ASYMMETRIC EMISSION REGULATIONS AND INTERVENTIONS OF THE LOCAL GOVERNMENT

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

TAHA YASIN GÜRLESİN

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
INDUSTRIAL ENGINEERING

APRIL 2024

Approval of the thesis:

ASYMMETRIC EMISSION REGULATIONS AND INTERVENTIONS OF THE LOCAL GOVERNMENT

submitted by **TAHA YASIN GÜRLESİN** in partial fulfillment of the requirements for the degree of **Master of Science in Industrial Engineering Department, Middle East Technical University** by,

Prof. Dr. N. Emre Altun
Dean, Graduate School of **Natural and Applied Sciences** _____

Prof. Dr. Z. Pelin Bayındır
Head of Department, **Industrial Engineering** _____

Assoc. Prof. Dr. Özgen Karaer
Supervisor, **Industrial Engineering, METU** _____

Prof. Dr. Z. Pelin Bayındır
Co-supervisor, **Industrial Engineering, METU** _____

Examining Committee Members:

Assoc. Prof. Dr. Mustafa Kemal Tural
Industrial Engineering, METU _____

Assoc. Prof. Dr. Özgen Karaer
Industrial Engineering, METU _____

Prof. Dr. Z. Pelin Bayındır
Industrial Engineering, METU _____

Assist. Prof. Dr. Sakine Batun
Industrial Engineering, METU _____

Assist. Prof. Dr. Ece Zeliha Demirci
Industrial Engineering, TED University _____

Date: 19.04.2024

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Surname: Taha Yasin Gürlesin

Signature :

ABSTRACT

ASYMMETRIC EMISSION REGULATIONS AND INTERVENTIONS OF THE LOCAL GOVERNMENT

Gürlesin, Taha Yasin
M.S., Department of Industrial Engineering
Supervisor: Assoc. Prof. Dr. Özgen Karaer
Co-Supervisor: Prof. Dr. Z. Pelin Bayındır

April 2024, 79 pages

The intensifying environmental and socio-economic problems accompanying the climate crisis drive countries to implement more sustainable development goals, enacting stringent laws and regulations to control industrial greenhouse gas emissions. The EU's carbon border adjustment mechanism (CBAM) potentially affects countries without ambitious climate policies, especially those trading with Europe. In this thesis, we analyze how a manufacturer exporting to two regions—one developed and one developing—and a local government respond to the CBAM imposed by the developed region. We study two models: a base model in which the manufacturer sets prices for both regions, and this model serves as a benchmark for the second model, the CBAM. In the CBAM model, the manufacturer faces a carbon border tax from developed region and can reduce its unit emission level by investing in green technology. In the first stage, the government, which aims to improve economic and environmental performance, decides on a subsidy rate for the government's technology investment cost. In the second stage, the manufacturer invest in green technology by incurring lump-sum cost for reduce emission level, and aims to maximize its profit. After technology

investment, the manufacturer sets prices for both regions. We compare the manufacturer's price decisions under the base and CBAM models. We characterize the manufacturer's emission reduction decision under the local government's subsidy.

Keywords: Carbon border adjustment mechanism, Asymmetric emission regulations, Government intervention, Green technology investment

ÖZ

ASİMETRİK EMİSYON DÜZENLEMELERİ VE YEREL YÖNETİMİN MÜDAHALELERİ

Gürlesin, Taha Yasin
Yüksek Lisans, Endüstri Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Özgen Karaer
Ortak Tez Yöneticisi: Prof. Dr. Z. Pelin Bayındır

Nisan 2024 , 79 sayfa

İklim krizi ile artan çevresel ve sosyoekonomik problemler, ülkeleri sürdürülebilir kalkınma hedeflerini uygulamaya, daha sıkı yasa ve düzenlemeler ile endüstrinin sebep olduğu sera gazı emisyonunu azaltmaya itiyor. Avrupa Birliği'nin uyguladığı sınırda karbon uygulaması, özellikle Avrupa ile ticareti gelişmiş ancak yeterli iklim politikaları olmayan ülkeleri potansiyel olarak etkileyebilir. Bu tezde iki ayrı bölgeye, gelişmiş ve gelişmekte olan, ihracat yapan bir üreticinin ve yerel bir hükümetin, gelişmiş bölgenin uyguladığı sınırda karbon uygulamasına nasıl tepki vereceğini inceliyoruz. Bunun için iki model üzerinde çalışıyoruz. İlk model temel model olarak adlandırılıyor ve ikinci modelimiz olan CBAM modeli için bir test görevi görüyor. Temel modelde üretici iki bölge için ürünün fiyatını belirliyor. CBAM modelinde ise, üretici gelişmiş bölge tarafından ithal edilen ürünlere uygulanan bir sınırda karbon uygulaması ile karşı karşıya kalıyor, üretici bu modelde yeşil teknolojiye yatırım yaparak birim emisyon seviyesini azaltabiliyor. Bu modelde öncelikle amacı ekonomik ve çevresel performansı iyileştirmek olan yerel hükümet, üreticiyi yeşil teknoloji

yatırımı için belirli bir oranda sübvanse edebilir. İkinci aşamada, üretici teknoloji yatırımına yaparak birim emisyon seviyesini ne kadar düşüreceğine karar veriyor. Son olarak ise yine üretici iki bölge için satış fiyatını belirliyor. Üreticinin temel ve CBAM modeldeki fiyat kararlarını karşılaştırdık. Ayrıca üreticinin, hükümet sübvansiyonları ile emisyon azaltma kararını ortaya koyduk.

Anahtar Kelimeler: Sınırda karbon uygulaması, Asimetrik emisyon düzenlemeleri, Hükümet müdahalesi, Yeşil teknoloji yatırımı

To my family and gentle souls...

ACKNOWLEDGMENTS

First and foremost, I would like to express my gratitude to my advisor, dear Dr. Özgen Karaer, who has been both a support and a guiding figure throughout this entire process. I sincerely thank for her invaluable knowledge and experience, which has played an instrumental role in bringing me to this point.

I extend my infinite thanks and gratitude to my dear co-advisor, Dr. Pelin Bayındır, who has made significant contributions both to this study and to my personal journey. Her valuable insights and guidance have been essential, and I am truly thankful for her support.

I thank my family, my mom, Kadriye; my dad, Salih, and my older-sister, Şeyma for their support, joy and true love. I can never forget the effort you put in for me to be where I am in life. Thank you for the invaluable contribution you made. I love each one of you.

I want to thank all my beloved friends for always there for me. I am grateful to all of you for your unconditional love and unwavering support.

My furry friend Luna, I love you dearly and am grateful for the joy you've brought into my life.

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

EU	European Union
CBAM	Carbon Border Adjustment Mechanism
FOC	First Order Derivative
SOC	Second Order Derivative
OBJ	Objective
FUNC	Function

CHAPTER 1

INTRODUCTION

Escalating greenhouse gas emissions, depleting natural resources, and increasing consumption habits have forced humanity to confront one of the most critical problems of recent times: the climate crisis. The global surface temperature from 2011 to 2020 was approximately 1.1°C higher than the period of 1850–1900 (Intergovernmental Panel on Climate Change, 2023). Increasing temperatures and ecosystem disruptions cause both severe environmental and socioeconomic problems. Droughts, floods, extreme weather, and ecosystem disruptions endanger basic human needs such as shelter and nutrition. Therefore, people living in the most affected areas must migrate, which will cause more significant problems. In 2015, 193 United Nations member countries formally adopted a sustainable development agenda. 17 Sustainable Development Goals were adopted at the UN Sustainable Development Summit in New York in September 2015. These goals aim to prevent or mitigate the potential environmental dangers and socioeconomic problems posed by the climate crisis (United Nations, 2023). Countries have been implementing laws and regulations to achieve sustainable development goals.

Power generation, manufacturing goods, producing foods, and transportation cause greenhouse gas emissions. Industries burn fossil fuels to maintain their activities, and greenhouse gas emissions cause the global temperature to rise (Nations, 2023). As the global temperature increases, the laws and regulations enacted by some countries have become more binding. In 2019, the EU introduced "the European Green Deal," a road-map towards a climate-neutral continent by 2050. The union has also presented the "European Climate Law" and has started implementing some laws and regulations (European Commission, 2019). In 2005, the EU launched the EU Emis-

sion Trading System (ETS), now in the fourth trading phase. The EU ETS works on a "cap-and-trade" mechanism, where a cap for their emission allowances limits carbon-intensive sectors, and companies can buy allowances from the EU Carbon market. The EU aims to reduce emissions and generate revenues to finance the EU's green transition with the EU ETS(Commission, 2023). Since the EU's regulations have enforcement power over domestic companies in the region, the thread of offshore production become a serious concern for the EU. The union wants to prevent regional companies from moving to other countries with less ambitious carbon policies, also known as "carbon leakage." In October 2023, the EU started implementing the transitional phase for the Carbon Border Adjustment Mechanism (CBAM). The EU charges carbon tax on imported goods with the CBAM at the border. Therefore, the union wants to prevent carbon leakage by imposing a carbon border tax on imported goods while continuing to regulate the domestic market. The CBAM aims to limit carbon emission levels in carbon-intensive sectors for regional companies and international trade partners. (European Commission, 2023)

Only some countries or regions have adopted and implemented emissions regulations. Furthermore, differentiation in emission regulations causes an regulation asymmetry between some countries. With a regulation like the CBAM, it is not possible for countries trading with the European Union to remain unaffected by the union's regulations. For instance, Türkiye's 40.6% share of exports with 103.1 billion dollars in 2022 is with the EU, and it ranks first in Türkiye's total exports(Republic of Turkey Ministry of Trade, 2023). Furthermore, for the Turkish economy, the CBAM may cause a loss of up to 2.6 to 3.6% of GDP by 2030 if necessary actions are not taken(Acar et al., 2022). Many countries, especially developing economies, are behind the developed world in adopting climate-related restrictions and regulations.

While countries force companies to reduce their emission levels by law and regulations, companies are adapting new strategies and investing in new technologies to prevent potential sanctions from governments. Also, increasing customer awareness forces companies to be more environmentally friendly. For example, Microsoft announced it would be carbon-negative by 2030. The company plans to remove all the carbon emitted from the environment, directly or by electrical consumption since it

was founded in 1975, by 2050. The company also plans to create a climate innovation fund and invest $1 billion in the fund over the next four years to speed up the development of carbon removal technology (The Guardian, 2020). Apple has provided $4.7 billion in three Green Bonds since 2016. The company aims to become carbon neutral across its supply chain by 2030. Apple has been developing low-carbon manufacturing and recycling projects (Apple Inc., 2022).

This thesis study focuses on a manufacturer producing and exporting its products in two regions. The first region is the developed region, which is more ambitious about emission regulations, while the other one, the developing region, is not. The manufacturer does not sell its product to the local market. We study two models: the base model and the Carbon Border Adjustment Mechanism (CBAM) model. The base model is intended to serve as a benchmark for the second model, which is the focus of our study. In both models, the manufacturer produces and exports its product under a capacity constraint and decides the prices for regions under different customer expectations. In both models, we assume that customers in the developed region are sensitive to the price and emission level of the product. In contrast, customers in the developing regions are only sensitive to the product's price.

In the base model, the manufacturer does not face emission regulation from either region while exporting goods. In the CBAM model, the developed region requires companies to pay a unit carbon tax at the border for imported goods. The developing region does not enforce any emission regulation for imported goods. Therefore, in the CBAM model, two regions are asymmetric in emission regulations. In the CBAM model, the manufacturer may invest in green technology to reduce its unit emission level by paying lump-sum costs. We assume that the manufacturer's unit production cost increases due to the emission reduction level. We also consider a local government that may subsidize the manufacturer to invest in green technology in the CBAM model. The sequence of events for the CBAM model is as follows: (1) The government decides on a subsidy rate for the manufacturer's technology investment. (2) The manufacturer invests to reduce unit emission level. (3) The manufacturer sets prices for both regions.

We consider the following research questions: (1) How may CBAM affect a manufacturer's economic and operational decisions? (2) How does CBAM affect a manufacturer's environmental performance? (3) How does a local government support its economy against potential threats of CBAM?

According to our analysis, CBAM damages the manufacturer's economic performance and causes a price hike in the regulated market without local government intervention. CBAM fails to effectively incentivize the manufacturer's green technology investment under asymmetric regulations. Moreover, the manufacturer chooses to increase its market share in the developing market and decrease it in the developed market. However, when local government intervention occurs, the manufacturer's environmental performance significantly improves, and the CBAM exerts its effectiveness. Furthermore, with local government intervention, the price level is decreased in the developed market, while the developing market is negatively affected. The local government intervention enhances producers' environmental performance against CBAM and economically safeguards them—additionally, the local government benefits from its intervention against CBAM.

In the next chapter, we summarize the literature related to this study. In Chapter 3, we define the problem environment. Chapter 4 gives the analytical results of our model. In Chapter 5, we summarize the numerical analysis of our model and comment on the results. Finally, Chapter 6 summarizes the main findings of this thesis study. We provide all proofs in the Appendix.

CHAPTER 2

LITERATURE REVIEW

In this chapter, we review the related literature to our study. This thesis is closely linked with three issues regarding sustainability: carbon border adjustment mechanism (CBAM) and its impact on supply chains and economies, consequences of asymmetric emission regulations, and government intervention for sustainability investments by companies. CBAM is a mechanism that is expected to be a remedy to asymmetric regulations, and hence the two issues are closely related. We review the related literature in this area as a whole in Section 2.1. Section 2.2 summarizes the literature where government intervention occurs for companies' sustainability investments.

2.1 CBAM and its Impact on Supply Chains and Economies

This stream mainly focuses on the potential effects of CBAM on economies and regulated and unregulated markets. The unilateral policies (i.e., asymmetric emission regulations), loss of competitive advantages and carbon-leakage problems due to the CBAM, and whether CBAM is a climate policy or a mechanism targeting the economic performance have been studied.

Sunar and Plambeck (2016) study emission allocation between co-products. There are one or more buyers in a region with a climate policy, and these firms buy a product from a supplier that operates in an unregulated region. The supplier sells its primary product to a buyer where the buyer incurs an emission cost voluntarily or due to a government-imposed climate policy. The supplier also sells co-products at the

local market without incurring any emissions costs. The authors study three candidate rules for allocating the supplier's emissions among its products: value-based and mass-based allocation and system expansion. Their results show that, under value-based allocation, introducing a carbon border tax on the primary product may cause increased emissions under certain market conditions because the supplier may lower the price to avoid the carbon border tax and produce higher sales overall. This paper, like in thesis, focuses on a supplier's decision when it faces carbon border tax on its exported product. The authors here study a setting with co-products and allocation mechanism whereas in this thesis, we focus on the supplier's pricing decisions and green technology investment and the local government's intervention.

Drake (2018) studies multiple domestic and foreign firms that compete in a market with Cournot competition. Domestic firms are mature in their emission regulations. Domestic firms may reallocate their operations (choose off-shore production) but must pay a fixed reallocation cost. Foreign firms may enter the regulated market, but they must cover the fixed operating cost whenever they choose to enter the market. If a foreign firm chooses to import, it faces transportation costs. Whether domestic or foreign, all firms can invest in greener technology to reduce the cost of carbon in the regulated region. Domestic firms choose local or off-shore production, and invest in greener technology to find a profitable way under carbon regulation. In most cases, carbon border adjustment strictly decreases global emissions, so the author suggests that the CBAM is a carbon policy rather than a mechanism for trade protection. While we share a similar approach to the technology investment decision of a manufacturer, our study does not consider a competitive market consequences like carbon leakage.

X. Huang et al. (2021) also study emission regulations. Their primary purpose is to show how asymmetric emission regulations may cause a potential carbon-leakage problem. They define two policies: border tax and output-based allocation. In their problem setting, the firm produces a single product, and it can invest in technology to reduce the emission level or choose off-shore production. They study a two-stage model where, in the first stage, the firm decides how much to invest in technology or build a capacity portfolio for off-shore production. After the emission price is realized between the two stages, the firm decides on local and off-shore production

volumes in the second stage. They find that if the main objective of the regulatory body is reducing off-shore production, then the border tax is a better policy option. However, if the primary objective is to invest in clean technology and decrease overall polluting activity, the output-based allocation policy works better when emission price uncertainty is high. In most cases, the border tax works better than the output-based allocation. We also study emission regulation asymmetry in this thesis and consider a firm's technology investment decision to reduce unit emission. However, we consider a firm exports two region and the overall consequences of CBAMn terms of emissions.

Eyland and Zaccour (2012) study the optimal strategies for both governments and firms under the border tax policy. They define two different regulatory bodies and their respective local firms. In their model, one of the regulators can react to the border tax by implementing carbon policies. Eyland and Zaccour (2014) study the strategic effects and impacts of carbon tariffs on cooperative outcomes among nations. They model a non-coalition cooperation environment, where regions have different responsibilities or goals for reducing carbon emissions. They characterize and compare the equilibrium results in three scenarios. In the first scenario, which is a benchmark, two regulators decide the carbon taxes non-cooperatively, and firms compete in a Cournot duopoly. In the second scenario, while firms compete, the regulators cooperate in determining the carbon taxes. In the third scenario, they introduce another player, such as the World Trade Organization. The third player announces a border tax at a prior stage after the players make decisions, as in the first scenario. They find carbon tariffs may result in better cooperation among nations, benefiting those in the coalition while affecting non-coalition nations differently.

Sanctuary (2018) studies the trade dynamics between two countries, called home and foreign. The two countries trade homogeneous goods, and producing them causes carbon emissions. Firms in the home country sell their goods only in the domestic market, while foreign firms can sell to their domestic market and export to the home country. They assume that two countries produce the same goods with different technologies, whereas one has a technological advantage. The foreign country enforces the carbon tax on its domestic firms, while the home country charges a carbon tax on

imported products. They assume that carbon tax of the home country is higher than that of the foreign country, and the home country rebates the portion of taxes from foreign firms faced in their country. This paper examines the trade between two countries and the potential effect of border tax imposed by one of the countries. Similar to this study, the manufacturer faces a carbon border tax when trading with a region in our model. However, we do not consider a competitive setting or a local government regulation in terms of carbon policies. We focus the consequences of regulation asymmetry on the manufacturer's price and green technology investment decisions under a local government intervention.

Zhong and Pei (2023) review literature related to CBAM. They find that from an economic perspective, the biggest concerns about CBAM are its effectiveness in promoting fair competition, potential carbon leakage problems, and improving global welfare. They classify the results into two groups: direct and indirect effects of CBAM. The direct effects are price changes due to variations in market outcomes because of CBAM, loss of competitiveness, and carbon leakage problems caused by unilateral climate policies. The indirect effects are supply chain disruptions due to failing to meet the CBAM requirements, which may cause delays and make it hard to maintain smooth operations for businesses reliant on international trade. Moreover, the CBAM may cover the scope two emissions in the future, which leads to more complexity in implementing the CBAM and international trade.

2.2 Government Intervention for Sustainability Investment by Companies

This section summarizes the literature on government interventions for companies to invest in sustainability. Different government interventions, such as carbon tax, cap-and-trade schemes, legislation, and subsidies, have been studied in the literature. The common objective is to understand how the government's intervention possibly affects the companies' sustainability investments and societies' welfare.

Krass et al. (2013) study a Stackelberg game between a profit-seeker firm and a regulator who wants to improve social welfare. The firm can choose different technologies to reduce emissions; each technology brings different emission reduction levels and comes with fixed and variable costs. The firm faces price-sensitive consumers. In this paper, the firm does not change its existing product or service but produces it with a different, possibly greener, technology. The government has alternative tools: setting carbon tax and subsidizing the firm's fixed or variable cost of technology when the firm adapts green technology. Also, the government may offer rebates to consumers if they purchase products manufactured with green technologies. The government aims to maximize "economic surplus," which consists of consumer and producer surplus, and minimize total emission levels. The authors find that the firm's response to taxation may be "non-monotone," meaning it may adopt dirtier technology under a high-emission tax. Rebates are efficient for increasing social welfare under given technology. However, it does not guarantee that the firm adapts the technology. With mixed policies that use taxes, subsidies, and rebates, the regulator can optimize social welfare with green technology. This paper's primary focus is to see how emission regulations and government intervention leverage a firm's choice of green technology. Even though our approach to technology investment is similar, both the manufacturer and the government react to the carbon regulation of a foreign trade partner. However, in this paper, the emission regulations as well as subsidies are offered by the local government.

Drake et al. (2016) study technology choice under emission regulations. In this paper, they work with uncertain demand, and there are two regulation models: carbon tax and cap-and-trade. While there is uncertainty about a carbon price in the cap-and-trade model, the carbon price is predetermined in the carbon tax model. They study a two-stage problem; in the first stage, the firm chooses a technology for better environmental performance, and in the second stage, it makes the production decision. Between the two stages, uncertain demand is realized. This study shows the effects of emission regulations on the firms' technology investment decisions. They find that the firm's expected profit is higher under the cap-and-trade scheme. When the production cost is high, an increase in carbon tax can decrease the clean technology investment. The primary goal of this study is to analyze how different emission regulations would affect the firm's technology portfolio decision. Our model only considers the CBAM as a regulation scheme and focuses on cross-border trade between a manufacturer and two different markets. We also consider a local government that subsidizes the manufacturer to invest as a reaction to CBAM from the regulated region.

Chen et al. (2019) study the effect of the government's subsidy on supply chains' sustainability innovation. They model a manufacturer and a retailer cooperating to develop a product with higher sustainability. The retailer sells the product to customers, and demand increases with the sustainability effort that the manufacturer can exert. The government may subsidize the retailer and the manufacturer with a tax credit for each unit produced or offer a fraction of the cost of innovation to increase sustainability efforts. The authors find that when the government only uses per-unit production subsidy, the manufacturer may only collaborate if innovation or production is costly. The government is indifferent to collaboration dynamics when it offers innovation subsidies. The primary focus of this paper is to analyze how different government subsidy schemes support the supply chain's sustainability effort. In our model, the government also subsidizes the manufacturer with a rate of the investment cost. However, we only consider a single manufacturer and study two markets with asymmertic regulations.

Fu et al. (2023) study two competing firms with different product emission levels. They model a Cournot duopoly and an imperfect competition setting. Firms have different emission levels; Firm 1 is carbon-efficient, and Firm 2 is carbon-inefficient. A government enforces carbon taxes per unit emission. Firms can invest in greener technology to reduce emission levels. First, they introduce a baseline model in which firms react to the carbon tax by only adjusting production volumes. Afterward, they analyze the green technology model to see how firms react to the emission regulations by investing in greener technology. The authors find that, under the green technology model, firms' green technology investment decisions are highly related to the emission efficiency of firms, carbon price, and the cost of green technology investment. A high carbon tax may lead to both firms investing in green technology. When the carbon tax is low, both firms choose not to invest in green technology. With an intermediate tax rate, only the carbon-inefficient firm invests in green technology. This paper also studies the investment in green technology under a carbon tax. However, we consider a single manufacturer that faces emission regulations from a foreign market and subsidies from a local government.

Jung and Feng (2020) study how government subsidies can affect the evolving industry and social welfare. They study a two-stage game where two firms enter the market sequentially. The leading firm enters the market in the first period and makes an R&D investment. Tthe success of the investment is uncertain. If R&D investment succeeds, the firm obtains high technology, which offers high environmental standards. Otherwise, the leading firm obtains a lower technology with lower environmental standards. In the second period, the leading firm can make an additional investment to increase its technology. The follower firm enters the market and invests in technology improvement in the second period. The products offered by the two firms are partially substituted and sold in the same market. Customers are high technology seekers, and the environmental performance of firms affects the customers' demand. The authors first analyze the model without government intervention and then introduce a government subsidizing a portion of the firms' R&D investments. The government aims to maximize social welfare by setting the subsidy level. The authors find that social welfare may increase when the government sets a proper level of subsidies. The firm's investment decision is highly related to R&D costs, but the

government's subsidy level does not depend on it. In our study, the government also subsidizes the manufacturers' green technology investment. However, in our problem setting, we have only one manufacturer and do not portray an evolving industry.

Anand and Giraud-Carrier (2020) study a problem with two or more rival firms, and each firm tries to maximize profit under a pollution regulator. The pollution regulator aims to encourage the firms to reduce pollution while discouraging a decrease in output. Firms compete in a Cournot game where products are partially substitutable. The authors analyze and compare two types of regulation: cap-and-trade mechanism and carbon tax. Companies can respond to regulations by employing various strategies, such as reducing pollution or cutting output. This paper mainly focuses on how pollution regulation affects a competitive market in which product substitution occurs at some levels. We share a similar approach in modeling technology investment; however, we consdier a single manufacturer that sells to two markets with asymmetric regulations.

Bian et al. (2020) investigate how environmental subsidies incentivize a manufacturer to invest in emission-reducing technologies under the growing environmental concerns among consumers. This paper analyzes the effects of different government subsidies on the manufacturer's emission reduction strategies. Consumer and manufacturer subsidies are studied and compared in this study. The primary focus of this paper is to show how government intervention affects the environmental performance of a manufacturer. Hua et al. (2023) study how government interventions in new technology adoption improve product greenness. They model a two-stage Stackelberg game between a manufacturer and a government. They compare the effectiveness of government interventions (subsidizing, regulating, and hybrid interventions) in consumer surplus, manufacturer profit, and social welfare. McDonald and Poyago-Theotoky (2017) study a Cournot duopoly producing a homogeneous good. They define a government that sets an emission tax to maximize social welfare. First, the government decides on the emission tax; after, firms invest in technology, and firms choose to cooperate and share costs of R&D or not. Lastly, firms decide on production volumes. We also study the technology investment decision of a manufacturer under a local government intervention. However we focus on two foreign markets

with asymmetric regulations.

Huang et al. (2019) study a duopoly competition under two government subsidy schemes. They define two firms that differ in production cost. The firms compete on their unit price and energy efficiency of products. The government specifies the amount of subsidies and a certain threshold for the energy consumption level of the product. Firms are qualified for the subsidy if the product is certificated for specific energy efficiency/saving. The authors identify necessary conditions for low-cost firms to produce a high or low-energy-efficiency product. We also study a local government intervention, however we do not consider a competitive market setting.

Sinayi and Rasti-Barzoki (2018) study a two-tier supply chain with a government. They study the three dimensions of sustainability (economic, social, and environmental). First, the government offers a subsidy or charges tax on the end product's price. The manufacturer supplies the green product to the retailer at wholesale price, and the customers buy the product from the retailer at a retail price. They assume the manufacturer has social and environmental concerns that align with corporate social responsibility. In our study, we consider a manufacturer exports two regions with asymmetric regulations under a local government.

Shao et al. (2017) study the electric-and-gasoline vehicle market under two different market structures (monopoly and duopoly). The government may offer two subsidy schemes: a subsidy incentive scheme or a price discount incentive scheme to buyers of electric vehicles to promote the adoption of electric vehicles. While the government aims to improve welfare, the manufacturers try to maximize profit, and customers want to increase their utility from consumption. They find that a monopolistic market subsidy scheme leads to higher welfare. Under price discounts, the government should pay more to achieve better environmental performance. We also study a local government intervention, however we focus on a two foreign markets with asymmetric regulations and a manufacturer's price and green technology investment decisions.

Other than regulators, non-governmental organizations (NGOs) can affect firms to invest in green technology. Kraft et al. (2013) study an NGO's strategies to pres-

sure two firms to remove potentially hazardous substances from products under two competing firms in the market. In their setting, two firms compete and sell a product containing a potentially hazardous substance. The hazardous substance is not regulated. However, NGOs may influence firms to replace the substance by influencing the regulator or by increasing the customer awareness in the market. The authors also consider alternative objective functions of an NGO where its pragmatism level affects how much it values the firms' profit. Finally, the regulation occurs with a probability, and a firm has to replace the hazardous substance if it has not already been replaced. This paper primarily focuses on an NGOs' strategies and the influential power of firms or regulatory bodies to remove potentially hazardous substances. Although the problem setting is substantially different from that in this thesis, both works investigate how firms' environmental investments can be incentivized by different mechanisms.

The literature analyzes government interventions in various environments with different policies or subsidy schemes. The primary purpose of these studies is to analyze how governments may affect the sustainability performance of companies or supply chains while improving social welfare. Carbon taxes, emission trading schemes, subsidies for manufacturers to invest in sustainability, or consumer subsidies to incentivize the consumption of green goods are potential government interventions from the sustainability perspective. Some studies show that carbon taxes might be more effective than emission trading schemes or government subsidies under specific market structures. Some studies analyze the subsidies for firms and consumers and offer insights about which conditions these subsidies are preferable.

We diverge from existing CBAM literature by examining its impact on an a manufacturer that exports its products and the strategies of the local government to support the manufacturer's technology investment. While most CBAM literature focuses on potential off-shore production and carbon leakage problems, we focus on green technology investment and a local government intervention amidst asymmetric emission regulations between foreign markets due to CBAM. The manufacturer can adjust prices to maximize profit and as well as invest in green technology as a response to CBAM. We define a regulated and unregulated market to see the effect of different dynamics between regions on the manufacturer's economic and environmental perfor-

mances. Essentially, we study how CBAM affects foreign firms, markets, countries and the overall environmental impact rather than focusing only the regulated market.

We contribute to the literature by investing in the effects of CBAM on not only the regulated region itself but also foreign regions that follow less ambitious climate policies. We study a manufacturer's price and green technology investment decisions and show how CBAM affects market prices and environmental performance. We study a local government intervention to investigate how a local government would affect the manufacturer's economic and environmental performance. We also show a perspective on the effectiveness of CBAM with a local government intervention.

CHAPTER 3

PROBLEM ENVIRONMENT

In this chapter, we introduce our problem environment, state our assumptions, and formulate our problems. We study two models: the base model and the Carbon Border Adjustment Mechanism (CBAM) model. The base model is intended to serve as a benchmark for the second model, which is the focus of our study.

We study a manufacturer that produces and exports its product to two different regions; one is a developed region, and the other one is a developing region. In both models, the manufacturer produces a single product with a unit cost of c and an exogenously given unit emission level e. The manufacturer has a production capacity of Ω units. We assume that the manufacturer exports all the products produced, and there is no local market. The manufacturer can differentiate the export prices of two regions.

Consumers have different expectations in different regions. In the developed region, we assume consumers are both price and emission-sensitive. The developing region has low environmental awareness, and consumers are only sensitive to the price.

In the base model, the manufacturer faces no emission regulation from either region. This model differentiates regions by only the customer's environmental awareness and price sensitivities. In addition to this differentiation, the developed region introduces an emission regulation in the CBAM model as a unit carbon border tax from imported products. The developing region does not require a carbon border tax, i.e., nothing changes for the developing region between the base and the CBAM models. Therefore, an emission regulation asymmetry occurs between developed and devel-

oping markets under the CBAM model.

In the CBAM model, the manufacturer can invest in greener technology to reduce unit emission levels by incurring a lump-sum investment cost. We assume that the unit production cost increases with the rate of reduction in unit emission. Also, the manufacturer sets prices for both regions. In the CBAM model, the manufacturer can pay a lower carbon border tax to the developed region and reach more customers in this region by reducing the unit emission level through technology investment. We also consider a local government that can subsidize a portion or all of the manufacturer's technology investment cost. In Section 3.1, we explain the base model in detail and continue with the details on the CBAM model in Section 3.2.

3.1 The Base Model

This section explains the base model, where the manufacturer determines the selling prices in two markets. Neither the developed, or the developing region apply a carbon border tax in this model.

First, we define the demand functions for both regions. Similar to the previous studies by Chen et al. (2019) and Bian et al. (2020), we assume linear demand functions. The developed and the developing regions are referred to as regions 1 and 2, respectively. We introduce p_i for prices, γ_i to show price sensitivities and θ for emission sensitivity, where $\gamma_i > 0$ for $i = 1, 2$ and, $\theta > 0$. We also define the quantities as $q_1(p_1)$ and $q_2(p_1)$ for developed and developing regions, respectively. In the following Equation 3.1, we define the demand functions for regions.

$$q_1(p_1) = K_1 - \theta e - \gamma_1 p_1, \quad q_2(p_2) = K_2 - \gamma_2 p_2 \tag{3.1}$$

Where $K_i > 0$ is the base market potential of the region $i = 1, 2$. In this thesis study, we assume that $K_1 = K_2 = K$ and avoid the difference arising from market potential to affect our analysis.

In the base model, the manufacturer decides on p_1 and p_2 to maximize its profit. The profit function is straightforward: revenue from sales minus total production cost. The manufacturer has a capacity constraint for its total production quantity, represented as Ω. The manufacturer has an exogenously given unit emission level e and unit production cost c. Thus, the manufacturer solves the problem below:

$$\begin{aligned} \underset{p_1,p_2}{\text{maximize}} \quad & \Pi_{base}(p_1, p_2) = p_1 q_1(p_1) + p_2 q_2(p_2) - c(q_1(p_1) + q_2(p_2)) \\ \text{subject to} \quad & q_1(p_1) + q_2(p_2) \leq \Omega \\ & q_1(p_1), q_2(p_2) \geq 0 \end{aligned} \tag{3.2}$$

We visualize the base model below in Figure 3.1:

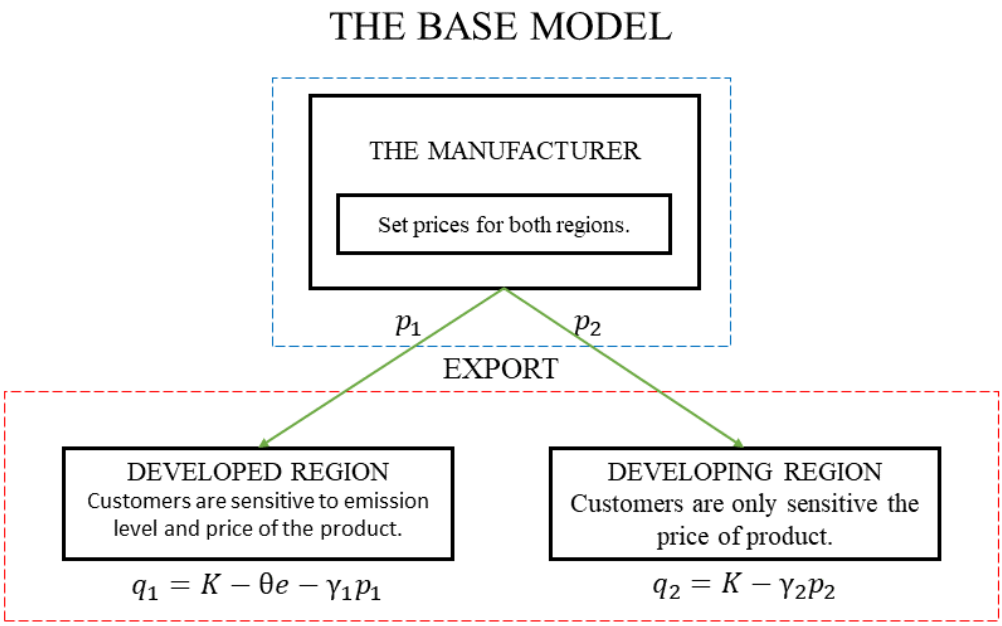


Figure 3.1: The Base Model

In the following section, we explain the Carbon Border Adjustment Mechanism (CBAM) model. We summarize the notation used throughout the thesis study below in Table 3.1.

Table 3.1: Notation

Variables	
p_i	Unit product price set by the manufacturer at region i, $i = 1, 2$;
α	Emission abatement level of the manufacturer; $0 \leq \alpha \leq$ e;
Δ	Government's subsidy fraction for the manufacturer's emission reduction effort; $0 \leq \Delta \leq 1$;
Parameters	
K	Base market potential; $K > 0$;
γ_i	Price sensitivity of customers in regions; $\gamma_i > 0$, and $i = 1, 2$;
θ	Emission sensitivity of customers in the developed region; $\theta > 0$;
β	Manufacturer's unit production cost increase with emission reduction; $\beta \geq 0$;
y	Manufacturer's cost factor to invest in technology; $y \geq 0$;
t	Tax per unit emission in the developed region ; $t > 0$;
c	Manufacturer's unit production cost; $c > 0$;
e	Manufacturer's initial unit emission level; $e > 0$;
Φ_1	Marginal benefit of the government over the total production; $\Phi_1 \geq 0$;
Φ_2	Marginal cost of the government over the total carbon emission; $\Phi_2 \geq 0$;
Φ_3	Weight for the manufacturer's profit on the government's objective function; $0 \leq \Phi_3 \leq 1$;

3.2 The Carbon Border Adjustment Mechanism (CBAM) Model

In this section, we first introduce the settings of the CBAM model and then explain the manufacturer's and the government's problems.

In the CBAM model, the developed region requires companies to pay an emission tax per emission unit for all products imported to the region. The initial emission

level of the manufacturer is exogenous and represented by e. The manufacturer has to pay a carbon tax t based on the unit emission level. The developing region does not have a carbon regulation on traded goods.

The manufacturer can invest in greener technology to reduce unit emission level e by α. To do this, the manufacturer must pay a lump-sum investment cost. We use a quadratic cost function $y\alpha^2$, which demonstrates diminishing returns. Similar structures are used to represent the cost of technology for emission reduction. For instance, Chen et al. (2019) and X. Huang et al. (2021) also use a quadratic cost function to represent investment where reducing emission becomes more difficult and expensive as investment increases. In both studies, a parameter for the cost factor of technology investment is defined, and they use a quadratic form of emission reduction or effort to represent the overall cost of technology investment.

We assume that the unit production cost increases with the emission reduction level. When the manufacturer reduces the emission level more, it faces a higher unit production cost. Investing in technology will affect the manufacturer's operations, and once the manufacturer reduces its unit emission level, unit production costs increase for both regions. Drake et al. (2016) and Chen et al. (2019) model similar dynamics in their papers. Drake et al. (2016) refer to this increase in the unit cost as the variable cost of investing in technology. To show an increase in unit production cost related to α, we define a parameter $\beta \geq 0$.

In this model, the local government may subsidize the manufacturer to support its green technology adoption effort. The government subsidizes the manufacturer by bearing Δ rate of the technology investment cost, where $\Delta \in [0, 1]$, hence, the manufacturer incurs only the $1 - \Delta$ rate of the investment cost. We assume that the local government does not impose any additional regulations on carbon emissions.

We define the sequence of events in the CBAM model as follows:

1. The government decides the subsidy rate of Δ for the manufacturer's investment on emission reduction effort.

2. The manufacturer decides the unit emission reduction level α.

3. The manufacturer sets the prices for both regions simultaneously.

Since the manufacturer can reduce its unit emission level e by investing in technology, and customers in the developed region are sensitive to unit emission levels, there is an opportunity to attract more customers who will respond to the final unit emission level $(e - \alpha)$. However, customers in the developing region are not sensitive to emission level, therefore the demand function for this region remains the same as in the base model. We define demand functions for the CBAM model as follows:

$$q_1(p_1) = K - \theta(e - \alpha) - \gamma_1 p_1, \quad q_2(p_2) = K - \gamma_2 p_2$$

where $(e - \alpha)$ represents the final unit emission level of the product. Figure 3.2 visualizes the CBAM model.

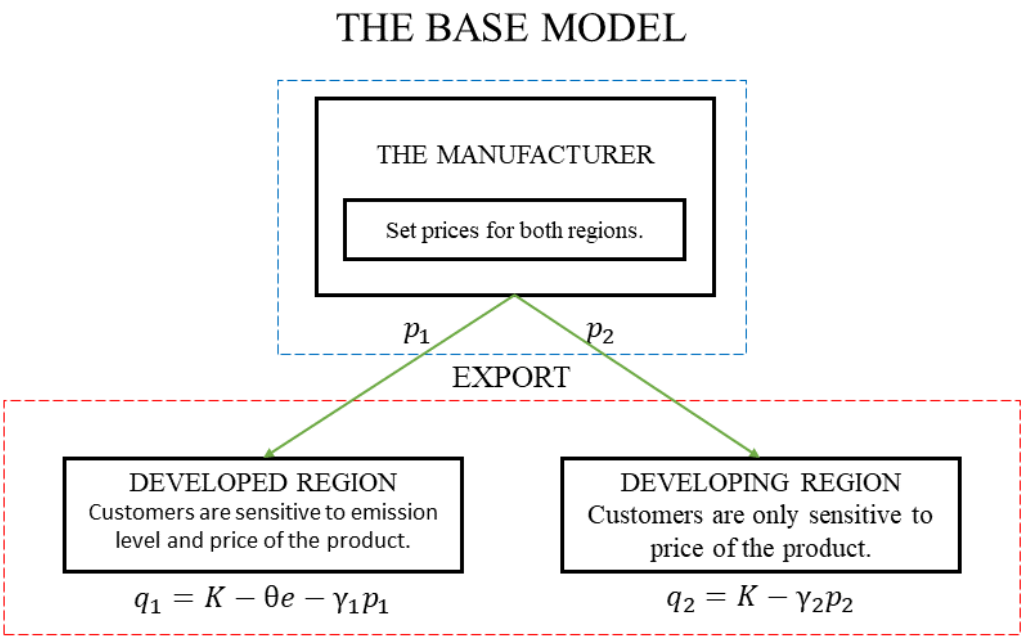


Figure 3.2: The CBAM Model

3.2.1 The Manufacturer's Problem in the CBAM Model

In the CBAM model, the manufacturer makes decisions in two stages. Since investing in technology is a long-term decision for a company, the manufacturer sets α first. After investing in technology, the manufacturer sets prices for both regions. The manufacturer faces the same capacity constraint in this model as in the base model. We define the manufacturer's problem as follows:

$$\begin{aligned} \underset{p_1,p_2,\alpha}{\text{maximize}} \quad & \Pi_{cbam}(p_1,p_2,\alpha) = p_1q_1(p_1) + p_2q_2(p_2) - (c+\beta\alpha)(q_1(p_1)+q_2(p_2)) \\ & - t(e-\alpha)q_1(p_1) - (1-\Delta)y\alpha^2 \\ \text{subject to} \quad & q_1(p_1) + q_2(p_2) \leq \Omega \\ & q_1(p_1), q_2(p_2) \geq 0 \end{aligned}$$

The first two terms of the objective function represent the total revenue, and the third shows the total production cost. The fourth term refers to the total tax cost that the regulated region requires. The final term explains the total cost of investment in technology in proportion to the emission reduction level. The manufacturer's production capacity unit is represented by a constraint.

3.2.2 The Government's Problem

In the CBAM model, the government's primary objective is to maximize the manufacturer's total production while reducing the environmental damage arising from production. Different approaches have been used to model governments' objective functions in the literature. For instance, Atasu et al. (2009) model a social planner that aims to maximize social welfare. They incorporate the manufacturer's profit, consumer surplus, total environmental hazard, and subsidy cost in the social planner's function. Chen et al. (2019) define a similar function for the government's objective. Similar to these studies, we define a government objective function that involves total production, the manufacturer's profit, total environmental hazard, and subsidy cost. We assume that the increase in the total quantity produced is related to growth in economic indicators, such as employment rate and export figures. We do not include a consumer surplus since, in our model, consumers are not from the domestic market.

Chen et al. (2019) define a parameter to show constant marginal benefit related to emission effort, and they assume that an increase in the manufacturer's emission effort turns into a positive environmental benefit. On the other hand, Atasu et al. (2009) define a parameter to represent the cost of each non-recycled product to the environment, and they measure the total environmental hazard. Raz and Ovchinnikov (2015) and Kraft et al. (2013) use a similar approach; they define constant marginal benefit or cost to measure total external or environmental benefit or cost. Similar to these studies, we define the parameter Φ_1 to express the constant marginal benefit of total production, hence $\Phi_1(q_1 + q_2)$ the local economic performance. The parameter Φ_2 represents the constant marginal cost of total carbon emissions. Thus, we measure the environmental hazard as $\Phi_2(e - \alpha)(q_1 + q_2)$. Finally, the parameter Φ_3 represents the weight of the manufacturer's profit function on the government's objective. We assume that $\Phi_1, \Phi_2 \geq 0$, and $0 \leq \Phi_3 \leq 1$. We define the government's problem as follows:

$$\begin{aligned} \underset{0 \leq \Delta \leq 1}{\text{maximize}} \quad & \Pi_{gov}(\Delta) = \Phi_1(q_1(p_1) + q_2(p_2)) - \Phi_2(e - \alpha)(q_1(p_1) + q_2(p_2)) \\ & + \Phi_3 \Pi_{cbam} - y\Delta\alpha^2 \end{aligned}$$

The first term in the objective function is for the total economic performance, and it represents the total benefits arising from production, such as export tax revenue, impact on employment rate, and GDP. The second term shows the potential environmental hazards of total carbon emissions due to production. The third term represents the government's weighted benefit from the manufacturer's profit. The final term is the government's subsidy cost.

CHAPTER 4

ANALYSIS

This chapter discusses the analytic results of the two models introduced in the previous chapter. First, we analyze the base model and continue our discussion with the results of the CBAM model.

4.1 Analysis of the Base Model

This section provides analytical results for the base model where the manufacturer simultaneously decides prices for the developed and developing markets.

We first solve the base model and find the optimal price decisions without capacity restriction Ω in the proposition below.

Proposition 4.1.1. *The optimal price decisions for the manufacturer without a capacity restriction are given by:*

$$p_1^* = \frac{K - \theta e}{2\gamma_1} + \frac{c}{2}, \quad p_2^* = \frac{K}{2\gamma_2} + \frac{c}{2}$$

Proposition 4.1.1 indicates that, without any capacity limit, the manufacturer's price decisions are affected by customers' price and emission sensitivities. Increasing unit production cost c leads to the manufacturer setting higher prices. As expected, the price set for the developed market can be lower to compensate for the customer's emission sensitivity.

Next, we analyze the price decisions of the manufacturer under a capacity constraint, and to do that, we formulate it as a Lagrange function. The following equation demonstrates the Lagrangian function for the manufacturer's problem in the base model.

$$\begin{aligned}\mathcal{L}_{base}(p_1, p_2, \lambda) &= p_1 q_1(p_1) + p_2 q_2(p_2) - c(q_1(p_1) + q_2(p_2)) \\ &\quad + \lambda(\Omega - q_1(p_1) - q_2(p_2)) \\ &= p_1(K - \theta e - \gamma_1 p_1) + p_2(K - \gamma_2 p_1) - c(2K - \theta e - \gamma_1 p_1 - \gamma_2 p_2) \\ &\quad + \lambda(\Omega - 2K + \theta e + \gamma_1 p_1 + \gamma_2 p_2)\end{aligned}$$

Where $\lambda \geq 0$ is the Lagrange multiplier. Utilizing the Lagrangian function, we find the optimal price decisions as stated in the following proposition.

Proposition 4.1.2. *The price decisions of the manufacturer under a capacity constraint Ω is:*

$$(p_1^*, p_2^*) = \begin{cases} \left(\frac{K-\theta e}{2\gamma_1} + \frac{c}{2}, \frac{K}{2\gamma_2} + \frac{c}{2}\right) & \text{if} \quad \frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} \leq \Omega \\ \left(\frac{K-\theta e}{2\gamma_1} + \frac{2(K-\Omega)-\theta e}{2(\gamma_1+\gamma_2)}, \frac{K}{2\gamma_2} + \frac{2(K-\Omega)-\theta e}{2(\gamma_1+\gamma_2)}\right) & \text{if} \quad \frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} > \Omega \end{cases}$$

From Proposition 4.1.2, the capacity becomes non-binding when $\Omega \geq \frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2}$, and the manufacturer can set the prices as given in 4.1.1. However, when the capacity is tight, both market prices are adjusted up, and the quantities are down to stay within the capacity limit. Interestingly, prices are adjusted by the same amount, i.e., by $\frac{2(K-\Omega)-\theta e}{2(\gamma_1+\gamma_2)} - \frac{c}{2} > 0$ for both markets, independently of their individual price sensitivity or base market potentials (i.e., K vs. $K - \theta e$).

4.2 Analysis of the Carbon Border Adjustment Mechanism (CBAM) Model

This section explains the analytical result of the CBAM model, where the manufacturer and the local government make decisions sequentially. Sequence of events for the CBAM model is as follows:

1. The government decides the subsidy rate $\Delta, 0 \leq \Delta \leq 1$, for the manufacturer's emission reduction effort.
2. The manufacturer decides the unit emission reduction level α by investing in a greener technology.
3. The manufacturer sets the prices for both regions simultaneously.

The manufacturer makes decisions in two stages; therefore, we call the manufacturer's problem a two-stage manufacturer problem. We first analyze the manufacturer's price decision for a given α and Δ under a capacity constraint by backward induction. The manufacturer sets prices in the second stage, and consequently relative production volumes for both regions are determined in this stage. To analyze the second stage problem of the manufacturer, we define a Lagrangian function as below.

$$\begin{aligned}
\mathcal{L}_{cbam}(p_1(\alpha), p_2(\alpha), \lambda) &= p_1(\alpha)q_1(p_1(\alpha)) + p_2(\alpha)q_2(p_2(\alpha)) \\
&\quad - (c + \beta\alpha)(q_1(p_1(\alpha)) + q_2(p_2(\alpha))) \\
&\quad - t(e - \alpha)q_1(p_1(\alpha)) - y(1 - \Delta)\alpha^2 \\
&\quad + \lambda(\Omega - q_1(p_1(\alpha)) - q_2(p_2(\alpha))) \\
&= p_1(K - \theta(e - \alpha) - \gamma_1 p_1) + p_2(K - \gamma_2 p_2) \\
&\quad - (c + \beta\alpha)(2K - \theta(e - \alpha) - \gamma_1 p_1 - \gamma_2 p_2) \\
&\quad - t(e - \alpha)(K - \theta(e - \alpha) - \gamma_1 p_1) - y(1 - \Delta)\alpha^2 \\
&\quad + \lambda(\Omega - 2K - \theta(e - \alpha) - \gamma_1 p_1 - \gamma_2 p_2)
\end{aligned} \tag{4.1}$$

Where $\lambda \geq 0$ is the Lagrange multiplier. After defining the Lagrangian function in equation 4.1, we derive the manufacturer's optimal price decisions, in the proposition below.

Proposition 4.2.1. *For a given government subsidy rate* $0 \leq \Delta \leq 1$*, and emission reduction* $0 \leq \alpha \leq e$*, price decisions of the manufacturer are:*

$$(p_1^*(\alpha), p_2^*(\alpha)) = \begin{cases} \left(\frac{K-(e-\alpha)(\theta-t\gamma_1)+(c+\beta\alpha)\gamma_1}{2\gamma_1}, \frac{K+(c+\beta\alpha)\gamma_2}{2\gamma_2}\right) \\ \quad \textit{if} \quad \frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} \leq \Omega \\ \left(\frac{K-\theta(e-\alpha)}{2\gamma_1} + \frac{2(K-\Omega)-(e-\alpha)(\theta-t\gamma_2)}{2(\gamma_1+\gamma_2)}, \frac{K}{2\gamma_2} + \frac{2(K-\Omega)-(e-\alpha)(\theta+t\gamma_1)}{2(\gamma_1+\gamma_2)}\right) \\ \quad \textit{if} \quad \frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} > \Omega \end{cases}$$

The capacity becomes non-binding if $\frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} \leq \Omega$, according to Proposition 4.2.1. When the additional cost pressure due to production and tax is higher than the increased demand from emission reduction level the manufacturer's production volume decreases and capacity may become non-binding. When the capacity is binding, prices are adjusted by the same amount, i.e., by $\frac{2(K-\Omega)-(e-\alpha)(\theta+t\gamma_1)}{2(\gamma_1+\gamma_2)} - \frac{c+\beta\alpha}{2} > 0$ for both markets.

When the capacity is non-binding, the carbon border tax, t, and the emission sensitivity of customers in the developed region, θ, do not affect the manufacturer's price decision for the developing market, $(p_2^*(\alpha) = \frac{K+(c+\beta\alpha)\gamma_2}{2\gamma_2})$. However, when the capacity is binding, customers in the developing market are also affected by the carbon border tax and emission sensitivity of customers in the developed region.

If we compare the prices between the base and CBAM models under the non-binding capacity, the price for the developed market increases by $\frac{(e-\alpha)t\gamma_1+\beta\alpha\gamma_1}{2\gamma_1}$. This is due to the resulting tax cost and increased production cost with the emission reduction. For the developing market, on the other hand, price increases only due to unit emission reduction cost, i.e., $\frac{\beta\alpha}{2}$.

When the capacity is binding in the base model, it can be non-binding under CBAM. The carbon border tax may force the manufacturer to retrain from overproduction. Consequently, prices would decrease in both regions. However, the price change would be greater in the developing region than in the developed one. This difference in price changes can be expressed as $\frac{\theta\alpha+t(e-\alpha)}{2\gamma_1} > 0$.

We derive the manufacturer's optimal price decision for a given α, and Δ in the manufacturer's second stage problem. We continue our analysis with finding the optimal unit emission reduction level,α, of the manufacturer for a given government's subsidy rate Δ, $0 \leq \Delta \leq 1$.

Lemma 4.2.1. *The manufacturer's first stage profit function becomes a two piece function subject to following conditions.*

$$\Pi_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha)) = \begin{cases} \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha)) & \textit{if } \alpha \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)} \\ \\ \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha)) & \textit{otherwise.} \end{cases}$$

Where;

$$\begin{aligned} &\underset{0\leq\alpha\leq\bar{\alpha}}{\text{maximize}} \quad \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha)) = p_1^*(\alpha)q_1(p_1^*(\alpha)) + p_2^*(\alpha)q_2(p_1^*(\alpha)) \\ &-(c+\beta\alpha)(q_1(p_1^*(\alpha)) + q_2(p_2^*(\alpha))) - t(e-\alpha)q_1(p_1^*(\alpha)) - y(1-\Delta)\alpha^2 \end{aligned}$$

$$\begin{aligned} &\underset{\bar{\alpha}<\alpha\leq e}{\text{maximize}} \quad \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha)) = p_1^*(\alpha)q_1(p_1^*(\alpha)) + p_2^*(\alpha)q_2(p_1^*(\alpha)) \\ &-(c+\beta\alpha)(q_1(p_1^*(\alpha)) + q_2(p_2^*(\alpha))) - t(e-\alpha)q_1(p_1^*(\alpha)) - y(1-\Delta)\alpha^2 \end{aligned}$$

We define an emission reduction threshold for capacity as $\bar{\alpha} = \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$. This is the threshold on α beyond which the capacity constraint becomes binding under the optimal solution of the second stage manufacturer's problem. The capacity is binding when $\alpha > \bar{\alpha}$ for the manufacturer's second stage problem. Consequently, the manufacturer's first-stage profit function, $\Pi_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ becomes a two-piece function. $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ and $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ represent the manufacturer's first stage profit function for $\alpha \leq \bar{\alpha}$, $\alpha > \bar{\alpha}$, where capacity is non-binding and binding, respectively.

In the following lemma, we explain the behavior of the manufacturer's first-stage profit function.

Lemma 4.2.2. *For a given government subsidy rate* $\Delta, 0 \leq \Delta \leq 1$*;*

1. *If* $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ *is concave in* α *and, for* $\alpha_1^\circ = \frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2-4y(1-\Delta)\gamma_1+\beta^2\gamma_1\gamma_2}$, $\frac{\partial\Pi^1_{cbam}(\alpha,p_1^*(\alpha),p_2^*(\alpha))}{\partial\alpha} = 0$.

2. *If* $\Delta > 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ *is convex in* α.

3. *If* $\Delta \leq 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$, $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ *is concave in* α *and, for* $\alpha_2^\circ = \frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1}$, $\frac{\partial\Pi^2_{cbam}(\alpha,p_1^*(\alpha),p_2^*(\alpha))}{\partial\alpha} = 0$.

4. *If* $\Delta > 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$, $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ *is convex in* α.

According to Lemma 4.2.2, each piece of the manufacturer's profit function becomes concave or convex in α depending on the given Δ value. We define shortcut expressions for the concavity thresholds as $\Delta_1 = 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, and $\Delta_2 = 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$. The government's subsidy rate, Δ, strongly influences the manufacturer's profit function; therefore, it's unit emission reduction decision, α.

Lemma 4.2.3. $\Delta_2 - \Delta_1 = \frac{(\theta+(t-\beta)\gamma_1-\beta\gamma_2)^2}{4y(\gamma_1+\gamma_2)} \geq 0$.

Lemma 4.2.3 indicates that while the manufacturer's first piece of the profit function, $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$, can not be concave, when the second piece of the function, $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$, is convex in α, because $\Delta_1 \geq \Delta > \Delta_2$ is an empty set.

Next, we derive the optimal unit emission reduction decision of the manufacturer in the following proposition.

Proposition 4.2.2. *For a given government subsidy rate of technology investment* $0 \leq \Delta \leq 1$*, we characterize the manufacturer's optimal unit emission reduction level. We define* $\alpha' = min(max(0, \alpha_1^\circ), e)$*, and* $\alpha'' = max(0, min(\alpha_2^\circ, e))$*.*

Case 1. If $\Delta \leq \Delta_1$*, then*

I. If $\alpha_1^\circ, \alpha_2^\circ \leq \bar{\alpha}$*, then* $\alpha^*(\Delta) = min(max(0, \alpha_1^\circ), e)$

II. If $\alpha_1^\circ, \alpha_2^\circ > \bar{\alpha}$*, then* $\alpha^*(\Delta) = (0, min(\alpha_2^\circ, e))$

III. If $\alpha_1^\circ > \bar{\alpha} \geq \alpha_2^\circ$*, then* $\alpha^*(\Delta) = \bar{\alpha}$

IV. If $\alpha_2^\circ > \bar{\alpha} \geq \alpha_1^\circ$*, then*

(a.) If $\Pi^1_{cbam}(\alpha', p_1^*(\alpha'), p_2^*(\alpha')) - \Pi^2_{cbam}(\alpha'', p_1^*(\alpha''), p_2^*(\alpha'')) \geq 0$*, then* $\alpha^*(\Delta) = \alpha' = min(max(0, \alpha_1^\circ), e)$*, otherwise* $\alpha^*(\Delta) = \alpha'' = (0, min(\alpha_2^\circ, e))$*.*

Case 2. If $\Delta > \Delta_2$*, then*

I. If $\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=\bar{\alpha}} > 0$*,* $\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=0} > 0$*, then* $\alpha^*(\Delta) = e$

II. If $\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=\bar{\alpha}} \leq 0$*,* $\frac{\partial \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=e} \leq 0$*, then* $\alpha^*(\Delta) = 0$

III. Otherwise, if $\Pi^1_{cbam}(p_1^*(0), p_2^*(0), 0) - \Pi^2_{cbam}(p_1^*(e), p_2^*(e), e) < 0$*, then* $\alpha^*(\Delta) = e$*, otherwise* $\alpha^*(\Delta) = 0$*.*

Case 3. If $\Delta_2 \geq \Delta > \Delta_1$*, then*

I. If $\alpha_2^\circ \leq \bar{\alpha}$*, then* $\alpha^*(\Delta) = 0$

II. If $\alpha_2^\circ > \bar{\alpha}$*, then*

(a.) If $\Pi^2_{cbam}(\alpha'', p_1^*(\alpha''), p_2^*(\alpha'')) - \Pi^1_{cbam}(p_1^*(0), p_2^*(0), 0) \geq 0$*, then* $\alpha^*(\Delta) = \alpha'' = max(0, min(\alpha_2^\circ, e))$*, otherwise* $\alpha^*(\Delta) = 0$*.*

According to Proposition 4.2.2, when the government's subsidy rate is high enough, depending on the market conditions, the manufacturer either fully reduces emission or does not invest at all (Case 2). Even when the government covers investment costs completely, i.e., $\Delta = 1$, the manufacturer may choose not to reduce emissions when the unit production cost increases too much with the technology investment, and carbon border tax and emission sensitivity of customers are relatively low. Instead of reducing emissions, the manufacturer pays all carbon taxes and loses potential customers in the developed market. In this case, market conditions push the manufacturer to do nothing or complete emission reduction. Thus the government's intervene may be weak even when it offers a subsidy for the whole investment cost.

The manufacturer may be willing to reduce emissions despite the government's low subsidy under convenient market conditions (Case 1). The manufacturer reach some level of emission reduction, and the this level increases with Δ (α_1°, and α_2° increase with government's subsidy rate, $0 \leq \Delta \leq \Delta_1$). In this case, the government can incentivize the manufacturer to invest in higher reduction level by offering a higher subsidy rate. This result indicates that when case 1 holds, i.e., $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, the government can offer subsidy in a range for the manufacturer's emission reduction decision. In contrast, when Case 2 holds, the government is left to offer a specific rate of subsidy or do nothing.

The manufacturer does nothing when $\alpha_2^\circ \leq \bar{\alpha}$ under Case 3. Therefore, the government subsidy is ineffective. However, when $\alpha_2^\circ > \bar{\alpha}$ holds, the manufacturer may reduce emission under the given government subsidy.

The following Table 4.1 contains a summary of results stated in Proposition 4.2.2. In Figures 4.1, 4.2, and 4.3, we represent the manufacturer's first-stage profit function under different Δ cases referring to Proposition 4.2.2.

Table 4.1: Unit emission reduction decision of the manufacturer for a given Δ

	Conditions	**Result** (α^*)
Case 1: $\Delta \leq \min(\Delta_1, \Delta_2)$		
I.	$\alpha_1^\circ, \alpha_2^\circ \leq \bar{\alpha}$	$min(max(0, \alpha_1^\circ), e)$
II.	$\alpha_1^\circ, \alpha_2^\circ > \bar{\alpha}$	$max(0, min(\alpha_2^\circ, e))$
III.	$\alpha_1^\circ > \bar{\alpha} \geq \alpha_2^\circ$	$\bar{\alpha}$
IV.	$\alpha_2^\circ > \bar{\alpha} \geq \alpha_1^\circ$	
(a.)	$\Pi^1_{cbam}(\alpha', p_1^*(\alpha'), p_2^*(\alpha')) - \Pi^2_{cbam}(\alpha'', p_1^*(\alpha''), p_2^*(\alpha'')) \geq 0$	$min(max(0, \alpha_1^\circ), e)$
(a.)	Otherwise	$max(0, min(\alpha_2^\circ, e))$
Case 2: $\Delta > \max(\Delta_1, \Delta_2)$		
I.	$\frac{\partial \Pi^1_{cbam}(p_1^*(\alpha), p_2^*(\alpha), \alpha)}{\partial \alpha}\|_{\alpha=\bar{\alpha}} > 0, \frac{\partial \Pi^1_{cbam}(p_1^*(\alpha), (p_2^*(\alpha), \alpha)}{\partial \alpha}\|_{\alpha=0} > 0$	e
II.	$\frac{\partial \Pi^1_{cbam}(p_1^*(\alpha), p_2^*(\alpha), \alpha)}{\partial \alpha}\|_{\alpha=\bar{\alpha}} \leq 0, \frac{\partial \Pi^2_{cbam}(p_1^*(\alpha), p_2^*(\alpha), \alpha)}{\partial \alpha}\|_{\alpha=e} \leq 0$	0
III.	Otherwise	
(a.)	$\Pi^1_{cbam}(p_1^*(0), p_2^*(0), 0) - \Pi^2_{cbam}(p_1^*(e), p_2^*(e), e) \geq 0$	0
(a.)	Otherwise	e
Case 3: $\Delta_2 \geq \Delta > \Delta_1$		
I.	$\alpha_2^\circ \leq \bar{\alpha}$	0
II.	$\alpha_2^\circ > \bar{\alpha}$,	
(a.)	$\Pi^2_{cbam}(\alpha'', p_1^*(\alpha''), p_2^*(\alpha'')) - \Pi^1_{cbam}(0) \geq 0$	$max(0, min(\alpha_2^\circ, e))$
(a.)	Otherwise	0

Following Figure 4.1 represents the manufacturer's first stage profit function where both pieces are concave in α (Case 1). For instance, the light blue curve represents a potential function for the manufacturer's first stage problem where $\alpha_1^\circ, \alpha_2^\circ \leq \bar{\alpha}$ holds under the Case 1.

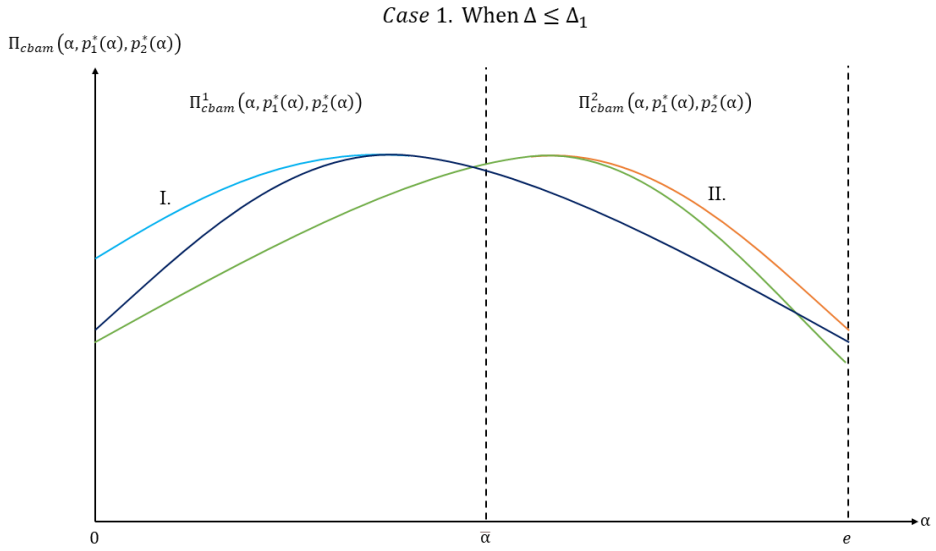


Figure 4.1: Case 1 from Proposition 4.2.2

Figure 4.2 represents the Case 2 where both pieces of the manufacturer's first stage profit function are convex in α. The orange curve represents the condition where $\frac{\partial \Pi^1_{cbam}(p_1^*(\alpha),p_2^*(\alpha),\alpha)}{\partial \alpha}|_{\alpha=\bar{\alpha}} \leq 0$, $\frac{\partial \Pi^2_{cbam}(p_1^*(\alpha),p_2^*(\alpha),\alpha)}{\partial \alpha}|_{\alpha=e} \leq 0$ holds under Case 2. Thus the optimal solution under this circumstances is equal to $\alpha^* = 0$.

Figure 4.3 represents the Case 3 where first piece of the manufacturer's first stage profit function is convex in α, while the second piece of the function is concave in α. The dark blue line is for the condition where $\alpha_2^\circ \leq \bar{\alpha}$ holds under Case 3, thus the optimal solution is equal to $\alpha^* = 0$.

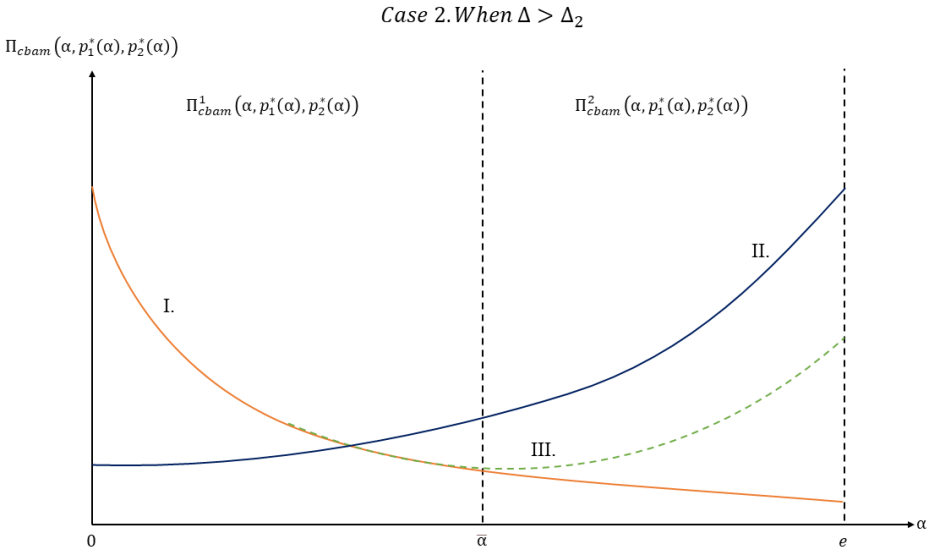


Figure 4.2: Case 2 from Proposition 4.2.2

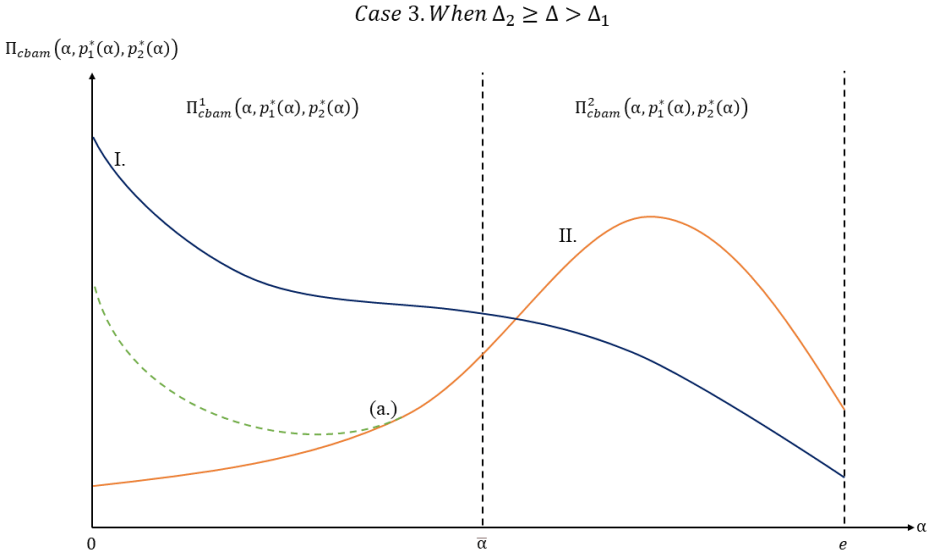


Figure 4.3: Case 3 from Proposition 4.2.2

4.2.1 Uncapacitated Problem for The CBAM Model

This part analyzes the manufacturer's unit emission reduction decision without a capacity restriction. In the following Proposition 4.2.3, we analyze the manufacturer's unit emission reduction decision α for the uncapacitated problem.

Proposition 4.2.3. *For a given government subsidy rate of technology investment Δ, the manufacturer's unit emission reduction decision, α, is as follows.*

(i.) If $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, *then*

- *(a) If* $\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1)) < 0$, *then* $\alpha^* = min(\frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)(K-\gamma_1(c-\beta e)-e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2-4y(1-\Delta)\gamma_1+\beta^2\gamma_1\gamma_2}, e)$
- *(b) Otherwise* $\alpha^* = 0$

(ii.) If $\Delta > 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, *then*

- *(a) If* $\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1)) < 0$, *then* $\alpha^* = e$.
- *(b) If* $\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1)) - e((\theta+(t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2) \geq 0$, *then* $\alpha^* = 0$.
- *(c) Otherwise, if* $2(\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1))) - e((\theta+(t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2) \geq 0$, *then* $\alpha^* = 0$, *otherwise* $\alpha^* = e$.

According to Proposition 4.2.3, if $\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1)) < 0$, the manufacturer always reduces its emission level, and increasing subsidy rate, Δ, motivates the manufacturer to engage in more significant reductions. Under this conditions, if $\Delta \geq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, then the manufacturer reduces emission fully $(\alpha^* = e)$.

If $\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K - \gamma_1(c-\beta e) - e(\theta+t\gamma_1)) \geq 0$, then the manufacturer does no investment, if $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$. Because the potential attraction of customers from the developed market and tax benefits derived from emission reduction fail to offset the increased unit costs incurred by technology investments. The government may need to offer a higher subsidy rate, i.e.

$\Delta > 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, to encourage the manufacturer for emission reduction.

While all other parameters are the same, the fact that the technology becomes more expensive (higher y values) makes the manufacturer more dependent on government subsidy. In this case, the manufacturer does no investment for a broader range of parameters or reduces emissions completely. Interestingly, even if the government provides a high subsidy when the technology is costly, the manufacturer may still do no investment. Here, β, the unit cost increase rate due to emission reduction, affects both markets, unlike other parameters, becomes a critical factor for the manufacturer's decision.

We analyzed and derived the analytical results for the base case and the manufacturer's problem in the CBAM model. Since it is not possible to define the government's problem in closed form, we analyze it by numerical experiments in Chapter 5. The following subsection introduces the short-run CBAM model, which helps analyze the transition between the base and CBAM models.

4.2.2 The Short Run CBAM Model

This section summarizes the results of the CBAM model in the short run. In our CBAM model, the manufacturer decides on unit emission reduction and sets prices for both regions afterward. We assume that the technology investment is a long-term decision for a company, while the price decision is a short-term decision. Therefore, we analyze the manufacturer's short-run decision. In this model, the manufacturer does not have a chance to consider technology investment. Moreover, there has yet to be any intervention from the local government. By analyzing this case, we look at how carbon border tax from the developed region could affect the manufacturer's prices and, consequently, its production volumes for both regions. This model also lays the groundwork for understanding the transition between the base and the CBAM cases.

For this model, the manufacturer's problem is as follows:

$$\begin{aligned}
\underset{p_1,p_2}{\text{maximize}} \quad & \Pi_{cbamsr}(p_1,p_2) = p_1q_1(p_1) + p_2q_2(p_2) - c(q_1(p_1) + q_2(p_2)) \\
& - teq_1(p_1) \\
\text{subject to} \quad & q_1(p_1) + q_2(p_2) \leq \Omega \\
& q_1(p_1), q_2(p_2) \geq 0
\end{aligned}$$

While first two terms represent the total revenue, the third term is the total production cost and the final term is for the total tax cost.

Following Tables 4.2, and 4.3 indicates the price decisions of the manufacturer, for the base and short run CBAM models.

Table 4.2: Price decisions of the Manufacturer for the Base Model

	p_1^*	p_2^*
If $\frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} \leq \Omega$	$\frac{K-\theta e}{2\gamma_1} + \frac{c}{2}$	$\frac{K}{2\gamma_2} + \frac{c}{2}$
If $\frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} > \Omega$	$\frac{K-\theta e}{2\gamma_1} + \frac{2(K-\Omega)-\theta e}{2(\gamma_1+\gamma_2)}$	$\frac{K}{2\gamma_2} + \frac{2(K-\Omega)-\theta e}{2(\gamma_1+\gamma_2)}$

Table 4.3: Price decisions of the Manufacturer for the Short Run CBAM Model

	p_1^*	p_2^*
If $\frac{2K-e(\theta+t\gamma_1)-c(\gamma_1+\gamma_2)}{2} \leq \Omega$	$\frac{K-e(\theta-t\gamma_1)}{2\gamma_1} + \frac{c}{2}$	$\frac{K}{2\gamma_2} + \frac{c}{2}$
If $\frac{2K-e(\theta+t\gamma_1)-c(\gamma_1+\gamma_2)}{2} > \Omega$	$\frac{K-\theta e}{2\gamma_1} + \frac{2(K-\Omega)-e(\theta-t\gamma_2)}{2(\gamma_1+\gamma_2)}$	$\frac{K}{2\gamma_2} + \frac{2(K-\Omega)-e(\theta+t\gamma_1)}{2(\gamma_1+\gamma_2)}$

We compare the results above; when the capacity is non-binding for both cases, the manufacturer's price decision for the developing region, p_2^*, does not change. The manufacturer increases the price for the developed region by $\frac{et}{2}$. However, when the capacity is binding in both models, the manufacturer lowers the price by $\frac{et\gamma_1}{2(\gamma_1+\gamma_2)}$ for the developing region and increases the price for the developed region by $\frac{et\gamma_2}{2(\gamma_1+\gamma_2)}$. When the tax pressure from the developed region gets higher, and the initial emission

level of the manufacturer is relatively high, the manufacturer lowers the price for the developing region. This means the manufacturer increases the sales for the developing region while it decreases for the developed region.

The difference in capacity utilization threshold between the two models is $\frac{et\gamma_1}{2}$. When the manufacturer fully utilizes its capacity under the base case, with carbon border tax, it may have a slack capacity in the short run. The carbon border tax may push the manufacturer to retrain from fully utilizing the capacity. Because the tax causes additional cost pressure, the manufacturer may choose to produce less than the capacity after the carbon border tax while using the capacity entirely in the base model. In this case, the price for the developed market is adjusted by $\frac{2(K-\Omega)-e\theta-(c+et)(\gamma_1+\gamma_2)}{2(\gamma_1+\gamma_2)}$, and for the developing market is adjusted by $\frac{2(K-\Omega)-e\theta-c(\gamma_1+\gamma_2)}{2(\gamma_1+\gamma_2)}$. Difference between change in prices (developed - developing) is $\frac{et}{2}$.

In any case, the manufacturer's profitability is higher under the base model because the tax imposed from the developed region causes additional costs.

If scarce capacity status is sustained under the carbon tax, then the total carbon emission does not change in the short run. Therefore, the carbon border tax only hurts the customers due to increased prices in the developed region. If the capacity is non-binding for both cases, the base model leads $\frac{e^2t\gamma_1}{2}$ more total emission than the short-run CBAM model. When the capacity is fully utilized in the base model, in the other model, it may not; in this case, the total emission will decrease with the carbon border tax.

CHAPTER 5

NUMERICAL STUDY

In this chapter, we conduct a numerical study to analyze the complete equilibrium including the government's decision for the subsidy rate. We compare the base and CBAM models for their environmental and economic performance. We evaluate the manufacturer's profit, total quantity, and total emission level, and the government's objective function value as performance measures. We answer our research questions where we state in Chapter 1 as follows: (1) How may CBAM affect a manufacturer's economic and operational decisions? (2) How does CBAM affect a manufacturer's environmental performance? (3) How does a local government support its economy against potential threats of CBAM?

This chapter organized as follows: we compare the manufacturer's profit, total quantity, and total emissions between the base and CBAM models in 5.2. To analyze the effect of CBAM on the manufacturer's economic and operational decisions, we compare the price levels and the manufacturer's profit in Sections 5.2 and 5.3. To examine how CBAM affects a manufacturer's environmental performance, we compare total emission levels in Sections 5.2 and 5.4. To understand the government's effect, we compare the results between CBAM and CBAM under $\Delta = 0$ cases.

5.1 Parameter Calibration

In this section, we explain how we determine the parameter values. We select base parameters by choosing specific values for each parameter in their ranges and show them in the following Table 5.1. We derive equilibrium results and comment on our

observations in 5.2 by utilizing the base parameter values.

Table 5.1: Base Parameter Values for Numerical Study

K	Ω	γ_i	θ	c	t
1.2×10^6	1×10^6	$\gamma_1 = 5.5 \times 10^3, \gamma_2 = 6 \times 10^3$	5×10^3	55	65
e	β	y	Φ_1	Φ_2	Φ_3
0.9	15	72×10^6	82.5	65	0.2

We create the base parameter values by choosing specific values for each parameter in their intervals. Table 5.2 presents our parameter values with their intervals. We utilize the data provided in the HeidelbergCement Case (Drake et al., 2014), and X. Huang et al. (2021) from the cement industry to conduct our numerical experiments.

Table 5.2: Parameter Values for Numerical Study

K	Ω	γ_i	θ	c	t
1.2×10^6	1×10^6	$[3 \times 10^3, 7 \times 10^3]$	$[3 \times 10^3, 7 \times 10^3]$	$[46, 58]$	$[0, 120]$
e	β	y	Φ_1	Φ_2	Φ_3
0.9	$[0, 20]$	$[60 \times 10^6, 75 \times 10^6]$	$[0, 120]$	$[0, 120]$	$[0, 1]$

For our numerical experiments, we use data from the cement industry, which is one of the carbon-intensive industries the EU regulates with CBAM. In October 2023, CBAM entered into the application in its transitional phase. Therefore, the cement industry has been regulated regarding emission levels with CBAM (European Commission, 2023).

We use the data from CEMBUREAU (2022) for the base market potential. According to the data, the EU imported approximately 10×10^6 tonnes of cement and clinker in 2022. Türkiye's world cement and clinker share in exports was 8.02% in 2019 (T.C. Sanayi ve Teknoloji Bakanlığı, 2020), and 15% in 2022 (PwC Turkey, 2024). Based on these data, we concentrate on a case where around 12% of the total import of a region is the base market potential, so set the base market potential for a region as $K = 1.2 \times 10^6\ tonnes$. We set the total production capacity of the manufacturer as

$\Omega = 1 \times 10^6\ tonnes.$

For the price sensitivity, we benefit from X. Huang et al. (2021), which they estimated; for the emission sensitivity, we use the same range as $\theta \in [3, 7 \times 10^3]$ by using price sensitivity. We set the unit production cost of cement as $c \in [46, 58]$ €/$(ton\ cement)$ by using the data from CEMBUREAU (2021).

The carbon tax price changes over time, and according to Trading Economics (2021), the highest value of carbon price in EU ETS was 105.73 $/(ton\ CO_2)$ at the time that report was published, therefore we define the range of carbon tax price as $t \in [0, 120]$.

For the initial emission level and the green technology costs, we use the data from X. Huang et al.(2021), and adjust as $e = 0.9\ (ton\ CO_2)/(ton\ cement)$. The unit cost of technology improvement and the lump-sum cost of investment are represented as 18.24 €/ $(ton\ CO_2)$ and $y = 73.22 \times 10^6$ € $(ton\ cement)^2/(ton\ CO_2)^2$ respectively. We consider the technology investment costs would decrease over time with new technologies. Therefore, we aim to minimize deviation from the base data while establishing the upper limit. We consider the $\beta \in [0, 20]$, and $y \in [60 \times 10^6, 75 \times 10^6]$.

We assume that the carbon tax paid by the manufacturer to a foreign country is a potential loss for the local government and may represent the cost of environmental hazard, so we use the range of parameter t to define the range for Φ_2. For Φ_1, we use the same range as Φ_2. Since Φ_3 represents a weight, it is already defined as $\Phi_3 \in [0, 1]$.

5.2 Numerical Results

We examine the equilibrium results and performances of the models by using the base parameter values. We summarized our equilibrium results in Table 5.3. In addition to the base and CBAM models, we examine the Short-Run CBAM model and the CBAM model without the local government intervention, i.e., $\Delta = 0$.

Table 5.3: Equilibrium Results with Base Parameter Values $(\Omega = 1,000,000)$

Results	Base	Short Run CBAM	CBAM $\Delta = 0$	CBAM
p_1^* (\$)	136.14	165.43	163.99	154.76
p_2^* (\$)	127.5	127.5	127.94	130.76
α^* (ton CO_2)/(ton cement)	-	-	0.06	0.43
Δ^*	-	-	-	0.810
Manufacturer's Profit (\$)	67.78×10^6	46.37×10^6	46.61×10^6	48.11×10^6
Government's Obj. Func. Value (\$)	-	-	29.52×10^6	38.31×10^6
Total Production (ton cement)	883,990	720,625	726,217	761,940
Total Emission (ton CO_2)	795,510	648,563	610,022	358,112

According to the equilibrium results with the base parameter values, we can make some observations. When the capacity is ample, and there is no intervention from the local government, the carbon border tax especially hurts the developed region because the manufacturer prefers to manipulate the price levels and production volumes for its profitability rather than reducing the emission level. However, in terms of prices, while the local government intervention in the CBAM model benefits the consumer in the developed market, the developing market faces the highest price in the four models. The manufacturer's emission reduction level is significant only with the government's subsidy. Without local government intervention, teh manufacturer refrains from a significant investment and the developed market faces very high price levels with the CBAM. The local government subsidy helps to reduce the total emissions and the price level for the developed market. On the other hand, the government intervention hurts the developing market with respect to price level due to increased costs. Consequently, the developed region benefits from the local government intervention. Even though the region enforces the carbon border tax, the region does not face a significant price hike. Although the developing region has no environmental

regulation, it suffers from CBAM when the government subsidizes the manufacturer for the technology investment.

While CBAM damages the manufacturer's profit significantly, it is not always effective in reducing the total emission level. If the local government does not subsidize the manufacturers, the total emission level decreases due to reduced production. In essence, the developed region's imposed carbon tax on imports results in price hikes within the region rather than effectively curbing emission levels. However, a significant decrease in total emissions is observed with the government intervention. At the same time, total production is also increasing. Here, the government prefers to subsidize the manufacturer. As a result, CBAM is more effective only with local government intervention.

We study the same setting under the total production capacity of $\Omega = 700,000$ and summarize the results in Table 5.4. The tight capacity causes an increase in prices in each model compared to the excess capacity case. Allocating production volume becomes more challenging for the manufacturer, leading to higher prices. However, when the capacity is binding, CBAM benefits the developing market in the short run with respect to price level. With the local government's intervention under CBAM, the price level for the developed market decreases and, the developing market price increases.

Table 5.4: Equilibrium Results with Base Parameter Values ($\Omega = 700,000$)

Results	Base	Short Run CBAM	CBAM $\Delta = 0$	CBAM
p_1^* (\$)	155.15	167.23	166.31	161.32
p_2^* (\$)	143.14	129.29	130.17	135.01
α^* (ton CO_2)/(ton cement)	-	-	0.06	0.36
Δ^*	-	-	-	0.815
Manufacturer's Profit (\$)	64.91×10^6	46.33×10^6	46.55×10^6	47.73×10^6
Government's Obj. Value (\$)	-	-	28.64×10^6	35.19×10^6
Total Production (ton cement)	700,000	700,000	700,000	700,000
Total Emission (ton CO_2)	630,000	630,000	588,000	378,000

Compared to the uncapacitated case, the manufacturer's unit emission reduction level is less when the capacity is binding in the CBAM model. This result indicates that the manufacturer becomes less inclined to reduce emissions when the production volume tightens. In fact, every model under tightened capacity causes lower total emissions since the production volume is lower than the uncapacitated case. When comparing the outcomes of CBAM models, we observe that despite lower total production due to capacity restriction, the total emission is higher. This result underscores that the manufacturer is more inclined to must and reduce emission levels he has a larger values and sales at stake. Parallel to the manufacturer, the government's subsidy rate is also lover in the capacitated case, mainly because the manufacturer is not motivated to invest easily.

Our results show that the manufacturer's emission reduction level is very low under base parameter values without local government intervention. Even though the total emission level decreases without subsidy, this happens mainly due to the reduced total production, not the reduced unit emission level. Therefore, local government intervention is crucial for significantly reducing emission levels. We ask the following question: Would government intervention still be crucial for a significant emission reduction level if we adjust to another setting with a higher carbon border tax and lower technology costs? To answer that, we adjust the carbon border tax level to the highest value, $t = 120\$$ and update the technology investment cost factor to the lowest value, $y = 60 \times 10^6$ € $(ton\ cement)^2/(ton\ CO_2)^2$. We also update the unit emission reduction cost to be lower than the base case, $\beta = 5$ €/ $(ton\ CO_2)$. The other parameter values remain the same as in the base parameter values.

According to equilibrium results (5.5), the emission reduction level without a government subsidy is still significantly lower compared to reduction level under the government intervention, even with the lower technology costs and the highest tax level. If we compare the equilibrium results of CBAM under $\Delta = 0$ model with the same model in 5.3, the total emission level significantly reduces, and the total production also decreases substantially, but the emission reduction level is not (0.06 vs 0.18). Once the government offers a subsidy, the manufacturer reduces the emission level fully, and the subsidy rate is not even aggressive, i.e., $\Delta^* = 0.55$ in the equilib-

rium. However, with the base parameter values, even though the government offers a higher subsidy ($\Delta^* = 0.81$), the emission reduction level only equals $\alpha^* = 0.43$ in the equilibrium. This outcome indicates that when the carbon border tax is very high, and the technology costs are low, the government's intervention leads to the best environmental performance with a lower subsidy rate. In addition, the government's objective function value is at the highest level. Also, the price levels for both regions are at their lowest value in all equilibrium results for the CBAM model.

Table 5.5: Equilibrium Results with Base Parameter Values Version 2

Results	Base	Short Run CBAM	CBAM $\Delta = 0$	CBAM
p_1^* (\$)	136.14	190.19	176.76	138.84
p_2^* (\$)	127.5	127.5	127.96	129.75
α^* (ton CO_2)/(ton cement)	-	-	0.18	0.9
Δ^*	-	-	-	0.552
Manufacturer's Profit (\$)	67.78×10^6	35.60×10^6	36.98×10^6	42.44×10^6
Government's Obj. Value (\$)	-	-	30.35×10^6	52.44×10^6
Total Production (ton cement)	$883,990$	$584,500$	$639,970$	$857,875$
Total Emission (ton CO_2)	$795,510$	$526,050$	$468,778$	0

where $t = 120$, $y = 60 \times 10^6$ and $\beta = 5$.

Consequently, CBAM introduced by the developed region is insufficient to encourage the manufacturer to must and reduce unit emissions, and damages the customers in the region because of higher prices. However, with the local government subsidy, CBAM becomes an effective tool for reducing unit emission level and total emissions. Moreover, the local government subsidy also benefits the developed region regarding price level. The developing region, however, suffers due to incrased price for a greener but costly product.

We further investigate our results in the following sections by utilizing parameter ranges we summarized in Table 5.2. First, we analyze the effect of different parameters on the manufacturer's profitability. Next, we focus on the environmental performance.

5.3 The Manufacturer's Profitability

We examine the effect of each parameter on the manufacturer's profit by changing their range while the rest of the parameter values remain the same as in their base values.

We first analyze the effect of capacity limit Ω on the manufacturer's profitability. We analyze the percentage change of the manufacturer's profit in the equilibrium between the base model and the other three models (Short Run CBAM, CBAM) $\Delta = 0$, CBAM with respect to capacity constraint, Ω. To show the percentage change between each model with the base model, we use $\%\Gamma$; for instance, $\%\Gamma(\Pi_{CBAM})$ represents the percentage change between the CBAM and base model in terms of the manufacturer's profit level in the equilibrium, and the formulation of it is as follows: $\%\Gamma(\Pi_{CBAM}) = ((\Pi_{CBAM} - \Pi_{Base})/(\Pi_{Base}))\,100$. We use $\Delta = 0$ to show the CBAM $\Delta = 0$ case as a shortcut in the figures.

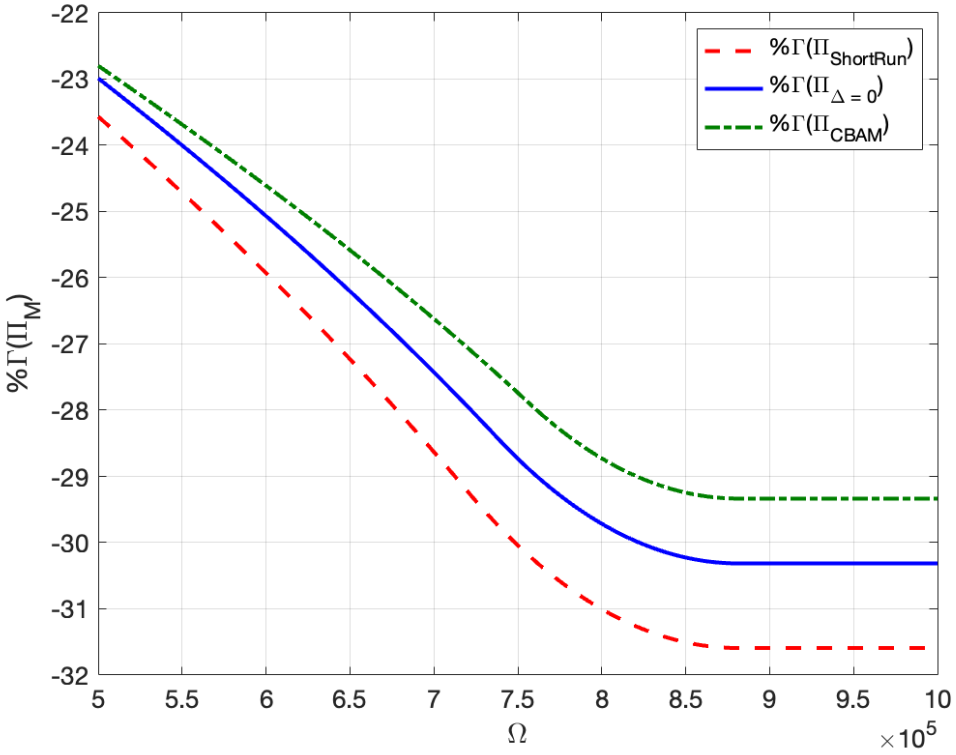


Figure 5.1: The Manufacturer's Profit Deviation via Capacity Constraint

As seen in Figure 5.1, compared to the base model, the manufacturer's profit level is lower in the other three cases. The deviation between the base and short-run CBAM regarding the manufacturer's profit is the highest in any capacity limit. The deviation between base and CBAM $\Delta = 0$ is close to the base and short-run CBAM. Even though the lowest deviation in the equilibrium is between the base and CBAM models, percentage change in the manufacturer's profit is notable compared to the base model. The deviation increases as capacity increases and stable when capacity is sufficient enough to be non-binding. Therefore, we see that the carbon border tax causes a significant decrease in the manufacturer's profitability, but local government intervention will reduce this deviation.

We continue our analysis by examining the effect of carbon border tax t on the manufacturer's profitability since it is the main argument of the CBAM model. We first analyze the manufacturer's unit emission reduction level and the government's subsidy rate with respect to carbon border tax under the CBAM model which can be seen in Figure 5.2.

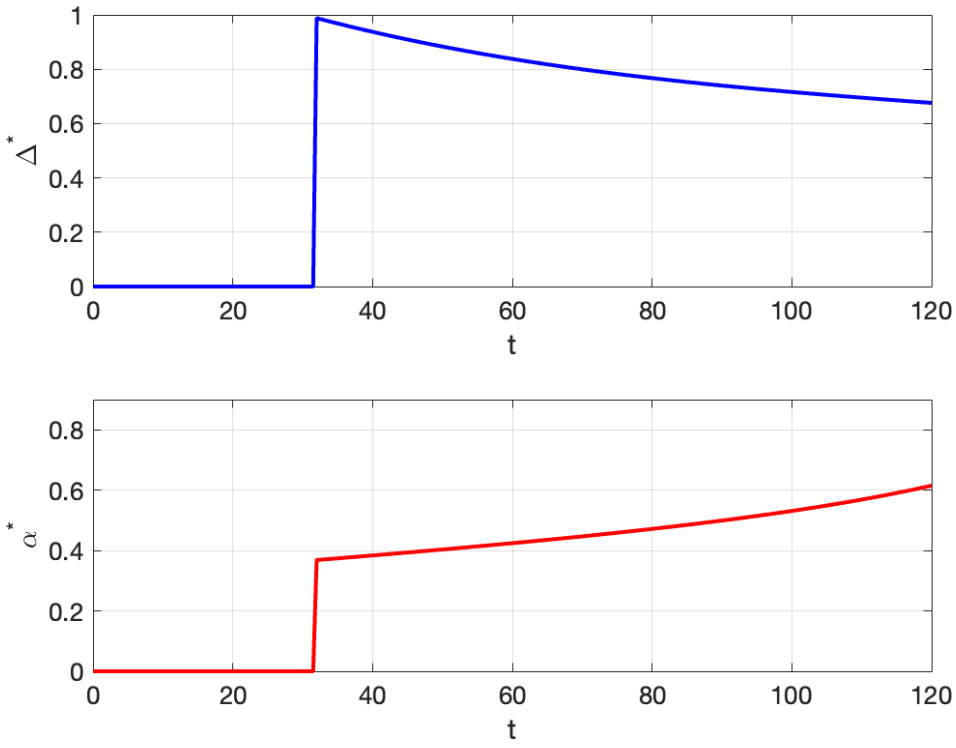


Figure 5.2: Δ^* and α^* via Carbon Border Tax in the CBAM Model

The carbon border tax is ineffective until a certain threshold, and the manufacturer chooses to do no investment. Therefore, the government does not offer any subsidy. However, after a certain level of carbon border tax, the manufacturer starts reducing emissions, and the government offers subsidy at the highest rate. As the manufacturer's incentive to invest increases with increased tax level, the government's subsidy rate decreases. Here, a carbon border tax below a certain level has no effect other than worsening market conditions. Therefore, a certain threshold must be crossed for the tax to be effective.

We continue to analyze the effect of carbon border tax on the performance metrics. We compare the percentage change in the equilibrium results of three models (Short Run CBAM, CBAM $\Delta = 0$, CBAM) with the base model with respect to carbon border tax, t, in Figure 5.3.

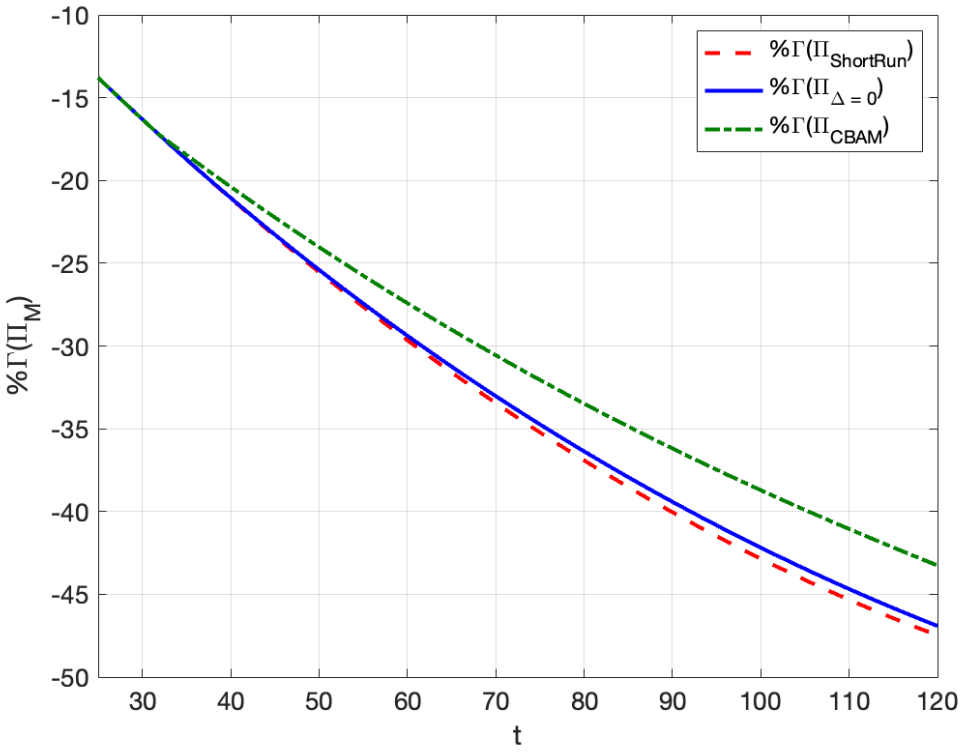


Figure 5.3: The Manufacturer's Profit Deviation via Carbon Border Tax

Carbon border tax hurts the manufacturer's profitability significantly compared to the base model. The manufacturer's profit loss in the short run CBAM and CBAM $\Delta = 0$ models are close to each other since the manufacturer's emission reduction level is significantly low without the local government subsidy. The local government subsidy helps to reduce the manufacturer's profit loss. However, the local government can only partially compensate the manufacturer's loss in profit. In essence, the carbon border tax is dysfunctional below a certain level. The local government subsidy helps the manufacturer to recover its loss in profit; however, in any case, CBAM dramatically hurts the manufacturer in terms of its profitability.

We continue our analysis with the effects of technology investment-related costs. First, we examine the effect of the unit emission reduction cost β on the manufacturer's emission reduction level and the government's subsidy rate. The manufacturer's unit emission reduction level decreases as β increases due to increased production cost. The government offers higher subsidy rates as β increases because the manufacturer leans toward reducing the emission level less as β increases.

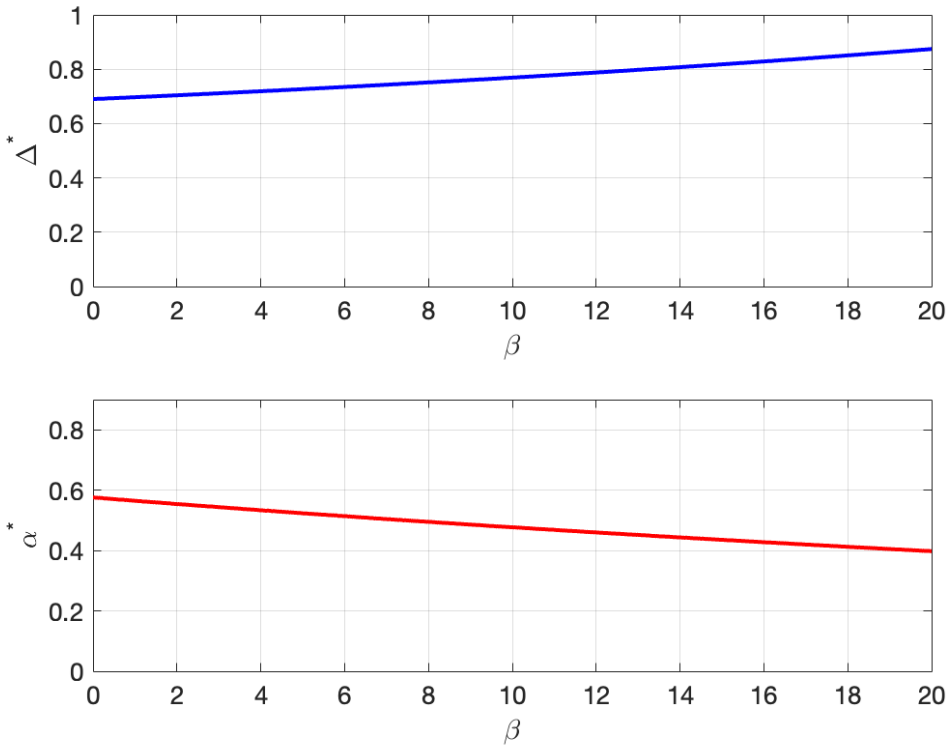


Figure 5.4: Δ^* and α^* via Unit Emission Reduction Cost in the CBAM Model

We also analyze the effect of the unit emission reduction cost, β, on the manufacturer's profitability between CBAM and CBAM $\Delta = 0$. As seen in Figure 5.5, the manufacturer's profitability between the two cases is at the highest level when β is small. However, the deviation between profits decreases as β increases due to increased production cost depending on unit emission reduction level.

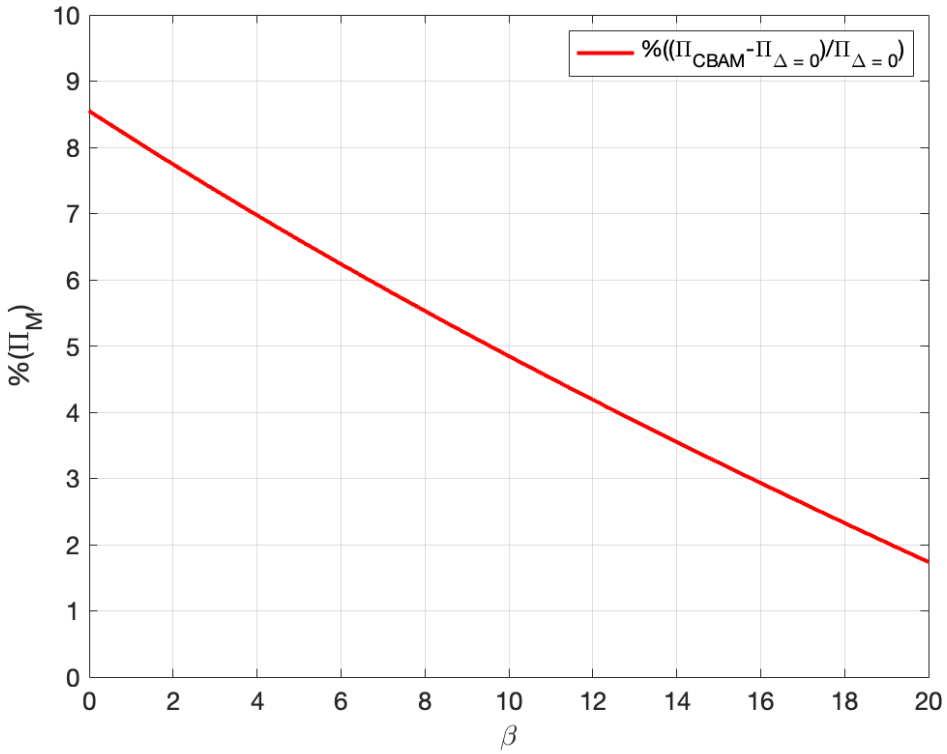


Figure 5.5: The Manufacturer's Profit Deviation via Unit Emission Reduction Cost

When we make the same analysis for the technology investment cost factor y, we observe that the government's subsidy rate is almost unaffected. However, the manufacturer's emission reduction level decreases as y increases (5.6). As y increases, the manufacturer faces a higher technology investment cost factor since the government's subsidy rate does not significantly change.

We also analyze at the price levels for both regions in Figure 5.7. The price for the developed market increases as y increases while the price in the developing market decreases. The manufacturer decreases its investment in the technology and increases the price for the developed market to bear the additional cost of carbon border tax.

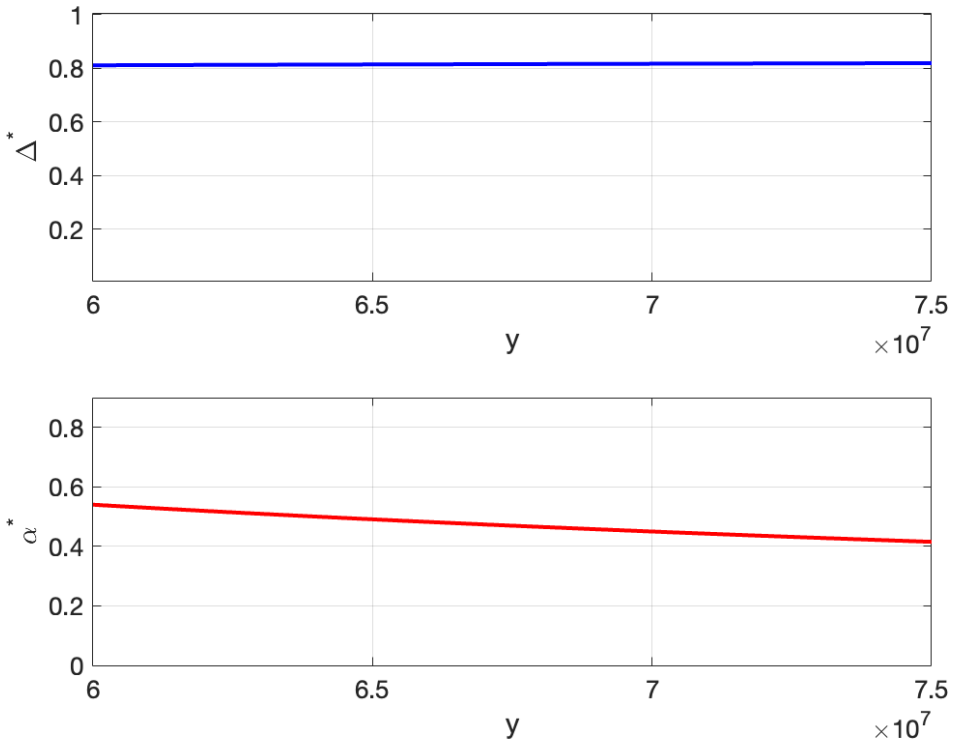


Figure 5.6: Δ^* and α^* via Technology Cost Factor in the CBAM Model

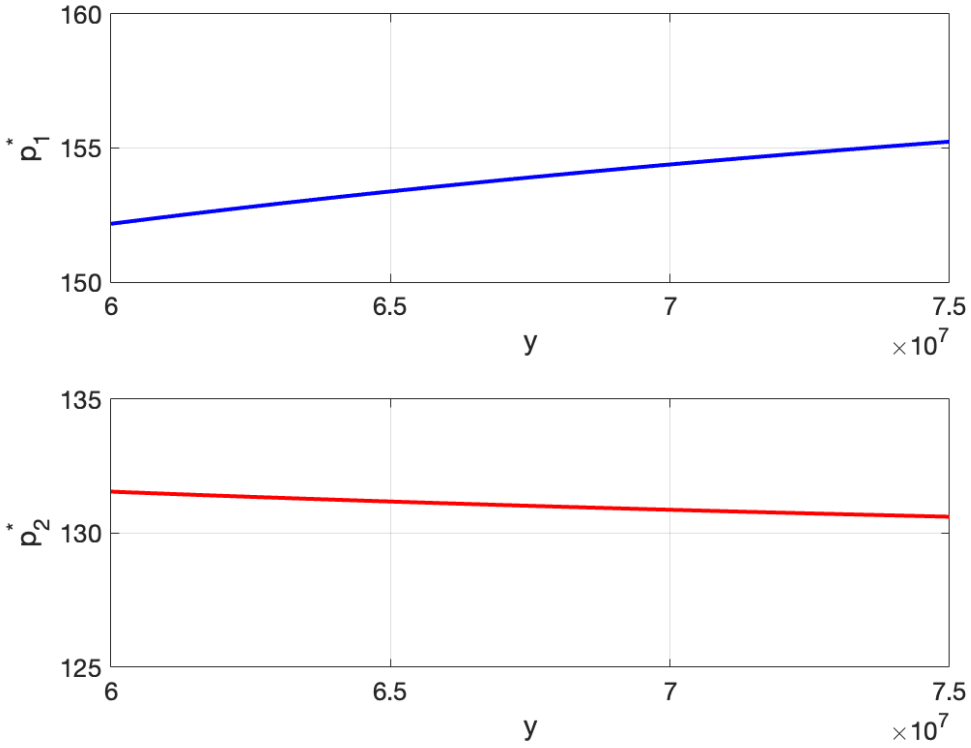


Figure 5.7: Price Levels via Technology Cost Factor in the CBAM Model

We investigate the effect of the technology cost factor, y, between CBAM and CBAM $\Delta = 0$ on the manufacturer's profitability in Figure 5.8. Regarding the technology cost factor, the manufacturer's profit deviation between the two models decreases slightly as y increases because the local government bears a high portion of the technology cost of investment. Therefore, the effect of the technology cost factor on the manufacturer's profit between the two models is low.

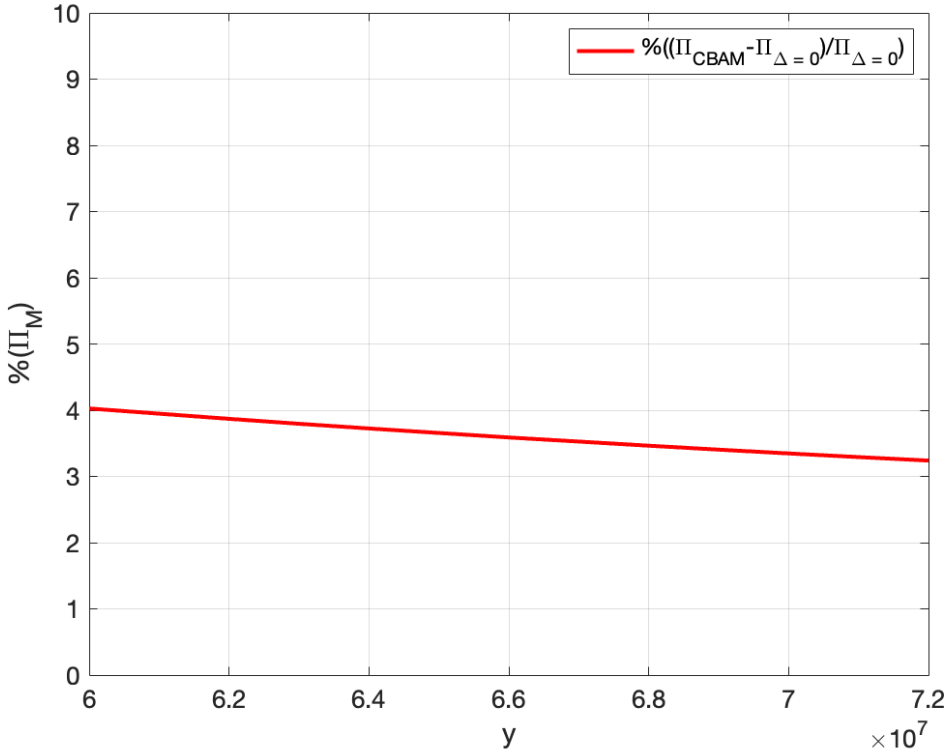


Figure 5.8: The Manufacturer's Profit Deviation via Technology Cost Factor

We further compare the manufacturer's profit concerning price sensitivities γ_1 and γ_2 in Figure 5.9. When the manufacturer faces lower price sensitivities in both regions, the profitability level is at its highest. If the customers have high price sensitivities in both regions, it adversely affects the manufacturer's profitability. If customers in one region are highly sensitive to price, then the manufacturer's profit increases when the other region's customers are less sensitive to price.

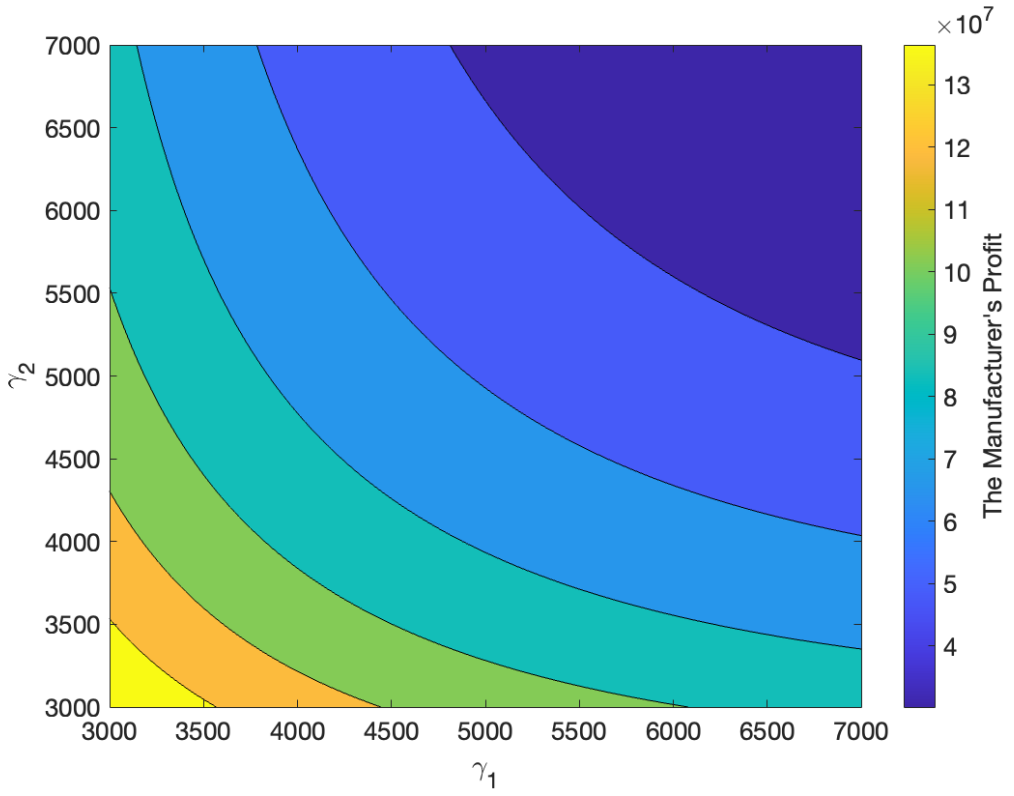


Figure 5.9: The Manufacturer's Profit Level via Price Sensitivities

5.4 Environmental Performance

This section investigates the potential factors that can affect environmental performance. To measure the environmental performance, we evaluate the total emission level. We also look at how total production is affected to analyze and understand the primary influence on the total environmental emission level for some parameters.

One main motivator for implementing a carbon border tax is to improve environmental performance. Therefore, we first analyze the relationship between the carbon border tax and environmental performance. As seen in Figure 5.10, after a certain level of tax, there is a significant decrease in total emissions. As we observe in Figure 5.2, the carbon border tax becomes effective after a certain threshold; before that threshold, the decrease in total emissions is due to a reduction in the total production. However, once the tax becomes effective, we observe a significant decrease in the total emission level, and it continues to decrease as the tax level increases. Also, we

find that the ratio of reduction in the total emission level with respect to tax is more than the ratio of reduction for total production. Therefore, the carbon border tax effectively helps reduce the manufacturer's total emission level after a certain tax level.

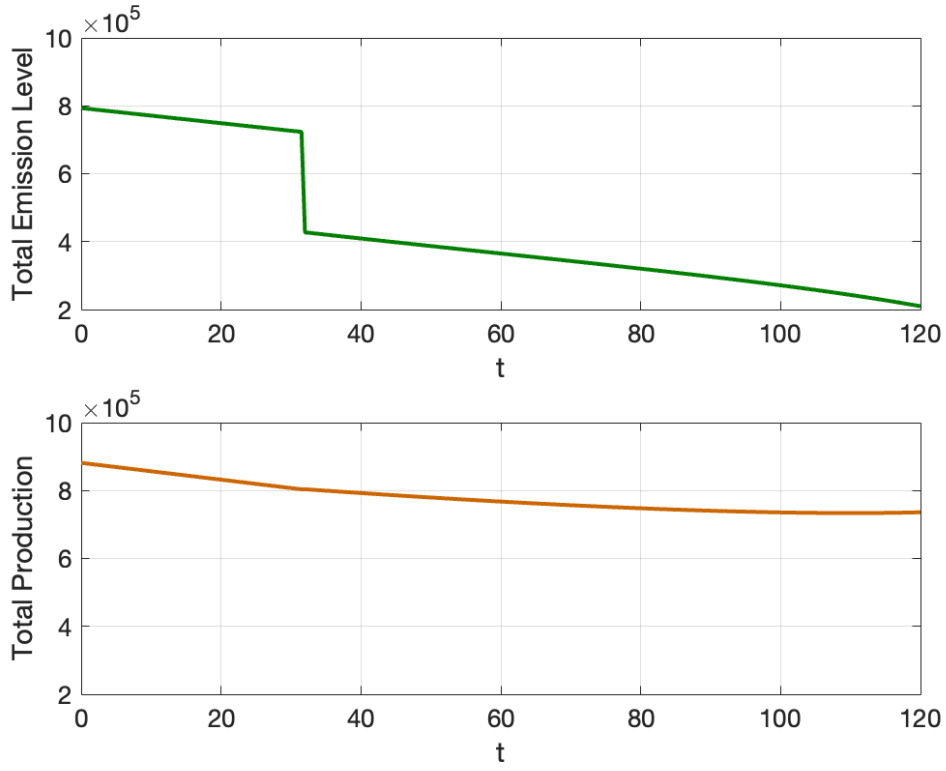
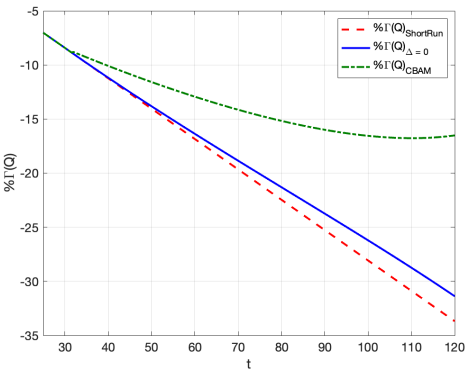
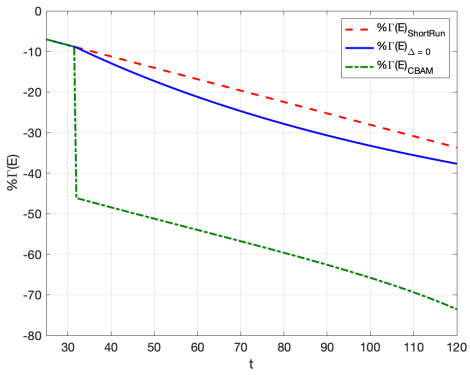


Figure 5.10: Total Emission and Production Levels via Carbon Border Tax in the CBAM Model

We continue to investigate the impact of carbon border tax on different cases. We analyze the percentage change in total production and emission level compared to the base model concerning carbon border tax in Figure 5.11. In any case, the total quantity is lower than the base model. However, the most minor deviation is from the CBAM model, which means the government subsidy leads to a higher total quantity level under CBAM. Regarding emission levels, the CBAM model with the government subsidy results in the lowest total emission level. The short-run CBAM and $\Delta = 0$ cases also have lower total emissions compared to the base model—however, the decrease in the emission levels is mainly due to decreased production instead of green technology investment. As a result, the local government's subsidy significantly improve total production and environmental performance against CBAM.



(a) Total Production Deviation ($\%\Gamma(Q)$)

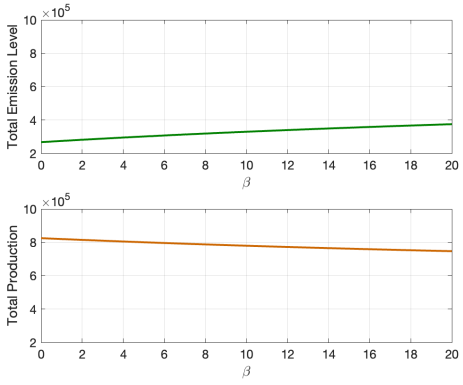


(b) Total Emission Level Deviation ($\%\Gamma(E)$)

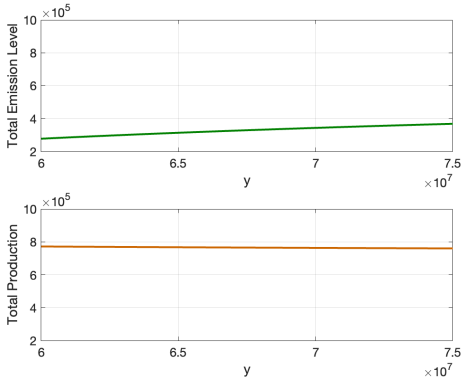
Figure 5.11: Total Emission and Production Levels Deviations via Carbon Border Tax

We examine the relation between total emission and the technology investment cost factor, y, and unit emission reduction cost β in Figure 5.12. If y increases, i.e., the lump-sum investment cost increases, the total emission level increases; on the other hand, the total production is almost unaffected (5.13b).

While total emission increases, total production decreases as β increases (5.13a). This result indicates that higher β values cause lower production and still worse environmental performance. Therefore, the nature of the technology investment becomes a significant factor in reducing environmental burden while sustaining production levels.



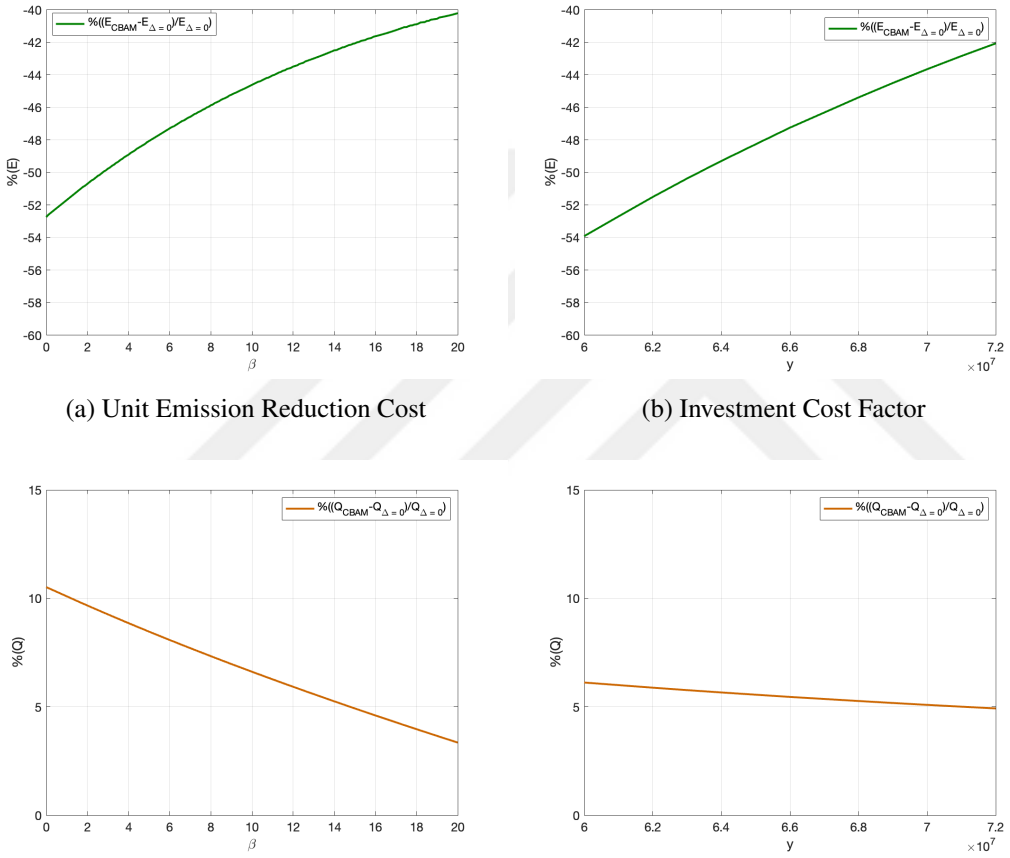
(a) Unit Emission Reduction Cost



(b) Investment Cost Factor

Figure 5.12: Total Emission and Production Levels via Technology Costs

We also compare the total production and emission levels deviation between CBAM and CBAM $\Delta = 0$ in Figure 5.13. Total emission level deviation, $\%(E)$, is affected by both technological costs significantly. The deviation of the total production, $\%(Q)$, is significant for the unit emission reduction cost, on the other hand, investment cost factor is less effective on the total production. Since the local government bears the high portion of the investment cost, the effect on the manufacturer's production level is minor. However, the manufacturer pays the unit emission reduction cost, therefore higher β leads to lower total production level.



(a) Unit Emission Reduction Cost

(b) Investment Cost Factor

(c) Unit Emission Reduction Cost

(d) Investment Cost Factor

Figure 5.13: Total Emission and Production Levels Deviation via Technology Costs

Finally, we examine the effect of Φ_1 and Φ_2 on the environmental performance in Figure 5.14. When Φ_1 and Φ_2 values increase, the total emission level decreases. When the marginal benefit for the government over the total production, Φ_1, is high, and the marginal cost for the government over the total emission level Φ_2, the total emission level is at the lowest value. Interestingly, higher Φ_1 does not necessarily cause

a worse environmental performance in all cases. However, when the ratio of Φ_1 over Φ_2 increases, the total emission level worsens. When Φ_2 is constant, the higher Φ_1 leads to better environmental performance. This result indicates that while the local government aims to increase overall production, the environmental performance does not worsen.

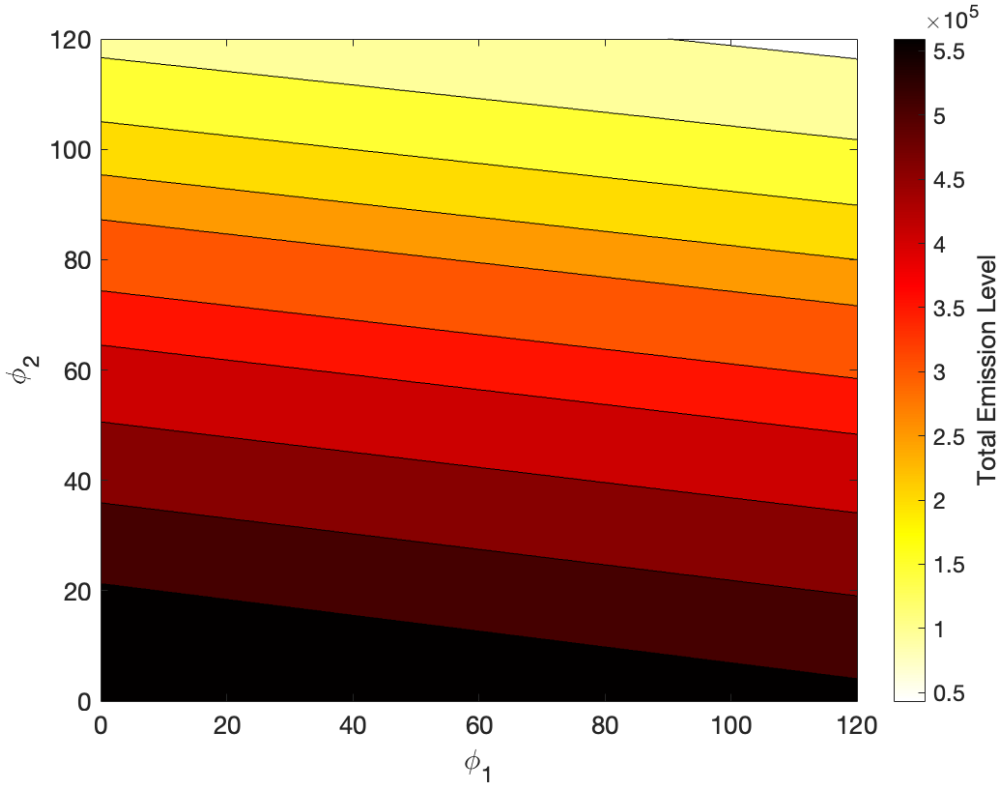


Figure 5.14: Total Emission Level with Respect to Φ_1 and Φ_2

In summary, CBAM is significantly effective with the local government intervention, and the local government subsidy, CBAM becomes an effective tool to regulate the manufacturer's overall emission level. Also, the local government subsidy benefits the developed market; conversely, CBAM with the local government subsidy negatively affects the developing market in terms ıf price. The manufacturer leans to adjust prices and production levels instead of reducing its emission level significantly when no subsidy is offered under CBAM. The local government subsidy not only helps to improve the manufacturer's environmental performance but also helps to increase production. The local government's subsidy is crucial for improving economic and environmental performance after the introduction of CBAM.

CHAPTER 6

CONCLUSION

In this thesis, we study a local government intervention under asymmetric emission regulations. We focus on a single manufacturer that exports its product to two regions (developed and developing) and faces a carbon border tax from the developed region. While we consider the customers in both regions sensitive to price, we assume that customers in the developed region are also sensitive to the emission level. We study two different models. The first is a base model, which serves as a benchmark for the CBAM model, our primary focus in this thesis study. We use a game theoretical setting, where the manufacturer adjusts prices and may invest in greener technology after the introduction of CBAM. The local government may subsidize the manufacturer for green technology investment. We also introduce a short run CBAM model where the manufacturer can only adjust price levels to react to the carbon border tax. This model helps us to understand the transition between the base and the CBAM models.

First, we analyze the base model and find that the prices increase by the same amount for both regions when the capacity is tightened. In the short run CBAM model, price levels always increase for the developed market. On the other hand, when the capacity is ample, the developing market is not affected by CBAM in the short run. If the capacity is limited, the developing region faces a higher price level due to CBAM. After the carbon border tax, the manufacturer may stop utilizing its capacity in full, in this case the price levels for both regions are adjusted.

In the CBAM model, prices increase by the same amount for both regions once the capacity is tightened, as in the base model. The high subsidy rate from the local gov-

ernment may not be effective under certain market conditions where the unit emission reduction cost is costly when tax rate is low. If the unit production cost increases and dominates the potential customer attraction due to emission reduction with a low carbon tax, the manufacturer may not be willing to invest in greener technology.

We conduct a numerical study and examine the equilibrium results of different cases, such as the base case, short-run CBAM, and the CBAM. We also investigate the CBAM model without local government intervention to understand its impact. First, we compare the equilibrium prices for different models and find that CBAM always causes price hikes for the developed region. However, the developing market is unaffected if capacity is ample in the short run scenario. Moreover, the limited capacity of CBAM benefits the developing market in the short run or without the local government intervention regarding the price level. Interestingly, with the local government intervention, the developed market reaps the benefits while the developing market suffers in pricing. In essence, CBAM hurts the developed market without the intervention of the local government. However, the developing market suffers from high prices if the local government intervenes for technology investment.

Our numerical study offers valuable insights into understanding the decisions and impacts of local governments. Without local government intervention to incentivize manufacturers to reduce emission levels, the effectiveness of CBAM is significantly diminished. Even if the carbon border tax is sufficiently high, and the technology is not expensive, the manufacturer's investment level remains very low without a local government subsidy. Nevertheless, the local government's subsidy is very effective under this scenario. CBAM helps to reduce total carbon emission levels even without a local government. However, the main reason for the reduced emission level is the reduced total production, not the lower unit emission level. This result implies that, in the absence of local government intervention, CBAM enhances environmental performance but adversely affects economic performance. On the other hand, the local government's subsidy helps to improve both the environmental and economic performance.

This study can be extended to include competition among manufacturers. The play-

ers' motivation for emission reduction might change in the competitive environment. The competitive setting can be adjusted between manufacturers in the same or different regions. Also, including a government budget for subsidization might be another extension with or without a competitive setting. Except for those, the local government might be studied regarding trade and carbon regulations to investigate the potential government actions against the CBAM in international trade.

REFERENCES

Acar, S., Atlı, A., & Yeldan, A. E. (2022). Potential effects of the eu's carbon border adjustment mechanism on the turkish economy. *Environment, Development and Sustainability*, *24*, 8162–8194. https://doi.org/10.1007/s10668-021-01779-1

Anand, K. S., & Giraud-Carrier, F. C. (2020). Pollution regulation of competitive markets. *Management Science*, *66*(9), 4193–4206. https://doi.org/10.1287/mnsc.2019.3413

Apple Inc. (2022, March). *Apple's four point seven billion in green bonds support innovative green technology*. https://www.apple.com/newsroom/2022/03/apples-four-point-seven-billion-in-green-bonds-support-innovative-green-technology/

Atasu, A., Van Wassenhove, L. N., & Sarvary, M. (2009). Efficient take-back legislation. *Production and Operations Management*, *18*(3), 243–258. https://doi.org/https://doi.org/10.1111/j.1937-5956.2009.01004.x

Bian, J., Zhang, G., & Zhou, G. (2020). Manufacturer vs. consumer subsidy with green technology investment and environmental concern. *European Journal of Operational Research*, *287*, 832–843. https://doi.org/https://doi.org/10.1016/j.ejor.2020.05.014

CEMBUREAU. (2021, December). *Co2 costs in eu cement production* [Accessed: March 20, 2024]. https://cembureau.eu/media/jpthbmva/co2-costs-in-eu-cement-production-december-2021.pdf

CEMBUREAU. (2022). *Eu cement industry trade statistics data*. Retrieved March 21, 2024, from https://www.cembureau.eu/media/js3ke4ou/eu-cement-industry-trade-statistics-2022.pdf

Chen, J.-Y., Dimitrov, S., & Pun, H. (2019). The impact of government subsidy on supply chains' sustainability innovation. *Omega*, *86*, 42–58. https://doi.org/https://doi.org/10.1016/j.omega.2018.06.012

Commission, E. (2023). *What is the EU ETS?* [Accessed: 16.01.2023]. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/what-eu-ets_en

Drake, D., Kleindorfer, P. R., & Van Wassenhove, L. N. (2014, March). Heidelbergcement: The baltic kiln decision [Revised June 2016, Case No. 614-025].

European Commission. (2019). *European commission press release: European green deal sets out how to make eu's economy sustainable, turning climate and environmental challenges into opportunities*. https://ec.europa.eu/commission/presscorner/detail/en/ip_19_6691

European Commission. (2023). *European commission press release: Commission proposes transitional phase for the carbon border adjustment mechanism*. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4685

Eyland, T., & Zaccour, G. (2012). Strategic effects of a border tax adjustment. *International Game Theory Review*, *14*(03), 1250016. https://doi.org/10.1142/S0219198912500168

Eyland, T., & Zaccour, G. (2014). Carbon tariffs and cooperative outcomes. *Energy Policy*, *65*, 718–728. https://doi.org/https://doi.org/10.1016/j.enpol.2013.10.043

Fu, K., Li, Y., Mao, H., & Miao, Z. (2023). Firms' production and green technology strategies: The role of emission asymmetry and carbon taxes. *European Journal of Operational Research*, *305*(3), 1100–1112. https://doi.org/https://doi.org/10.1016/j.ejor.2022.06.024

Hua, J., Lin, J., Wang, K., & Liu, G. (2023). Government interventions in new technology adoption to improve product greenness. *International Journal of Production Economics*, *262*, 108924. https://doi.org/https://doi.org/10.1016/j.ijpe.2023.108924

Huang, Zhou, W., Chen, J., & Chen, X. (2019). The government's optimal subsidy scheme under manufacturers' competition of price and product energy efficiency. *Omega*, *84*, 70–101. https://doi.org/https://doi.org/10.1016/j.omega.2018.04.006

Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report. contribution of working groups i, ii and iii to the sixth assessment report of the intergovernmental panel on climate change* (H. L. Core Writing

Team & J. Romero, Eds.). IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Jung, S. H., & Feng, T. (2020). Government subsidies for green technology development under uncertainty. *European Journal of Operational Research*, *286*(2), 726–739. https://doi.org/https://doi.org/10.1016/j.ejor.2020.03.047

Kraft, T., Zheng, Y., & Erhun, F. (2013). The ngo's dilemma: How to influence firms to replace a potentially hazardous substance. *Manufacturing & Service Operations Management*, *15*(4), 649–669. https://doi.org/10.1287/msom.2013.0440

Krass, D., Nedorezov, T., & Ovchinnikov, A. (2013). Environmental taxes and the choice of green technology. *Production and Operations Management*, *22*(5), 1035–1055. https://doi.org/https://doi.org/10.1111/poms.12023

McDonald, S., & Poyago-Theotoky, J. (2017). Green technology and optimal emissions taxation. *Journal of Public Economic Theory*, *19*(2), 362–376. https://doi.org/https://doi.org/10.1111/jpet.12165

Nations, U. (2023). *Causes and Effects of Climate Change* [Accessed: 16.01.2023]. https://www.un.org/en/climatechange/science/causes-effects-climate-change

PwC Turkey. (2024). *Dünyada ve türkiye'de çimento sektörü* [Accessed on April 4, 2024]. https://www.pwc.com.tr/tr/sektorler/i%CC%87nsaat-ve-muhendislik/pdf/dunyada-ve-turkiyede-cimento-sektoru.pdf

Raz, G., & Ovchinnikov, A. (2015). Coordinating pricing and supply of public interest goods using government rebates and subsidies. *Engineering Management, IEEE Transactions on*, *62*, 65–79. https://doi.org/10.1109/TEM.2014.2380999

Republic of Turkey Ministry of Trade. (2023). *Turkey-european union relations: The giant market next door*. https://ticaret.gov.tr/dis-iliskiler/avrupa-birligi/yani-basimizdaki-dev-pazar-avrupa-birligi#:~:text=AB%2C%202022%20y%C4%B1l%C4%B1nda%20103%2C1,aralar%C4%B1nda%20yapt%C4%B1%C4%9F%C4%B1%20ticaret%20hari%C3%A7%20tutuldu%C4%9Funda

Sanctuary, M. (2018). Border carbon adjustments and unilateral incentives to regulate the climate. *Review of International Economics*, *26*(4), 826–851. https://doi.org/https://doi.org/10.1111/roie.12344

Shao, L., Yang, J., & Zhang, M. (2017). Subsidy scheme or price discount scheme? mass adoption of electric vehicles under different market structures. *European Journal of Operational Research*, *262*(3), 1181–1195. https://doi.org/https://doi.org/10.1016/j.ejor.2017.04.030

Sinayi, M., & Rasti-Barzoki, M. (2018). A game theoretic approach for pricing, greening, and social welfare policies in a supply chain with government intervention. *Journal of Cleaner Production*, *196*, 1443–1458. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.05.212

Sunar, N., & Plambeck, E. (2016). Allocating emissions among co-products: Implications for procurement and climate policy. *Manufacturing & Service Operations Management*, *18*(3), 414–428. https://doi.org/10.1287/msom.2015.0572

T.C. Sanayi ve Teknoloji Bakanlığı. (2020). Cimento sektör raporu 2020 [Accessed: April 4, 2024].

The Guardian. (2020, January). *Microsoft aims to be carbon negative by 2030*. https://www.theguardian.com/technology/2020/jan/16/microsoft-carbon-emissions-negative-2030

Trading Economics. (2021). *Trading economics* [Accessed: March 20, 2024]. https://tradingeconomics.com/commodity/carbon

United Nations. (2023). *Sustainable Development Goals* [Accessed: 16.01.2023]. https://sdgs.un.org/goals#history

Zhong, J., & Pei, J. (2023). Carbon border adjustment mechanism: A systematic literature review of the latest developments. *Climate Policy*, *0*(0), 1–15. https://doi.org/10.1080/14693062.2023.2190074

APPENDIX A

APPENDICES

A.1 Proof of Proposition 4.1.1

The manufacturer maximizes its profit function based on decision variables p_1, and p_2. To prove the joint concavity of the manufacturer's profit function, we take the second-order partial derivatives of the profit function with respect to p_1 and p_2.

$$\frac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_1^2} = -2\gamma_1 < 0, \quad \frac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_2^2} = -2\gamma_2 < 0 \tag{A.1}$$

Since $\gamma_1, \gamma_2 > 0$, second-order partial derivatives of the profit function by p_1 and p_2 are negative. We analyze the determinant of the Hessian matrix as below:

$$\mathbf{H}_{\Pi_{base}(p_1,p_2)} = \begin{bmatrix} \dfrac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_1^2} & \dfrac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_1 \, \partial p_2} \\ \dfrac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_1 \, \partial p_2} & \dfrac{\partial^2 \Pi_{base}(p_1, p_2)}{\partial p_2^2} \end{bmatrix} = \begin{bmatrix} -2\gamma_1 & 0 \\ 0 & -2\gamma_2 \end{bmatrix}$$

The determinant of the Hessian matrix is $4\gamma_1\gamma_2 > 0$, and the second-order derivatives from equation A.1 are already negative. The manufacturer's profit function is jointly concave in p_1 and p_2. We derive optimal prices from first-order conditions:

$$\begin{aligned} \frac{\partial \Pi_{base}(p_1, p_2)}{\partial p_1} &= K - \theta e + c\gamma_1 - 2p_1\gamma_1, & p_1^* &= \frac{K - \theta e + c\gamma_1}{2\gamma_1} \\ \frac{\partial \Pi_{base}(p_1, p_2)}{\partial p_2} &= K + c\gamma_2 - 2p_2\gamma_2, & p_2^* &= \frac{K + c\gamma_2}{2\gamma_2} \end{aligned}$$

A.2 Proof of Proposition 4.1.2

From the previous Proof A.1, we already show that the $\Pi_{base}(p_1, p_2)$ is jointly concave in p_1, p_2. To utilize the Lagrangian function, we take first order partial derivatives with p_1, p_2 and λ.

$$\begin{aligned}
\frac{\partial \mathcal{L}_{base}(p_1, p_2, \lambda)}{\partial p_1} &= K - \theta e + c\gamma_1 - 2p_1\gamma_1 + \lambda\gamma_1 \\
\frac{\partial \mathcal{L}_{base}(p_1, p_2, \lambda)}{\partial p_2} &= K + c\gamma_2 - 2p_2\gamma_2 + \lambda\gamma_2 \\
\frac{\partial \mathcal{L}_{base}(p_1, p_2, \lambda)}{\partial \lambda} &= \Omega - 2K + \theta e + \gamma_1 p_1 + \gamma_2 p_2
\end{aligned} \tag{A.2}$$

We equate each partial derivative to 0 from equation A.2, and derive p_1^* and p_2^*. We find the Lagrange multiplier, λ, as $\frac{2(K-\Omega)-\theta e-c(\gamma_1+\gamma_2)}{\gamma_1+\gamma_2}$. To define a condition where the capacity constraint is non-binding, we set the Lagrange multiplier $\lambda = 0$, keeping the Ω value unchanged on the right side of the constraint. If $\frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} \leq \Omega$ the capacity constraint is non-binding, thus $p_1^* = \frac{K-\theta e+c\gamma_1}{2\gamma_1}$, and $p_2^* = \frac{K+c\gamma_2}{2\gamma_2}$. When, $\frac{2K-\theta e-c(\gamma_1+\gamma_2)}{2} > \Omega$, capacity constraint is binding, thus we find that, $p_1^* = \frac{K-\theta e}{2\gamma_1} + \frac{2K-2\Omega-\theta e}{2(\gamma_1+\gamma_2)}$ and $p_2^* = \frac{K}{2\gamma_2} + \frac{2K-2\Omega-\theta e}{2(\gamma_1+\gamma_2)}$.

A.3 Proof of Proposition 4.2.1

The manufacturer's second stage problem is jointly concave in p_1 and p_2. To prove jointly concavity, we took the second order partial derivative of $\Pi_{cbam}(p_1(\alpha), p_2(\alpha), (\alpha))$ with respect to p_1 and p_2. Analytic results are same as the proof of Proposition 4.1.1. After proving the jointly concavity, to find the optimal p_1 and p_2 we take the first order partial derivatives of the Lagrangian function as follows:

$$\begin{aligned}
\frac{\partial \mathcal{L}_{cbam}(p_1(\alpha), p_2(\alpha), \lambda)}{\partial p_1(\alpha)} &= K - (e-\alpha)(\theta - t\gamma_1) + (c+\beta\alpha)\gamma_1 - 2p_1\gamma_1 + \lambda\gamma_1 \\
\frac{\partial \mathcal{L}_{cbam}(p_1(\alpha), p_2(\alpha), \lambda)}{\partial p_2(\alpha)} &= K + (c+\beta\alpha)\gamma_2 - 2p_2\gamma_2 + \lambda\gamma_2 \\
\frac{\partial \mathcal{L}_{cbam}(p_1(\alpha), p_2(\alpha), \lambda)}{\partial \lambda} &= \Omega - 2K + (e-\alpha)\theta + p_1\gamma_1 + p_2\gamma_2
\end{aligned} \tag{A.3}$$

To find the optimal price decisions, we equate each equation in A.3 to 0. By doing that, we find the $\lambda = \frac{2(K-\Omega)-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{\gamma_1+\gamma_2}$. To find the threshold where the capacity constraint is non-binding, we equate the $\lambda = 0$, and keeping the Ω value unchanged on the right side of the constraint.

We find that, when $\frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} \leq \Omega$, the capacity constraint is non-binding; and $p_1^*(\alpha) = \frac{K-(e-\alpha)(\theta-t\gamma_1)+(c+\beta\alpha)\gamma_1}{2\gamma_1}$, and $p_2^*(\alpha) = \frac{K+(c+\beta\alpha)\gamma_2}{2\gamma_2}$.

We find that, when $\frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} > \Omega$ the capacity constraint is binding and; $p_1^*(\alpha) = \frac{K-\theta(e-\alpha)}{2\gamma_1} + \frac{2(K-\Omega)-(e-\alpha)(\theta-t\gamma_2)}{2(\gamma_1+\gamma_2)}$, and $p_2^*(\alpha) = \frac{K}{2\gamma_2} + \frac{2(K-\Omega)-(e-\alpha)(\theta+t\gamma_1)}{2(\gamma_1+\gamma_2)}$.

A.4 Proof of Lemma 4.2.1 and Lemma 4.2.2

Conditions stated in Proposition 4.2.1 can be represented in terms of α. The expression $\frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} \leq \Omega$, becomes, $\alpha \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$. And the latter condition becomes, $\alpha > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$.
Using the respective prices, we can formulate $\Pi_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ when $\alpha \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, and refer to it as $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$. To understand the function behaviour we take the second order partial derivative,

$$\frac{\partial^2 \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha^2} = \frac{(\theta + (t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2}{2\gamma_1} \tag{A.4}$$

From equation A.4 we derive a threshold for Δ where $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is concave in α, i.e., where the equation is non-positive.
Since $\gamma_1 > 0$, when $(\theta + (t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2 \leq 0$, , or equivalently $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is concave in α. After finding a threshold for concavity, we take the first order partial derivative of $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ and equate to zero to find the corresponding α value which maximizes the function.

$$\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha} = \frac{\alpha((\theta + (t-\beta)\gamma_1)^2 + 4y(-1+\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2)}{2\gamma_1}$$
$$- \frac{\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)((K - \gamma_1(c-\beta e) - (e(\theta+t\gamma_1))}{2\gamma_1}$$

equating the first order partial derivative to zero and find;

$$\alpha_1^\circ = \frac{\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)((K - \gamma_1(c-\beta e) - (e(\theta+t\gamma_1))}{(\theta + (t-\beta)\gamma_1)^2 + 4y(-1+\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2}$$

When $\alpha > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, we can similarly formulate the profit and refer to it as $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$. To analyze the function's behaviour, we follow the same steps above.

$$\frac{\partial^2 \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha^2} = \frac{(\theta + t\gamma_1)^2\gamma_2 - 4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1}{2\gamma_1(\gamma_1+\gamma_2)} \tag{A.5}$$

We derive the threshold for the concavity from equation A.5 as $(\theta+t\gamma_1)^2\gamma_2 - 4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1 \leq 0$, or equivalently, $\Delta \leq 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$.

After finding a threshold for concavity, we take the first order partial derivative of the $\Pi^2_{cbam}(\alpha, p^*_1(\alpha), p^*_2(\alpha))$ and equate to zero.

$$\frac{\partial \Pi^2_{cbam}(\alpha, p^*_1(\alpha), p^*_2(\alpha))}{\partial \alpha} = \frac{\alpha(\theta + t\gamma_1)^2\gamma_2 - 4y(1-\Delta))}{2\gamma_1(\gamma_1+\gamma_2)}$$
$$- \frac{(\theta + t\gamma_1)(K(\gamma_1-\gamma_2) - 2\Omega\gamma_1 + e(\theta+t\gamma_1)\gamma_2) + 2\beta\Omega(\gamma_1+\gamma_2)\gamma_1}{2\gamma_1(\gamma_1+\gamma_2)}$$

and find;

$$\alpha^\circ_2 = \frac{(\theta + t\gamma_1)(K(\gamma_1-\gamma_2) - 2\Omega\gamma_1 + e(\theta+t\gamma_1)\gamma_2) + 2\beta\Omega(\gamma_1+\gamma_2)\gamma_1}{4y(-1+\Delta)(\gamma_1+\gamma_2)\gamma_1 + (\theta+t\gamma_1)^2\gamma_2}$$

A.5 Proof of Lemma 4.2.3

$\Delta_1 = \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$, and $\Delta_2 = 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$.
$\Delta_2 - \Delta_1 = \frac{((\theta+(t-\beta)\gamma_1-\beta\gamma_2)^2}{4y(\gamma_1+\gamma_2)} \geq 0$. Since $y \geq 0$, and $\gamma_1, \gamma_2 > 0$, $4y(\gamma_1+\gamma_2) \geq 0$ always holds. $(\theta + (t-\beta)\gamma_1 - \beta\gamma_2)^2 \geq 0$ always holds, since it is a quadratic expression. Therefore, If $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$ holds, $\Delta > 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}$ does not hold, and $\Delta_1 \geq \Delta > \Delta_2$ is an empty set. Consequently, if we recall the conditions from Proof of Lemma 4.2.1 and Lemma 4.2.2, when $\Pi^1_{cbam}(\alpha, p^*_1(\alpha), p^*_2(\alpha))$ concave in α, $\Pi^2_{cbam}(\alpha, p^*_1(\alpha), p^*_2(\alpha))$ can not be convex in α.

A.6 Proof of Proposition 4.2.2

Since the manufacturer's profit function is a two piece-function, we prove that the profit function is continuous in α. To do that we compare the profits at $\bar{\alpha}$, and from that:

$$\Pi^1_{cbam}(\bar{\alpha}, p_1^*(\bar{\alpha}), p_2^*(\bar{\alpha})) - \Pi^2_{cbam}(\bar{\alpha}, p_1^*(\bar{\alpha}), p_2^*(\bar{\alpha})) = 0$$

Since profits are equal to each other at $\bar{\alpha}$, and each piece is already continuous in α, we say $\Pi_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is continuous in α.

To understand how the manufacturer's profit function behave, we look at the first order partial derivatives of $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$, and $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ at the threshold $\bar{\alpha} = \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$. We find that:

$$\left.\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}\right|_{\alpha=\bar{\alpha}} - \left.\frac{\partial \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}\right|_{\alpha=\bar{\alpha}} = 0$$

With these findings, for a given Δ, we derive the manufacturer's decision for $\alpha^* \in [0, e]$.

Case 1. When $\Delta \leq min\left(1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}, 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}\right)$, then $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$, and $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ are concave in α.

I. If $\alpha_1^\circ, \alpha_2^\circ \leq \bar{\alpha}$, then we get $\alpha^* = min(max(0, \alpha_1^\circ), e)$. This translates into the following form:

If $\frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(\Delta-1)\gamma_1+\beta^2\gamma_1\gamma_2} \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, and $\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then $\alpha^* = min(max(0, \frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(\Delta-1)\gamma_1+\beta^2\gamma_1\gamma_2}), e)$.

II. If $\alpha_1^\circ, \alpha_2^\circ > \bar{\alpha}$, then we get $\alpha^* = max(0, min(\alpha_2^\circ, e))$. This translates into the following form:

If $\frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(-1+\Delta)\gamma_1+\beta^2\gamma_1\gamma_2} > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, and

$\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then

$\alpha^* = max(0, min(\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1}, e))$.

III. If $\alpha_1^\circ > \bar{\alpha} \geq \alpha_2^\circ$, then $\alpha^* = \bar{\alpha}$. This translates into the following form:

If $\frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(-1+\Delta)\gamma_1+\beta^2\gamma_1\gamma_2} > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, and

$\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then

$\alpha^* = \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$.

IV. If $\alpha_2^\circ > \bar{\alpha} \geq \alpha_1^\circ$, then we compare the profits at $min(max(0, \alpha_1^\circ), e)$ and $max(0, min(\alpha_2^\circ, e))$, and choose the one that gives the maximum profit in the feasible range of e. The following form explains these conditions:

If $\frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(-1+\Delta)\gamma_1+\beta^2\gamma_1\gamma_2} \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, and

$\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then

(a.) If $\Pi^1_{cbam}(min(max(0, \alpha_1^\circ), e), p_1^*(min(max(0, \alpha_1^\circ), e)), p_2^*(min(max(0, \alpha_1^\circ)), e))$ $-\Pi^2_{cbam}(max(0, min(\alpha_2^\circ, e))), p_1^*(max(0, min(\alpha_2^\circ, e))), p_2^*(max(0, min(\alpha_2^\circ, e))) \geq 0$, then

$\alpha^* = min(max(0, \alpha_1^\circ), e)$

(b.) If $\Pi^1_{cbam}(min(0, max(0, \alpha_1^\circ))), p_1^*(min(max(0, \alpha_1^\circ)), e), p_2^*(min(max(0, \alpha_1^\circ)), e)$ $- \Pi^2_{cbam}(min(\alpha_2^\circ, e), p_1^*(min(\alpha_2^\circ, e)), p_2^*(min(\alpha_2^\circ, e))) < 0$, then

$\alpha^* = max(0, min(\alpha_2^\circ, e))$

Case 2. When $\Delta > max\left(1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}, 1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1}\right)$, then $\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is convex, and $\Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is convex in α.

I. If $\frac{\partial\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial\alpha}|_{\alpha=\bar{\alpha}} > 0$, $\frac{\partial\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial\alpha}|_{\alpha=0} > 0$, then we get $\alpha^* = e$.

This translates into the following form:

If $\frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}((\theta+(t-\beta)\gamma_1)^2-4y(1-\Delta)\gamma_1+\beta^2\gamma_1\gamma_2)-\beta\gamma_1(2K-$ $c(\gamma_1+\gamma_2)) + (\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1)) > 0$, and

$-\beta\gamma_1(2K - c(\gamma_1 + \gamma_2)) + (\theta + t\gamma_1)((K - \gamma_1(c - \beta e) - (e(\theta + t\gamma_1)) > 0$, then

$\alpha^* = e$.

II. If $\frac{\partial \Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=\bar{\alpha}} \leq 0$, $\frac{\partial \Pi^2_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))}{\partial \alpha}|_{\alpha=e} \leq 0$, then $\alpha^* = 0$. This translates into the following form:

If $\frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}((\theta+(t-\beta)\gamma_1)^2-4y(1-\Delta)\gamma_1+\beta^2\gamma_1\gamma_2)-\beta\gamma_1(2K-$

$c(\gamma_1 + \gamma_2)) + (\theta + t\gamma_1)((K - \gamma_1(c - \beta e) - (e(\theta + t\gamma_1)) \leq 0$, and

$e((\theta + t\gamma_1)^2\gamma_2 - 4y(1 - \Delta)(\gamma_1 + \gamma_2)\gamma_1) - 2\beta\Omega(\gamma_1 + \gamma_2)\gamma_1 - (\theta + t\gamma_1)(K(\gamma_1 -$

$\gamma_2) - 2\Omega\gamma_1 + e(\theta + t\gamma_1)\gamma_2) \leq 0$, then

$\alpha^* = 0$.

III. Since derivatives at $\bar{\alpha}$ are equal, for the remaining cases we compare the profits at $\{0\}$ and $\{e\}$. And we get:

$\frac{4(K-\Omega)^2}{\gamma_1+\gamma_2} - \frac{\theta e(2K-\theta e)}{\gamma_1} + 4c(\Omega - K) + 4(1 - \Delta)e^2 + c^2(\gamma_1 + \gamma_2) + 2(2\Omega\beta - Kt)e$

$+ 2c(\theta + t\gamma_1)e + t(2\theta + t\gamma_1)e^2 \geq 0$, then $\alpha^* = 0$, otherwise $\alpha^* = e$.

Case 3. When $\left(1 - \frac{(\theta+t\gamma_1)^2\gamma_2}{4y(\gamma_1+\gamma_2)\gamma_1} \geq \Delta > 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}\right)$, then

$\Pi^1_{cbam}(\alpha, p_1^*(\alpha), p_2^*(\alpha))$ is convex, and $\Pi^2_{cbam}(\alpha, p_1^*(\alpha)p_2^*(\alpha))$ is concave in α.

I. If $\alpha_2^\circ \leq \bar{\alpha}$, then we get $\alpha^* = 0$. This translates into the following form:

If $\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then

$\alpha^* = 0$.

II. If $\alpha_2^\circ > \bar{\alpha}$, then we compare the profits at $\{0\}$ and $max(0, min(\alpha_2^\circ, e))$ and choose the one that gives the maximum profit in the feasible range of e. The following form explains these conditions:

If $\frac{2\beta\Omega(\gamma_1+\gamma_2)\gamma_1+(\theta+t\gamma_1)(K(\gamma_1-\gamma_2)-2\Omega\gamma_1+e(\theta+t\gamma_1)\gamma_2)}{(\theta+t\gamma_1)^2\gamma_2-4y(1-\Delta)(\gamma_1+\gamma_2)\gamma_1} > \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$, then

(a.) If $\Pi^2_{cbam} max(0, (min(\alpha_2^\circ, e)), p_1^*(max(0, min(\alpha_2^\circ, e))), p_2^*(max(0, min(\alpha_2^\circ, e))))$

$- \frac{1}{4}\left(\frac{(K-e\theta)^2}{\gamma_1} + \frac{K^2}{\gamma_2} - 2K(2c + et) + (c + et)^2\gamma_1 + c^2\gamma_2 + 2\theta(c + et)e\right) \geq 0$,

then $\alpha^* = max(0, min(\alpha_2^\circ, e))$, otherwise $\alpha^* = 0$.

A.7 Proof of Proposition 4.2.3

When the problem is uncapacitated, $\frac{2K-(e-\alpha)(\theta+t\gamma_1)-(c+\beta\alpha)(\gamma_1+\gamma_2)}{2} \leq \Omega$ always holds, and accordingly $\alpha \leq \frac{2(\Omega-K)+e(\theta+t\gamma_1)+c(\gamma_1+\gamma_2)}{(\theta+t\gamma_1)-\beta(\gamma_1+\gamma_2)}$ always holds. If we recall the Proof of Lemma 4.2.1 and Lemma 4.2.2, when $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$ holds the manufacturer's first-stage problem is concave in α. Otherwise it is convex in α. When $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$ holds, we already derive the optimal solution by equating the FOC to zero at Proof of Lemma 4.2.1 and Lemma 4.2.2, and find $\alpha_1^\circ = \frac{\beta\gamma_1(2K-c(\gamma_1+\gamma_2))-(\theta+t\gamma_1)((K-\gamma_1(c-\beta e)-(e(\theta+t\gamma_1))}{(\theta+(t-\beta)\gamma_1)^2+4y(-1+\Delta)\gamma_1+\beta^2\gamma_1\gamma_2}$. The denominator of α_1° is always negative, therefore if the numerator of α_1° is negative the optimal solution will be equal to $min(\alpha_1^\circ, e)$ when $\Delta \leq 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$ holds. If the numerator is non-negative, the optimal solution will be equal to zero, i.e., $\alpha^* = 0$.

When $\Delta < 1 - \frac{(\theta+(t-\beta)\gamma_1)^2+\beta^2\gamma_1\gamma_2}{4y\gamma_1}$ holds, the manufacturer first-stage problem will be convex in α. In that case, we compare the FOC at lower and upper bounds of α to find optimal solution.

If $\frac{\partial\Pi_{cbam}(\alpha,p_1^*(\alpha),p_2^*(\alpha))}{\partial\alpha}\Big|_0 = \beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K-\gamma_1(c-\beta e) - e(\theta+t\gamma_1)) < 0$ then the the function is increasing, and $\alpha^* = e$.

If $\frac{\partial\Pi_{cbam}(\alpha,p_1^*(\alpha),p_2^*(\alpha))}{\partial\alpha}\Big|_e e\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K-\gamma_1(c-\beta e) - e(\theta+t\gamma_1)) - e((\theta+(t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2) \geq 0$ then the function is decreasing, and $\alpha^* = 0$.

When neither of the conditions above holds, we compare the manufacturer's first stage profit function at $\{0\}$ and $\{e\}$. If $\Pi_{cbam}(0, p_1^*(0), p_2^*(0)) - \Pi_{cbam}(e, p_1^*(e), p_2^*(e)) \geq 0$, or equivalently, $2(\beta\gamma_1(2K - c(\gamma_1+\gamma_2)) - (\theta+t\gamma_1)(K-\gamma_1(c-\beta e) - e(\theta+t\gamma_1))) - e((\theta+(t-\beta)\gamma_1)^2 - 4y(1-\Delta)\gamma_1 + \beta^2\gamma_1\gamma_2) \geq 0$, then the optimal solution is equal to $\alpha^* = 0$, otherwise $\alpha^* = e$.