.40}$$

Then, we can repeat the same calculation process as in the 'trade war,' so we can use the calculations from the previous section to get $\nabla_t W_j$. Here, we calculate $\nabla_t W_j^*$,

$$\begin{aligned}\frac{\partial W_j^*}{\partial t_j} =& \frac{\partial p_j^w}{\partial t_j} t_j^* y_j^* - \ell_j^* d_j^* \frac{\partial p_j^w}{\partial t_j} t_j^* \\ &+ \frac{\ell_j}{N}\left[\frac{\partial p_j^w}{\partial t_j}(t_j^*-1)M_j^* + (p_j^w(t_j^*-1))\frac{\partial p_j^w}{\partial t_j} t_j^* M_j^{*'} + \theta_{d_j^*}^{*'} \frac{\partial d_j^*}{\partial p_j^*}\frac{\partial p_j^w}{\partial t_j} t_j^*\right],\end{aligned} \tag{4.41}$$

$$\begin{aligned}\frac{\partial W_i}{\partial t_j} =& - \ell_i^* d_j^* \frac{\partial p_j^w}{\partial t_j} t_j^* \\ &+ \frac{\ell_i}{N}\left[\frac{\partial p_j^w}{\partial t_j}(t_j^*-1)M_j^* + (p_j^w(t_j^*-1))\frac{\partial p_j^w}{\partial t_j} t_j^* M_j^{*'} + \theta_{d_j^*}^{*'} \frac{\partial d_j^*}{\partial p_j^*}\frac{\partial p_j^w}{\partial t_j} t_j^*\right],\end{aligned} \tag{4.42}$$

$$\begin{aligned}\frac{\partial W_0}{\partial t_j} =& - (N-\ell) d_j^* \frac{\partial p_j^w}{\partial t_j} t_j^* \\ &+ \frac{N-\ell}{N}\left[\frac{\partial p_j^w}{\partial t_j}(t_j^*-1)M_j^* + (p_j^w(t_j^*-1))\frac{\partial p_j^w}{\partial t_j} t_j^* M_j^{*'} + \theta_{d_j^*}^{*'} \frac{\partial d_j^*}{\partial p_j^*}\frac{\partial p_j^w}{\partial t_j} t_j^*\right].\end{aligned} \tag{4.43}$$

First we focus on (4.39), as we can get (4.40) easily, as they are symmetric. As we can see in (4.39), the welfare of organized lobby groups in their home country receives a higher weight ($a^*(1+a)$) than that of the unorganized group (aa^*). For the foreign country, the welfare of organized lobby groups receives a weight of ($a(1+a^*)$), and the unorganized group receives a weight of (aa^*). Then, aggregating the weighted sum and assuming a negligible portion of lobby groups ($\alpha_L = 0$) for the ease of the arguments, as in Grossman and Helpman (1995), give us the result:

$$\begin{aligned}&a^*[\delta_j y_j + a(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}](p_j^w + \frac{\partial p_j^w}{\partial t_j} t_j) \\ &\qquad + a[\delta_j^* y_j^* + a^*(p_j^* - p_j^w)M_j^{*'} + \frac{\partial \theta_j^*}{\partial d_j^*}\frac{\partial d_j^*}{\partial p_j^*}]\frac{\partial p_j^w}{\partial t_j} t_j^* = 0.\end{aligned} \tag{4.44}$$

As the same way, we get the next result:

$$a[\delta_j^* y_j^* + a^*(p_j^* - p_j^w)M_j^{*'} + \frac{\partial \theta_j^*}{\partial d_j^*}\frac{\partial d_j^*}{\partial p_j^*}](p_j^w + \frac{\partial p_j^w}{\partial \rho_j} t_j^*) + a^*[\delta_j y_j + a(p_j - p_j^w)M_j' + \frac{\partial \theta_j}{\partial d_j}\frac{\partial d_j}{\partial p_j}]\frac{\partial p_j^w}{\partial \rho_j} t_j = 0. \tag{4.45}$$

As in Grossman and Helpman (1995), these two equations are linearly dependent, so we cannot get the exact number of t_j and t_j^* but their ratio. Using the results of (4.32) and with some manipulations, we can arrange the relationship in (4.44) and (4.45) as below:

$$t_i - t_i^* = \frac{\delta_i^* y_i^*}{a^* M_i^{*'} p_i^w} - \frac{\delta_i y_i}{a M_i' p_i^w} + \frac{\frac{\partial \theta_i^*}{\partial d_i^*}\frac{\partial d_i^*}{\partial p_i^*}}{a^* M_i^{*'} p_i^w} - \frac{\frac{\partial \theta_i}{\partial d_i}\frac{\partial d_i}{\partial p_i}}{a M_i' p_i^w}. \tag{4.46}$$

As in Grossman and Helpman (1995), we can see that the inverse of the trading partner's elasticity term disappears. This is because, as a result of the trade agreement, they do not pursue the terms of trade gain. In free trade, $t_i = 1, t_i^* = 1$, so the left-hand side is equal to 0, but in other cases, the trade agreement requires that the tariff ratio should follow the relationship in the above equation. The first two terms on the right-hand side are the same as in Grossman and Helpman (1995). They represent the political economy factors. As $M_i' < 0, M_i^{*'} < 0$, and the remaining parts are greater than 0, the signs of both terms are negative. If an industry is organized at home and unorganized abroad, the home industry could get more protection and vice versa. If an industry is organized in both countries, more protection goes to the country which has more production (y_i and y_i^*), less government weight on overall welfare (a and a^*), and less price sensitivity to net imports ($|M_i'|$ and $|M_i^{*'}|$). The third and fourth terms appear as we consider externalities. The signs of the third and fourth terms are negative, as $\frac{\partial \theta_i}{\partial d_i} < 0$, $\frac{\partial d_i}{\partial p_i} < 0$ and $M_i' < 0$. Thus, as we saw in the 'trade war' case, considering externalities affects the trade agreement results. If the home country's marginal benefit by increasing the domestic price is higher than the foreign country's, the trade protection in the domestic country is higher than that of the foreign country even under the trade agreement.

4.6. Conclusion

In this chapter, I added domestic externalities and regulations to the 'Protection for Sale' model in three cases: a small open economy, an uncooperative large country, and a cooperative large country. As I consider domestic externalities and regulations, the trade policy was more protective. This is because higher prices as a result of trade protection reduce the demand for that good, and consequently, less spending on that good can improve social welfare, as fewer externalities are created. As trade protection is used to deter domestic consumption externalities, this is not the first best in the view of Johnson's proposition but can be a second-best policy. If a government cannot address the consumption externalities directly, or even if it can but that is not enough, this second-best policy could be an alternative way to address it. The determination of domestic regulations is also affected by the political power in this model. Under the usual concave utility and convex cost function, the lobbying industries are under-regulated, and non-lobbying industries are over-regulated.

In the large country case, the trade policy is determined by political considerations and the terms of trade, as in the original model, and is also affected by the added factors of externalities. Here, the externalities act to increase the tariffs again as higher tariffs reduce consumption of the numeraire goods, which in turn decreases the externalities. The domestic regulation is determined in the same way as in the small open economy case.

In a trade agreement, under the condition that trade policy is negotiable, we could get a condition that the trade policies should satisfy under the trade agreement. The domestic externalities affect the agreed trade protection. For a country with a higher marginal benefit from increasing domestic price (thus reducing the consumption of that good and thus creating fewer externalities), the desired tariff in that country will be higher than the tariff in the partner country.

APPENDIX A

Appendices for the Second Chapter

A.1. Derivation of the Mass of the Entry

A.1.1. The Masses. To derive the mass of the entry, we need to define the other masses. As $(\varphi_l/\varphi_h)^\theta$ is the ratio of the high-technology-adopting firms among the existing firms, the mass of the high-technology-adopting firms is

$$M_h = M(\frac{\varphi_l}{\varphi_h})^\theta = \frac{M_e \varphi_h^{-\theta}}{\delta},$$

where M_h is the mass of the high-technology-adopting firms. Among the existing firms, the mass of the low-technology-adopting firms is that of the remaining firms after excluding the high-technology-adopting firms, so

$$M_l = M - M_h = \frac{M_e}{\delta}(\varphi_l^{-\theta} - \varphi_h^{-\theta}),$$

where M_l is the mass of the low-technology-adopting firms. $(\varphi_l/\varphi_x)^\theta$ is the ratio of the exporters among the existing firms. Among the exporters, the low-technology-adopting firms are the remaining firms, so

$$M_x = M(\frac{\varphi_l}{\varphi_x})^\theta - M_h = \frac{M_e}{\delta}(\varphi_x^{-\theta} - \varphi_h^{-\theta}),$$

where M_x is the mass of the exporters which adopt the low technology.

A.1.2. Calculating the Mass of the Entry Using Full Employment Condition. Here, we will derive the mass of the entry using the full employment condition. The full employment condition in the manufacturing sector is

$$\begin{aligned} kL =& M_e f_e + M_l \int_{\varphi_l}^{\varphi_h} \left(f_l + \frac{c_l(\tau) q_{ld}}{\varphi} \right) \gamma_l(\varphi) d\varphi + M_x \int_{\varphi_x}^{\varphi_h} \left(f_x + \frac{t c_l(\tau) q_{lx}}{\varphi} \right) \gamma_x(\varphi) d\varphi \\ &+ M_h \int_{\varphi_h}^{\infty} \left(f_h + f_x + \frac{c_h(\tau) q_{hd}}{\varphi} + \frac{t c_h(\tau) q_{hx}}{\varphi} \right) \gamma_h(\varphi) d\varphi, \end{aligned} \tag{A.1.1}$$

where k is the ratio of the labor which is employed in the manufacturing sector. Using the Pareto distribution of φ, $\gamma_l(\varphi) = \theta\varphi^{-\theta-1}/(\varphi_l^{-\theta} - \varphi_h^{-\theta})$, $\gamma_x(\varphi) = \theta\varphi^{-\theta-1}/(\varphi_x^{-\theta} - \varphi_h^{-\theta})$, $\gamma_h(\varphi) = \theta\varphi^{-\theta-1}/\varphi_h^{-\theta}$. Then, we can arrange the fixed-cost terms first.

$$kL = M_e f_e + M_l f_l + M_x f_x + M_h(f_h + f_x)$$
$$+\rho\left(M_l\int_{\varphi_l}^{\varphi_h} p_{ld}(\varphi)q_l\gamma_l(\varphi)d\varphi + M_x\int_{\varphi_x}^{\varphi_h} p_{lx}(\varphi)q_l\gamma_x(\varphi)d\varphi + M_h\int_{\varphi_h}^{\infty}(p_{hd}(\varphi)q_{hd} + p_{hx}(\varphi)q_{hx})\gamma_h(\varphi)d\varphi\right).$$

The second line is derived from the relationship between the cost and the price and is equal to ρkL, as the total revenue from the manufacturing goods is the labor which is employed in the manufacturing goods' production. Then, $kL = \sigma(M_e f_e + M_l f_l + M_x f_x + M_h(f_h + f_x))$ holds. The above full employment condition in (A.1.1) is

$$\rho kL = M_l\int_{\varphi_l}^{\varphi_h}\frac{c_l(\tau)q_{ld}}{\varphi}\gamma_l(\varphi)d\varphi + M_x\int_{\varphi_x}^{\varphi_h}\frac{tc_l(\tau)q_{xd}}{\varphi}\gamma_x(\varphi)d\varphi + M_h\int_{\varphi_h}^{\infty}(\frac{c_h(\tau)q_{hd}}{\varphi} + \frac{tc_h(\tau)q_{hx}}{\varphi})\gamma_h(\varphi)d\varphi.$$

Using the property in (2.12) and Pareto distribution, we can represent the above as

$$\rho kL = M_l\frac{q_{ld}(\varphi_l)}{\varphi_l^{\sigma}}\int_{\varphi_l}^{\varphi_h}\frac{\theta c_l(\tau)\varphi^{\sigma-\theta-2}}{\varphi_l^{-\theta} - \varphi_h^{-\theta}}d\varphi + M_x\frac{q_{ld}(\varphi_x)}{\varphi_x^{\sigma}}\int_{\varphi_x}^{\varphi_h}\frac{\theta tc_l(\tau)\varphi^{\sigma-\theta-2}}{\varphi_x^{-\theta} - \varphi_h^{-\theta}}d\varphi$$
$$+ M_h\frac{q_{hd}(\varphi_h)}{\varphi_h^{\sigma}}\int_{\varphi_h}^{\infty}\frac{\theta c_h(\tau)\varphi^{\sigma-\theta-2}}{\varphi_h^{-\theta}}d\varphi + +M_h\frac{q_{hx}(\varphi_h)}{\varphi_h^{\sigma}}\int_{\varphi_h}^{\infty}\frac{\theta tc_h(\tau)\varphi^{\sigma-\theta-2}}{\varphi_h^{-\theta}}d\varphi.$$

Solving the integral,

$$\rho kL = M_l\frac{q_{ld}(\varphi_l)}{\varphi_l^{\sigma}}\frac{\theta c_l(\tau)}{\theta+1-\sigma}\frac{\varphi_l^{\sigma-\theta-1} - \varphi_h^{\sigma-\theta-1}}{\varphi_l^{-\theta} - \varphi_h^{-\theta}} + M_x\frac{q_{ld}(\varphi_x)}{\varphi_x^{\sigma}}\frac{\theta tc_l(\tau)}{\theta+1-\sigma}\frac{\varphi_x^{\sigma-\theta-1} - \varphi_h^{\sigma-\theta-1}}{\varphi_x^{-\theta} - \varphi_h^{-\theta}}$$
$$+\frac{M_h\theta}{\theta+1-\sigma}\left(\frac{q_{hd}(\varphi_h)c_h(\tau)}{\varphi_h} + \frac{q_{hx}(\varphi_h)tc_h(\tau)}{\varphi_h}\right).$$

Using the ZCP of $\frac{c_l(\tau)q_{ld}}{\varphi_l} = (\sigma-1)f_l$, $\frac{tc_l(\tau)q_{lx}}{\varphi_x} = (\sigma-1)f_x$, and ZCP for φ_h,

$$kL = \frac{\theta M_l\sigma f_l}{\varphi_l^{\sigma-1}(\theta+1-\sigma)}\frac{\varphi_l^{\sigma-\theta-1} - \varphi_h^{\sigma-\theta-1}}{\varphi_l^{-\theta} - \varphi_h^{-\theta}} + \frac{\theta M_x\sigma f_x}{\varphi_x^{\sigma-1}(\theta+1-\sigma)}\frac{\varphi_x^{\sigma-\theta-1} - \varphi_h^{\sigma-\theta-1}}{\varphi_x^{-\theta} - \varphi_h^{-\theta}}$$
$$+\frac{M_h\theta\sigma}{\theta+1-\sigma}\left(\frac{\varphi_h^{\sigma-1}}{\varphi_l^{\sigma-1}}f_l + \frac{\varphi_h^{\sigma-1}}{\varphi_x^{\sigma-1}}f_x + (f_h - f_l)\right).$$

Arranging the terms,

$$\frac{(\theta+1-\sigma)}{\theta\sigma}kL = \frac{M_l f_l}{\varphi_l^{\sigma-1}}\frac{\varphi_l^{\sigma-\theta-1}-\varphi_h^{\sigma-\theta-1}}{\varphi_l^{-\theta}-\varphi_h^{-\theta}} + \frac{M_x f_x}{\varphi_x^{\sigma-1}}\frac{\varphi_x^{\sigma-\theta-1}-\varphi_h^{\sigma-\theta-1}}{\varphi_x^{-\theta}-\varphi_h^{-\theta}}$$
$$+ M_h\left(\frac{\varphi_h^{\sigma-1}}{\varphi_l^{\sigma-1}}f_l + \frac{\varphi_h^{\sigma-1}}{\varphi_x^{\sigma-1}}f_x + (f_h - f_l)\right).$$

Using the definition of M_l, M_x, M_h in the subsection A.1,

$$\frac{(\theta+1-\sigma)}{\theta\sigma}kL = \frac{M_e}{\delta}[f_l\varphi_l^{-\theta} + f_x\varphi_x^{-\theta} + (f_h - f_l)\varphi_h^{-\theta}].$$

Using the definition of M_l, M_x, M_h in subsection A.1 again, we can represent $kL = \sigma(M_e f_e + M_l f_l + M_x f_x + M_h(f_h + f_x))$ as below.

$$kL - \sigma M_e f_e = \frac{\sigma M_e}{\delta}[f_l\varphi_l^{-\theta} + f_x\varphi_x^{-\theta} + (f_h - f_l)\varphi_h^{-\theta}].$$

Combining the two equations above, we get the mass of the entry, which is almost identical to the one we could get in autarky and an open economy in the textbook.

$$M_e = \frac{(\sigma-1)kL}{\sigma f_e \theta}.$$

The difference is that it contains k, which is the ratio of the labor which is employed in manufacturing, and as we have seen in the body text, k is dependent on the average revenues.

A.1.3. Average Revenues. The average revenue of the existing firms is

$$\bar{r} = \int_{\varphi_l}^{\varphi_h} r_{ld}(\varphi)\gamma(\varphi)d\varphi + \int_{\varphi_h}^{\infty} r_{hd}(\varphi)\gamma(\varphi)d\varphi + \int_{\varphi_x}^{\varphi_h} r_{lx}(\varphi)\gamma(\varphi)d\varphi + \int_{\varphi_h}^{\infty} r_{hx}(\varphi)\gamma(\varphi)d\varphi.$$

The first two terms are average revenue from domestic sales($\bar{r}_d$), and the last two terms are average revenue from exports($\bar{r}_x$). Using the definition of the revenue and ZCP condition, and with the Pareto distribution,

$$\bar{r}_d = \int_{\varphi_l}^{\varphi_h} \sigma\theta f_l \frac{\varphi^{\sigma-\theta-2}}{\varphi_l^{\sigma-\theta-1}}d\varphi + \int_{\varphi_h}^{\infty} \sigma\theta f_l \left(\frac{c_l}{c_h}\right)^{\sigma-1}\frac{\varphi^{\sigma-\theta-2}}{\varphi_l^{\sigma-\theta-1}}d\varphi,$$
$$= \frac{\sigma\theta f_l}{\theta+1-\sigma}\left\{1 + \left[\frac{\varphi_h}{\varphi_l}\right]^{\sigma-\theta-1}\left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\},$$

$$\bar{r}_x = \int_{\varphi_x}^{\varphi_h} \sigma\theta f_x \frac{\varphi^{\sigma-\theta-2}}{\varphi_x^{\sigma-1}\varphi_l^{-\theta}} d\varphi + \int_{\varphi_h}^{\infty} \sigma\theta f_x \left(\frac{c_l}{c_h}\right)^{\sigma-1} \frac{\varphi^{\sigma-\theta-2}}{\varphi_x^{\sigma-1}\varphi_l^{-\theta}} d\varphi.$$

$$= \frac{\sigma\theta f_x}{\theta+1-\sigma} \left[\frac{\varphi_x}{\varphi_l}\right]^{-\theta} \left\{1 + \left[\frac{\varphi_h}{\varphi_x}\right]^{\sigma-\theta-1} \left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\}$$

The total revenue can be calculated by multiplying the mass of the firms.

$$\bar{R}_d = M\bar{r}_d = M\frac{\sigma\theta f_l}{\theta+1-\sigma} \left\{1 + \left[\frac{\varphi_h}{\varphi_l}\right]^{\sigma-\theta-1} \left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\},$$

$$\bar{R}_x = M\bar{r}_x = M\frac{\sigma\theta f_x}{\theta+1-\sigma} \left[\frac{\varphi_x}{\varphi_l}\right]^{-\theta} \left\{1 + \left[\frac{\varphi_h}{\varphi_x}\right]^{\sigma-\theta-1} \left(\left[\frac{c_l}{c_h}\right]^{\sigma-1} - 1\right)\right\}.$$

A.2. The Directions of the Low-Technology Cutoffs Curve Shifts

A.2.1. The Shift of Curve (2.36) under the Unilateral Higher Emission Tax. To check the direction of the graph (2.36) shift, we first consider the first term of the left-hand side of (2.36), which is

$$(h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(\varphi_l^{1-\sigma} + \left[\frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*\right]^{1-\sigma}\right)^{\frac{1}{\kappa}}.$$

The terms which are affected by the increase of the emission tax are $c_l(\tau)/c_h(\tau)$, $c_l(\tau)$, $c_h(\tau)$, φ_l, and φ_l^*. To check a vertical shift, we will further assume that φ_l is fixed. Then, by the increase of $c_l(\tau)/c_h(\tau)$, $c_l(\tau)$ due to the increase of the emission tax, we can easily see that φ_l^* should decrease for the term above to be constant. Then, we consider the remaining terms on the left-hand side of (2.36).

$$\varphi_l^{-\theta} + \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} \left(\frac{c_l(\tau)}{c_l^*(\tau^*)} t\varphi_l^*\right)^{-\theta}.$$

We can also see that given the fixed φ_l and the increase of $c_l(\tau)$, φ_l^* should decrease for the term above to be constant. Therefore, considering the constant value of the right-hand side of (2.36), φ_l^* should decrease if we fix the value of φ_l. This means that by the increase of the emission tax, curve (2.36) shifts downward or left.

A.2.2. The Shift of Curve (2.37) under the Unilateral Higher Emission Tax. To check the shift of curve (2.37), we first take the total derivative.

(A.2.1)

$$
\begin{aligned}
&-\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(\frac{c_l^*(\tau^*)t}{c_l(\tau)}\right)^{-\theta}{\varphi_l}^{-\theta-1}d\varphi_l+\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(c_l^*(\tau^*)t\varphi_l\right)^{-\theta}c_l(\tau)^{\theta-1}dc_l(\tau)-\theta{\varphi_l^*}^{-\theta-1}d\varphi_l^*\\
&-(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\right]^{1-\sigma}\varphi_l^{-\sigma}d\varphi_l\\
&-(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}{\varphi_l^*}^{-\sigma}d\varphi_l^*\\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[c_l^*(\tau^*)t\varphi_l\right]^{1-\sigma}c_l(\tau)^{\sigma-2}dc_l(\tau)=0.
\end{aligned}
$$

We will check the horizontal shift, so assume that there is no vertical shift, thus $d\varphi_l^*=0$, then divide the equation by $d\tau$.

(A.2.2)

$$
\begin{aligned}
&-\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(\frac{c_l^*(\tau^*)t}{c_l(\tau)}\right)^{-\theta}{\varphi_l}^{-\theta-1}\frac{d\varphi_l}{d\tau}+\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(c_l^*(\tau^*)t\varphi_l\right)^{-\theta}c_l(\tau)^{\theta-1}\frac{dc_l(\tau)}{d\tau}\\
&-(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\right]^{1-\sigma}\varphi_l^{-\sigma}\frac{d\varphi_l}{d\tau}\\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[c_l^*(\tau^*)t\varphi_l\right]^{1-\sigma}c_l(\tau)^{\sigma-2}\frac{dc_l(\tau)}{d\tau}=0.
\end{aligned}
$$

Then,

(A.2.3)

$$
\begin{aligned}
&\theta \left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}} \left(c_l^*(\tau^*)t\varphi_l\right)^{-\theta} c_l(\tau)^{\theta-1}\frac{dc_l(\tau)}{d\tau} \\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[c_l^*(\tau^*)t\varphi_l\right]^{1-\sigma}c_l(\tau)^{\sigma-2}\frac{dc_l(\tau)}{d\tau} \\
&=\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}\left(\frac{c_l^*(\tau^*)t}{c_l(\tau)}\right)^{-\theta}{\varphi_l}^{-\theta-1}\frac{d\varphi_l}{d\tau} \\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_l^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\varphi_l\right]^{1-\sigma}\right)^{\frac{1}{\kappa}-1}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)}t\right]^{1-\sigma}\varphi_l^{-\sigma}\frac{d\varphi_l}{d\tau}.
\end{aligned}
$$

Around the initial equilibrium point of E, $\varphi_l=\varphi_l^*$ and $c_l(\tau)=c_l^*(\tau^*)$, and arranging the terms,

$$
\begin{aligned}
&\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}t^{-\theta}c_l(\tau)^{-1}\frac{dc_l(\tau)}{d\tau} \\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left(1+t^{1-\sigma}\right)^{\frac{1}{\chi}}t^{1-\sigma}c_l(\tau)^{-1}\frac{dc_l(\tau)}{d\tau} \\
&=\theta\left(\frac{f_x}{f_l}\right)^{-\frac{1}{\chi}}t^{-\theta}{\varphi_l}^{-1}\frac{d\varphi_l}{d\tau} \\
&+(h-1)^{-\frac{1}{\chi}}\theta\left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left(1+t^{1-\sigma}\right)^{\frac{1}{\chi}}t^{1-\sigma}\varphi_l^{-1}\frac{d\varphi_l}{d\tau}.
\end{aligned}
\tag{A.2.4}
$$

As the terms in front of $\frac{d\varphi_l}{d\tau}$ and the terms on the left-hand side of the equality are all positive, this curve will shift to the right.

A.2.3. The Shift of Curve (2.37) under the Unilateral Higher Emission Tax with the BCA. In the body text, I described that the shift of the curve (2.52) will be very close to the original curve when the home country imposes the same level of the emission tax. To check this, we rewrite (2.37) when the home country imposes the same level of the emission tax, which results in $c_l(\tau) = c_l^*(\tau^*)$, $c_h(\tau) = c_h^*(\tau^*)$, and $c_l(\tau)/c_h(\tau) = c_l^*(\tau^*)/c_h^*(\tau^*)$.

$$\text{(A.2.5)} \qquad (h-1)^{-\frac{1}{\chi}} \left\{ \left(\left[\frac{c_l(\tau)}{c_h(\tau)} \right]^{\sigma-1} - 1 \right) (t\varphi_l)^{1-\sigma} + \left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)} \right]^{\sigma-1} - 1 \right) \varphi_l^{*1-\sigma} \right\}^{\frac{1}{\kappa}}$$

$$+ \varphi_l^{*-\theta} + \left(\frac{f_x}{f_l} \right)^{-\frac{1}{\chi}} (t\varphi_l)^{-\theta} = \frac{\delta f_e}{\chi f_l}.$$

This is the same as (2.52) except that here, $c_l(\tau)/c_h(\tau) = c_l^*(\tau^*)/c_h^*(\tau^*)$, but in (2.52), $c_l(\tau)/c_h(\tau) > c_l^*(\tau^*)/c_h^*(\tau^*)$. Therefore, if the difference between the cost ratio is not big, we can expect that the shift of (2.52) will be very close to the original curve when the home country imposes the same level of the emission tax.

A.3. The Directions of the Export Cutoffs Curve Shifts

A.3.1. The Shift of Curve (2.55) under the Unilateral Higher Emission Tax. To check the direction of the graph (2.55) shift, we first consider the first term of the left-hand side of (2.55), which is

$$\left[\frac{f_x}{f_l} \right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)} \right)^{\sigma-1} - 1 \right]^{\frac{1}{\kappa}} \left(\left[\frac{c_l(\tau)}{c_l^*(\tau^*)t} \right]^{1-\sigma} \varphi_x^{*1-\sigma} + \varphi_x{}^{1-\sigma} \right)^{\frac{1}{\kappa}}.$$

As we did in the low-technology adoption cutoff case, to check a vertical shift, we further assume that φ_x is fixed. Then, by the increase of $c_l(\tau)/c_h(\tau)$, $c_l(\tau)$ due to the increase of the emission tax, we can easily see that φ_x^* should decrease for the term above to be constant. Then, we consider the remaining terms of the left-hand side of (2.55).

$$\frac{f_x}{f_l} \varphi_x^{-\theta} + \left(\frac{f_x}{f_l} \right)^{\frac{1}{\kappa}} \left(\frac{c_l^*(\tau^*)}{c_l(\tau)} \frac{t}{\varphi_x^*} \right)^{\theta}.$$

We can also see that given the fixed φ_x and the increase of $c_l(\tau)$, φ_x^* should decrease for the term above to be constant. Therefore, considering the constant value of the right-hand side of (2.55), φ_x^* should decrease if we fix the value of φ_l. This means that by the increase of the emission tax, curve (2.55) shifts downward or left.

A.3.2. The Shift of Curve (2.56) under the Unilateral Higher Emission Tax. We repeat the same steps for (2.56); thus, the total derivative is

(A.3.1)

$$\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{t}{c_l^*(\tau^*)\varphi_x}\right)^{\theta}c_l(\tau)^{\theta-1}dc_l(\tau)$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)\varphi_x}{t}\right]^{1-\sigma}c_l(\tau)^{\sigma-2}dc_l(\tau)$$

$$-\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}{\varphi_x^*}^{-\sigma}d\varphi_x^*-\theta\frac{f_x}{f_l}{\varphi_x^*}^{-\theta-1}d\varphi_x^*$$

$$-\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\right]^{1-\sigma}{\varphi_x}^{-\sigma}d\varphi_x$$

$$-\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{c_l(\tau)t}{c_l^*(\tau^*)}\right)^{\theta}{\varphi_x}^{-\theta-1}d\varphi_x=0.$$

Again, we will check the horizontal shift, so assume that there is no vertical shift; thus, $d\varphi_x^*=0$. Then, we divide the equation by $d\tau$.

(A.3.2)

$$\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{t}{c_l^*(\tau^*)\varphi_x}\right)^{\theta}c_l(\tau)^{\theta-1}\frac{dc_l(\tau)}{d\tau}$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)\varphi_x}{t}\right]^{1-\sigma}c_l(\tau)^{\sigma-2}\frac{dc_l(\tau)}{d\tau}$$

$$-\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\right]^{1-\sigma}{\varphi_x}^{-\sigma}\frac{d\varphi_x}{d\tau}$$

$$-\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{c_l(\tau)t}{c_l^*(\tau^*)}\right)^{\theta}{\varphi_x}^{-\theta-1}\frac{d\varphi_x}{d\tau}=0.$$

Then,

(A.3.3)

$$\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{t}{c_l^*(\tau^*)\varphi_x}\right)^{\theta}c_l(\tau)^{\theta-1}\frac{dc_l(\tau)}{d\tau}$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)\varphi_x}{t}\right]^{1-\sigma}c_l(\tau)^{\sigma-2}\frac{dc_l(\tau)}{d\tau}$$

$$=\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left({\varphi_x^*}^{1-\sigma}+\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\varphi_x\right]^{1-\sigma}\right)^{\frac{1}{\chi}}\left[\frac{c_l^*(\tau^*)}{c_l(\tau)t}\right]^{1-\sigma}{\varphi_x}^{-\sigma}\frac{d\varphi_x}{d\tau}$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{c_l(\tau)t}{c_l^*(\tau^*)}\right)^{\theta}{\varphi_x}^{-\theta-1}\frac{d\varphi_x}{d\tau}.$$

Around the initial equilibrium point of E, $\varphi_x=\varphi_x^*$ and $c_l(\tau)=c_l^*(\tau^*)$, and arranging the terms,

(A.3.4)

$$\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}\left(\frac{t}{\varphi_x}\right)^{\theta}c_l(\tau)^{-1}\frac{dc_l(\tau)}{d\tau}$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left(1+t^{\sigma-1}\right)^{\frac{1}{\chi}}\varphi_x^{-\theta}t^{\sigma-1}c_l(\tau)^{-1}\frac{dc_l(\tau)}{d\tau}$$

$$=\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}(h-1)^{-\frac{1}{\chi}}\left[\left(\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right)^{\sigma-1}-1\right]^{\frac{1}{\kappa}}\left(1+t^{\sigma-1}\right)^{\frac{1}{\chi}}\varphi_x^{-\theta-1}t^{\sigma-1}\frac{d\varphi_x}{d\tau}$$

$$+\theta\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}}t^{\theta}{\varphi_x}^{-\theta-1}\frac{d\varphi_x}{d\tau}.$$

As the terms in front of $\frac{d\varphi_x}{d\tau}$ and the terms on the left-hand side of the equality are all positive, so this curve will shift to the right.

A.3.3. The Shift of Curve (2.55) under the Unilateral Higher Emission Tax with the BCA. In the body text, I described that the shift of the curve (2.62) will be very close to the original curve when the home country imposes the same level of the emission tax. To check this, we rewrite (2.55) when the home country imposes the same level of the emission tax, which results in $c_l(\tau) = c_l^*(\tau^*)$, $c_h(\tau) = c_h^*(\tau^*)$, and $c_l(\tau)/c_h(\tau) = c_l^*(\tau^*)/c_h^*(\tau^*)$.

(A.3.5)

$$\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left[\left(\frac{c_l(\tau)}{c_h(\tau)}\right)^{\sigma-1} - 1\right]^{\frac{1}{\kappa}} \left(t^{\sigma-1}\varphi_x^{*\,1-\sigma} + \varphi_x{}^{1-\sigma}\right)^{\frac{1}{\kappa}} + \frac{f_x}{f_l}\varphi_x^{-\theta} + \left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}} \left(\frac{t}{\varphi_x^*}\right)^{\theta} = \frac{\delta f_e}{\chi f_l}.$$

This is the same as (2.62) except that here, $c_l(\tau)/c_h(\tau) = c_l^*(\tau^*)/c_h^*(\tau^*)$, but in (2.62), $c_l(\tau)/c_h(\tau) > c_l^*(\tau^*)/c_h^*(\tau^*)$. Therefore, if the difference between the cost ratio is not big, we can expect that the shift of (2.62) will be very close to the original curve when the home country imposes the same level of the emission tax.

A.3.4. The Shift of Curve (2.56) under the Unilateral Higher Emission Tax with the BCA. In the body text, I described that the shift of the curve (64) will be to the right of the solid red line in Figure 2.4. To check this, we rewrite (2.56) when the home country imposes the same level of the emission tax, which results in $c_l(\tau) = c_l^*(\tau^*)$, $c_h(\tau) = c_h^*(\tau^*)$ and $c_l(\tau)/c_h(\tau) = c_l^*(\tau^*)/c_h^*(\tau^*)$. This is drawn as a solid red line in Figure 2.4.

$$\left[\frac{f_x}{f_l}\right]^{\frac{1}{\kappa}} (h-1)^{-\frac{1}{\chi}} \left\{\left(\left[\frac{c_l(\tau)}{c_h(\tau)}\right]^{\sigma-1} - 1\right)\varphi_x^{*\,1-\sigma} + t^{\sigma-1}\left(\left[\frac{c_l^*(\tau^*)}{c_h^*(\tau^*)}\right]^{\sigma-1} - 1\right)\varphi_x{}^{1-\sigma}\right\}^{\frac{1}{\kappa}}$$
$$+ \frac{f_x}{f_l}\varphi_x^{*\,-\theta} + \left(\frac{f_x}{f_l}\right)^{\frac{1}{\kappa}} \left(\frac{t}{\varphi_x}\right)^{\theta} = \frac{\delta f_e}{\chi f_l}. \tag{A.3.6}$$

The first line is the same as that of (2.64) except that here, only $t^{\sigma-1}$ appears in the second term in the curly brackets, whereas $c_l(\tau)t^{\sigma-1}/c_l^*(\tau^*)$ is in the same place as in (2.64). This means that if we assume a fixed value of φ_x^*, φ_x should have a bigger value in (2.64). In the second line, $[c_l(\tau)/c_l^*(\tau^*)]^{\theta}$ disappears from the second term here compared to (2.64). This also requires a higher value of φ_x in (2.64) if we assume a fixed value of φ_x^*. Thus, curve (2.64) lies to the right of curve (2.56) when both countries impose the same level of emission tax.

A.4. Graphical Analysis of the Simulation

A.4.1. Low-Technology Cutoffs Interactions. The results of the simulation for the low-technology cutoffs are drawn as below. Here, we suppose that the home country imposes the BCA at the same level as the home emission tax ($\tau_b^* = \tau = 1.2$).

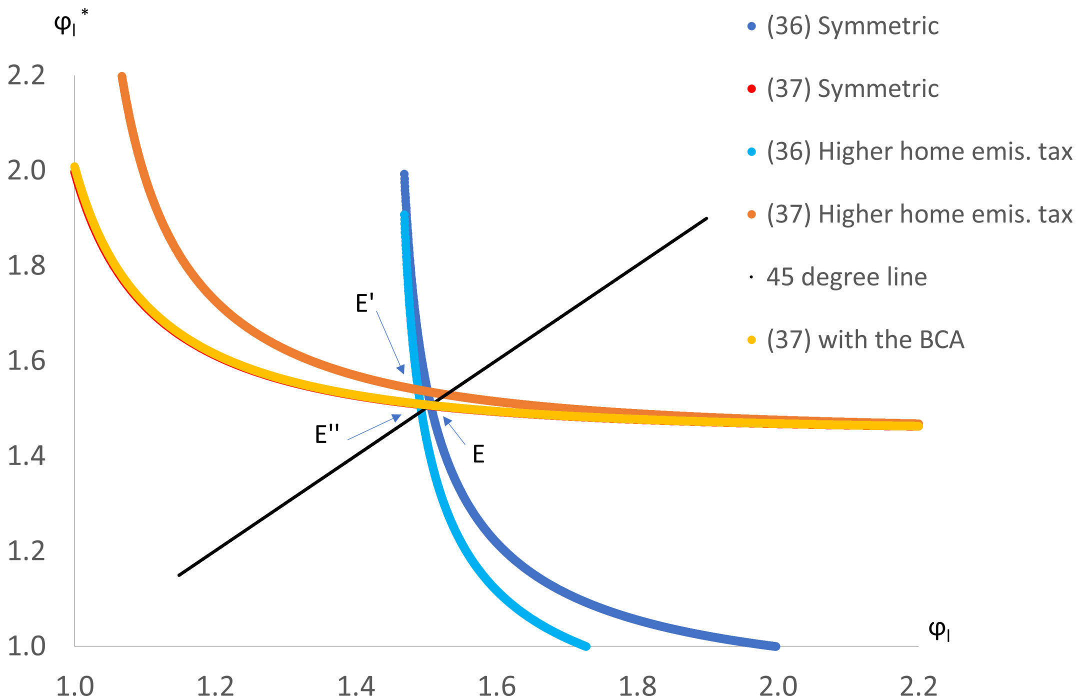


Figure A.1. The Interactions of Low-Technology Adoption Cutoffs from the Numerical Simulation

A.4.2. Export Cutoffs Interactions. The results of the simulation for the export cutoffs are drawn as below. Here, we suppose that the home country imposes the BCA at the same level as the home emission tax ($\tau_b^* = \tau = 1.2$).

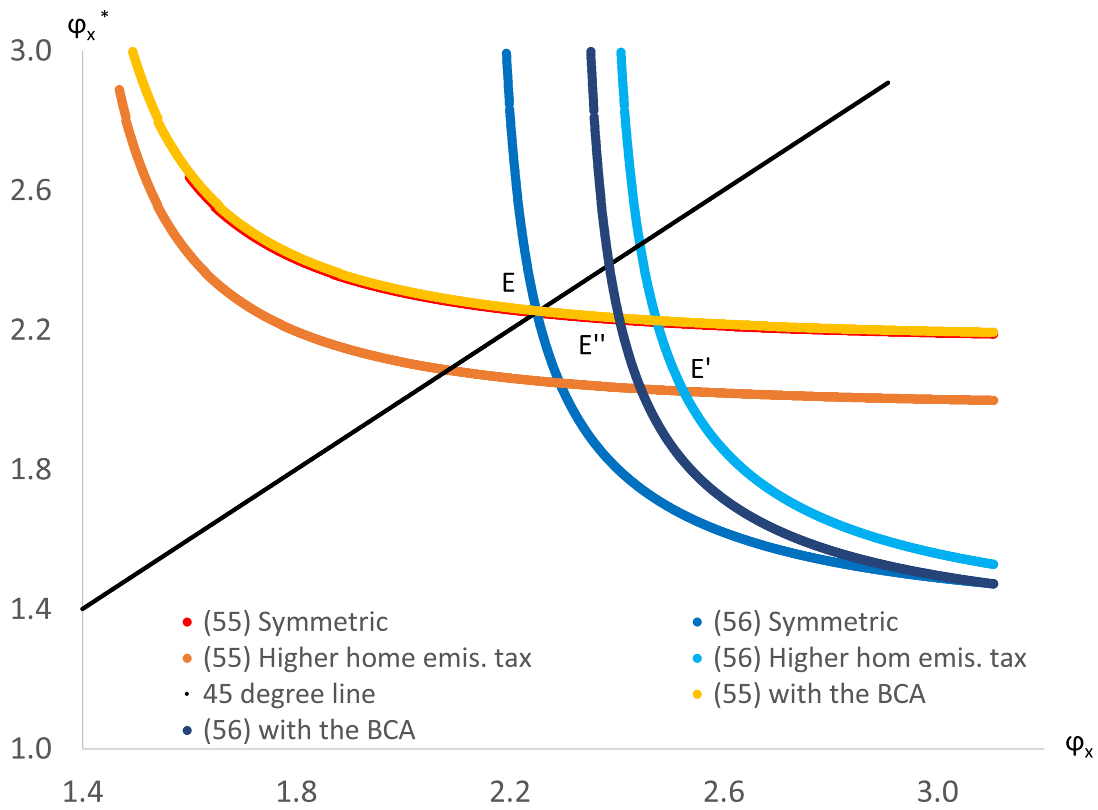
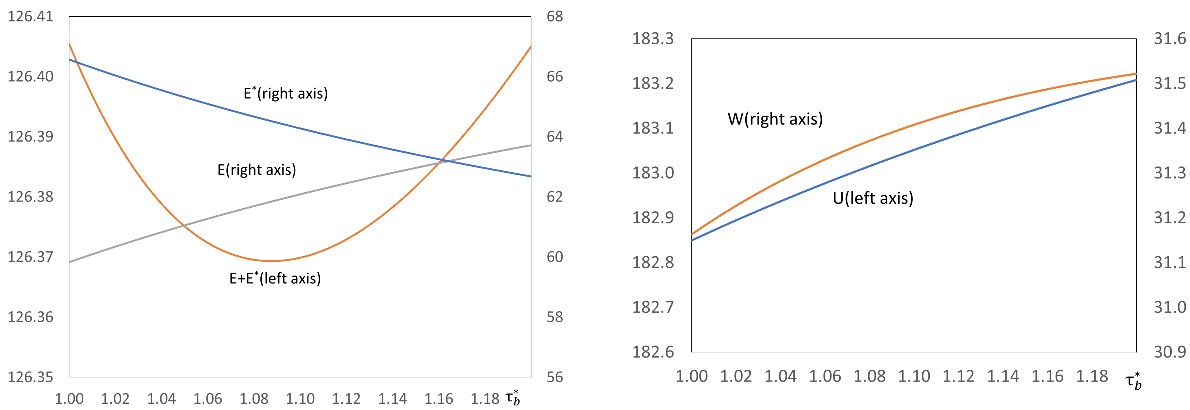


FIGURE A.2. The Interactions of Export Cutoffs from the Numerical Simulation

A.4.3. The Emissions under Asymmetric Technology. Here, I simulate the case where the home country has a higher emission efficiency. Specifically, I changed the abatement efficiencies at home to $a_h = 1.5$, $a_l = 1.1$, keeping the foreign abatement efficiencies at $a_h^* = 1.2$, $a_l^* = 1.0$. As in the symmetric case, the foreign emissions decrease and home emissions increase with the rise of the BCA. There is a point where the total emissions are minimized ($\tau_b^* = 1.0875$), but the amount of the reduction is quite small. As the utility from consumption dominates the disutility from emissions, the welfare-maximizing level of the BCA is the possible highest point, $\tau_b^* = 1.2$.



(a) Emissions

(b) Utility and Total Welfare

FIGURE A.3. Simulation Under Asymmetric Technology

Table A.1. Simulation Results of the Emissions under Asymmetric Technology

Variables	Symbols	Policy scenarios			
		Symmetric	Unilateral Policy($\tau = 1.2$)		Symmetric
		$\tau = \tau^* = 1$	Without BCA	With BCA	$\tau = \tau^* = 1.2$
Home country					
Emission from the domestic market	E_d	66.78	54.32	57.54	58.46
Low-tech. production	E_{dl}	24.44	19.82	20.90	20.25
High-tech. production	E_{dh}	42.34	34.49	36.65	38.21
Emission from the export market	E_x	10.82	5.51	6.18	9.81
Low-tech. production	E_{xl}	1.73	0.36	0.47	1.43
High-tech. production	E_{xh}	9.09	5.15	5.71	8.38
Home Total	E	77.60	59.83	63.72	68.27
Foreign country					
Emission from the domestic market	E_d^*	53.51	60.56	59.35	46.05
Low-tech. production	E_{dl}^*	29.65	32.89	32.74	24.96
High-tech. production	E_{dh}^*	23.86	27.67	26.61	21.09
Emission from the export market	E_x^*	3.23	6.02	3.34	2.71
Low-tech. production	E_{xl}^*	0.64	1.70	0.68	0.47
High-tech. production	E_{xh}^*	2.59	4.32	2.66	2.24
Foreign Total	E^*	56.74	66.57	62.68	48.760
Total emission	$E + E^*$	134.34	126.41	126.40	117.03

APPENDIX B

Appendices for the Third Chapter

B.1. Trends of the Distribution of GHG Emissions

B.1.1. Total Emissions and Economic Growth. Total emissions and GDP growth show a negative correlation of -0.32. Between 2012 and 2019, GDP growth was stable at around 3%. However, GHG emissions increased from 2014 to 2018 but decreased from 2012 to 2014 and from 2018 to 2019.

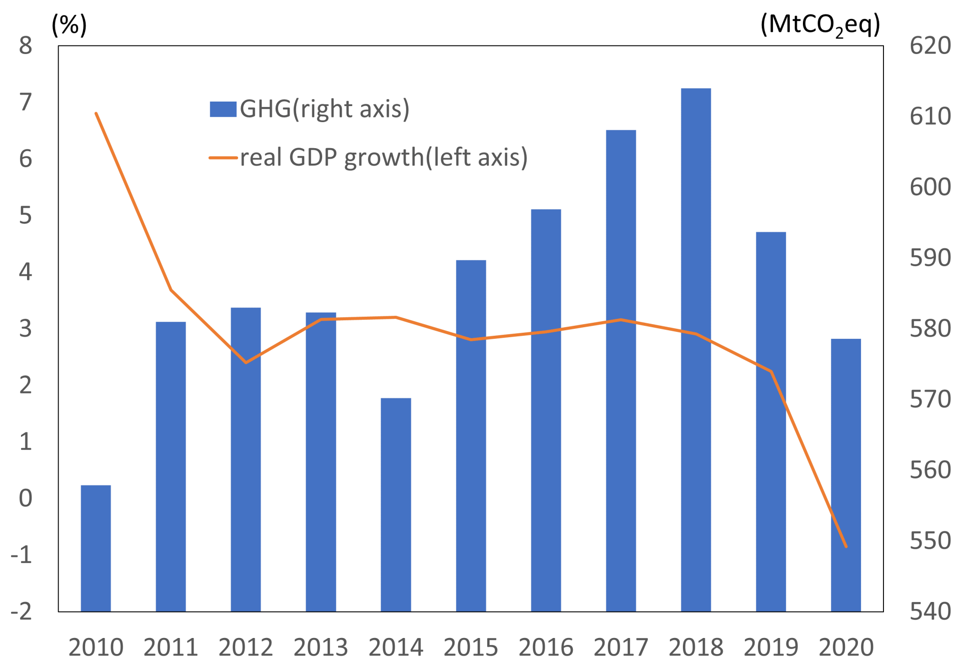
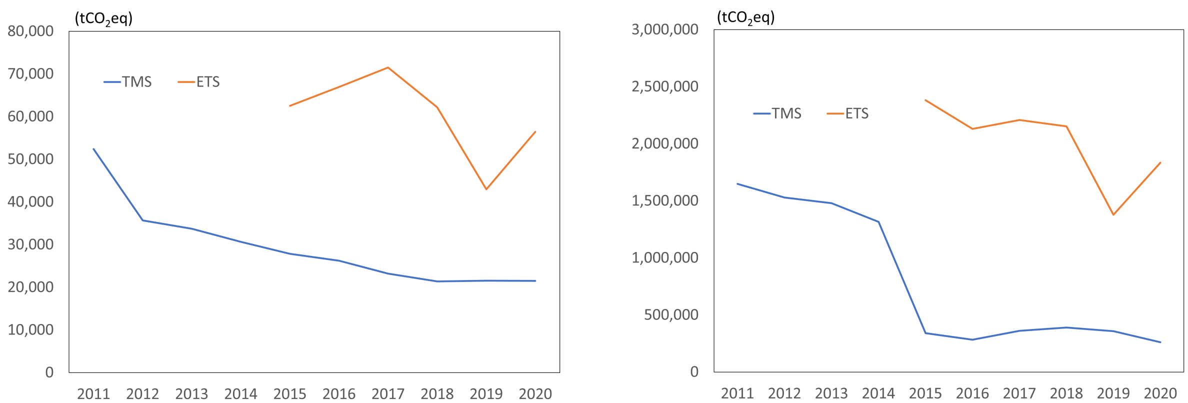


Figure B.1. Emissions and growth

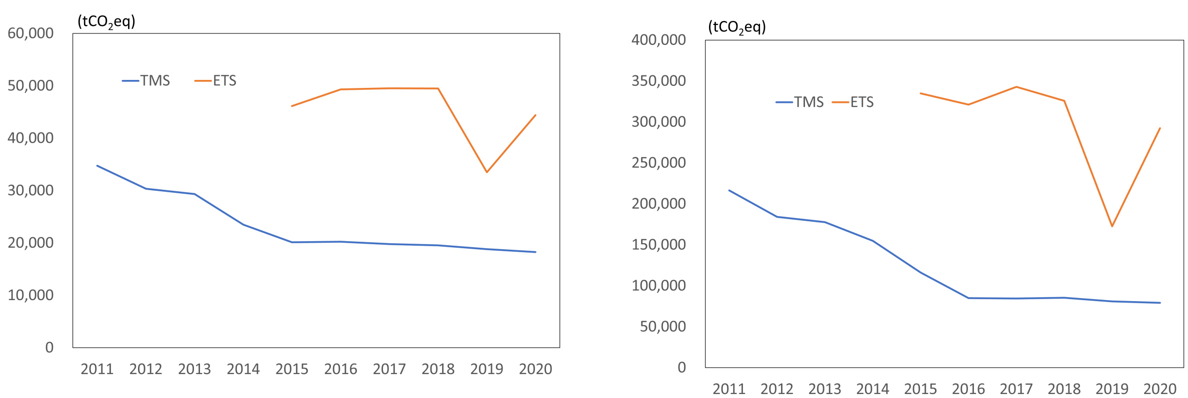
B.1.2. Mean Emissions. Next, we will check the trend of the mean and median of our dataset. The trend of the mean emissions shows that the mean of ETS-regulated firms' emissions decreased sharply in 2019 for both facility-reporting firms and business-reporting firms. The stiff decrease of the TMS firms' emissions in 2015 is because the high-emitting firms are now classified as ETS firms.



(a) Facility (b) Business

FIGURE B.2. Mean of the Emissions

B.1.3. Median Emissions. The trend of the median emissions shows a similar pattern to the mean emissions. The median emissions from the ETS firms decreased a lot in 2019 for both facility-reporting firms and business-reporting firms.



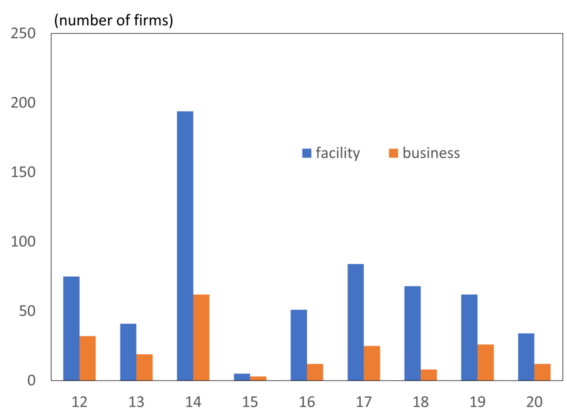
(a) Facility (b) Business

FIGURE B.3. Median of the Emissions

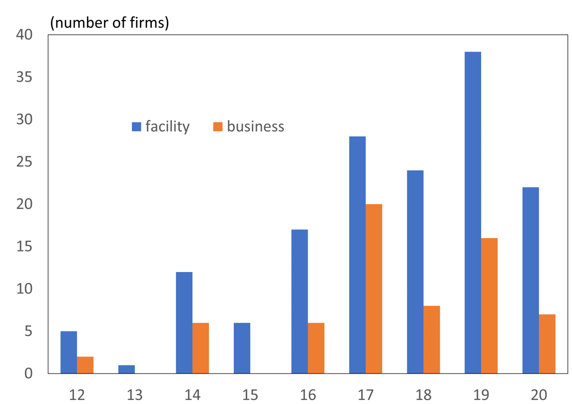
B.2. Changes of the Firms in the Dataset

The dataset that I used in the third chapter is from the firms' annual GHG emission reports. One problem of this dataset is that there are some missing observation periods for some firms. This is because some firms started to report later as their emissions exceeded the criteria later, or they opened their business later, and so on. On the other hand, some firms stopped reporting because they emitted less than the criteria or they closed their business. There are 200 business-reporting firms and 85 facility-reporting firms that have all the observations during the analysis period (2011–2020). The remaining firms have observations for only parts of that period.

The figures below show the entry and exit of the firms in the dataset. In 2014, there was a huge influx of firms as the criteria lowered from 87.5 kt CO_2 eq emissions or 350 TJ energy use (for facilities, 20 kt CO_2 eq or 90 TJ) to 50 kt CO_2 eq emissions or more than 200 TJ energy use (for facilities, 15 kt CO_2 eq or 80 TJ). Meanwhile, there were a lot of exits in 2019, as the emissions reduced a lot that year. Another finding is that the entry and exit of the firms in the dataset are more frequent for facility-reporting firms than for business-reporting firms.



(a) Entry



(b) Exit

FIGURE B.4. Changes of the Firms in the Dataset

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