The Effect of Production- Versus Consumption-Based Emission Tax under Demand Uncertainty

by

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Table of Contents

Acknowledgements ii

List of Tables v

List of Figures vi

List of Appendices vii

Abstract viii

Chapter 1: Introduction 1

1.1 Greenhouse Gas Emissions 1

1.2 Emission Tax 2

1.3 Abatement Technology 3

1.4 Contributions 4

Chapter 2: Literature Review 7

2.1 Economics Literature 7

2.2 Operations Management Literature 10

Chapter 3: Model Formulation 13

Chapter 4: Manufacturer Performance Analysis under PTX 17

4.1 Optimal Solution 17

4.2 Analysis 21

Chapter 5: Manufacturer Performance Analysis under CTX 30

5.1 Optimal Solution 30

5.2 Analysis 33

Chapter 6: Case Study 37

Chapter 7: Discussion and Conclusion..51

Appendix I. Proofs 53

Appendix II. Optimal Investment Decision 58

AppendixIII. The Number of Times The Slope of Profit Difference Switches Directions 60

References 63

List of Tables

Table 3.1: Notation 15

Table 4.2.1: Solution of figure 4.2.2 26

Table 6.1: Parameter values 38

Table Appendix 3.1: Optimal investment decision under PTX...58

Table Appendix 3.2: Optimal investment decision under CTX 59

Table Appendix 4.2.1: Number of times profit difference switches slope directions under PTX.60

Table Appendix 4.2.2: α values under PTX 61

Table Appendix 4.2.3: Number of times profit difference switches slope directions under CTX 62

Table Appendix 4.2.4: α values under CTX..62

List of Figures

Figure 4.1.1: Profit Difference Curve 19

Figure 4.2.2: Effect of emission tax rate t 25

Figure 4.2.3: Impact of abatement technology efficiency on manufacturer profit 28

Figure 6.1: Optimal profit-t...42

Figure 6.2: Emission-t 44

Figure 6.3: Relationship between optimal profit and demand uncertainty.................................45

Figure 6.4: Relationship between emission and demand uncertainty 47

Figure 6.5: Relationship between optimal profit and emission 48

Figure 6.6: Analysis between optimal profit and emission 49

List of Appendices

Appendix I: Proofs 53

Appendix II: Optimal Investment Decision 58

Appendix III: The Number of Times the Slope of Profit Difference Switches Directions 60

Abstract

Emission tax is an instrument widely adopted by countries and regions to incentivize emission abatement by emission-intensive manufacturers. However, policies differ in the methods using which emissions are accounted for. For example, the Chile emission tax direct penalizes manufacturers for the emissions they generate during their production (production-based emission tax), whereas the Sweden electricity emission tax penalizes the consumption of electricity rather than its production (consumption-based emission tax). The two differing methods have potentially varying implications on manufacturers, their emission abatement decisions, as well as the resulting emission levels, especially when demand uncertainty is involved. In this thesis, I investigate the impact of the two distinct methods by studying a profit-maximizing manufacturer facing stochastic demand. Under either both production- and consumption-based emission tax, the manufacturer's optimal decisions on its product price, production quantity and emission abatement investment are derived. Interestingly, it is shown that under either tax, an increase in the emission tax can discourage the manufacturer from investing in emission abatement in some cases. The impact of tax rate, abatement technology efficiency and demand uncertainty on the manufacturer's profitability and abatement decision are also studied. Perhaps surprisingly, higher demand uncertainty may motivate the manufacturer to invest in emission abatement. A case study based on a real-world electricity power generator is provided at the end. Using the case study, I offer further insights into the comparison between the two taxes and find that there exist cases for either tax to dominate the other in terms of both profit and emissions.

Keywords: emission tax, green technology, operations management, emission abatement, sustainability

Chapter 1: Introduction

1.1 Greenhouse Gas Emissions

Greenhouse gases (GHG) are gases that trap heat in the atmosphere. United States Environmental Protection Agency (EPA) shows that GHG emissions can result in disastrous consequences, such as severe sea level rising, extreme weather, and melting of mountain glaciers etc. In 2015, 82.2% of U.S. GHG was anthropogenic emission[1]. The majority of anthropogenic GHG emission is CO_2, which stays in the atmosphere for centuries. Emissions Database for Global Atmospheric Research (EDGAR) shows fossil fuels CO_2 dominates CO_2 emission, nearly doubling from 24.3 Gton[1] CO_2/yr (1970) to 46.4 (2012) Gton CO_2/yr. GHG emissions are also causing loss to the economy. William R (1992) calculates GHG emission indirectly leads to 6%～20% loss of U.S. GDP per year, or 350 billion dollars loss.[2] As a result, there has been increasing efforts worldwide in mitigating the effect of GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) and Albert Arnold Gore Jr. won the Nobel Peace Prize jointly in 2007 for spreading knowledge of the GHG emission effect and laying foundations.[3] The United Nations Framework Convention on Climate Change (UNFCCC) was initiated in 1992 to stabilize atmosphere GHG concentrations,

[1] 1 Gton CO_2 = 103 Megatonnes of CO_2 (Mt CO_2) ; 1 Megatonne of CO_2 (Mt CO_2) = 106 tonnes of CO_2

setting non-binding limits on GHG emissions for each country. The Kyoto Protocol, signed in 1997, is an important milestone linked to UNFCCC setting internationally binding emission reduction targets that held developed countries more responsible for emission reduction than developing countries. Significant progress of global GHG emission control was made at Conference of the Parties (COP 21) Paris in 2015, which signaled the starting point of real global collaboration with countries taking on individual responsibility to mitigate GHG emission in order to control global temperature rise within 2°C.[4] Nearly 190 countries made a commitment to enforce GHG emission abatement via Intended Nationally Determined Contributions (INDCs), while covering 96% of GHG emissions and 98% global population.

Currently, there are two common methods for measuring GHG emissions (i.e., emission accounting): production-based accounting and consumption-based accounting. Boitier (2012)[5] states that the former is based upon “production within territory and offshore areas over which the country has jurisdiction” while the latter counts emission from “domestic ultimate consumption”. Production-based accounting is currently more prevalent in practical implementation than consumption-based accounting, for having more straightforward accounting procedures and for placing arguably more “direct” motivation on the generators of emissions. However, production-based emissions accounting brings about inherent risks. For example, Pickering et al. (2013) reveal that international agreements for establishing uniform emission policy are not frequently reached, and as a result, different countries often neither share a common target nor take equal responsibility.[6] Van et al. (2009) shows the phenomenon that unfair regional emission regulations naturally cause more emission influxes to the region with less strict emission rules, offsetting emission abatement achievement and even bringing negative effect. This effect is called “emission leakage”.[7] Consumption-based emissions accounting has been identified by several researchers and experts (see Karl et al. (2014)[8]) as a solution to mitigate the emission leakage effect. In addition, consumption-based accounting is argued to be superior various other ways, such as it covers more emission sources, and it reduces the incentives to import carbon-intensive goods and services.

1.2 Emission Tax

Emission tax has been one of the mechanisms widely adopted by countries and regions to incentivize the mitigation of GHG emission since 1970s. It is a type of Pigovian tax[9] levied on market activities that contribute to the mission abatement. When the Organization for Economic Co-operation and Development (OECD) developed the "Polluter pays principle" (PPP) in 1972, emission tax became the most typical representation of this principle. In the 1992 Rio Declaration, emission tax was regarded as a key consideration for production and consumption decisions. In the last two decades, emission tax has been highly recommended by economists and international organizations as one of the most efficient instrument for motivating emission reduction. Countries like Denmark, Finland, Sweden, Netherlands, and Norway were the first adopters of emission tax.[10] Simon (2017) [11] credits the U.K. emission tax for much of the reduction in coal use and carbon emissions (Coal use had fallen 74% since 2006).

According to the latest World Bank Report, as of 2017, over 40 national and 25 subnational jurisdictions have either implemented or planned to implement carbon pricing, covering about 50% of the emissions in these jurisdictions, which increased almost four times over the past 10 years.[12] Carbon pricing usually takes the form either of a carbon tax or a tradable emission allowance, usually known as "cap-and-trade".

Compared to cap-and-trade policy, emission tax is easier to implement, while it can generate significant revenues to be used for public expenditure on emission reduction activities or emission abatement research and development. Another key difference between emission tax and cap-and-trade is that the emission price is fixed under emission tax while it is subject to uncertainty and determined by market dynamics under cap-and-trade. This certainty can be a desirable feature for both manufacturers and the government for planning purposes. Carbon Tax Center (2017) stresses that without emission tax, even the most combative regime will fail grievously in emission abatement implementation.[13] Per those advantages, former U.S. Secretary of State, James A. Baker III, proposed carbon tax as the most efficient way of reducing emissions in September 2017.[14] In addition, World Bank reports that 18 countries have implemented or are scheduled to implement carbon tax in 2017.

There are two types of emission tax frameworks in this thesis, which are production-based emission tax (PTX) and consumption-based emission tax (CTX). It is important to note that the approach in this study is from a different angle from most discussions of PTX versus CTX in existing literature, which focuses on the emission leakage effect in settings involving different policies between locations of production and consumption. However, what remains unclear is if and how the performances of PTX and CTX differ absent the issue of emission leakage. To answer this question, this work focuses on illustrating the impact of PTX and CTX on production, pricing, and emission abatement decisions where production and consumption are within the same region or different regions under the same emission policy.

1.3 Abatement Technology

A crucial aspect of the effectiveness of emission tax is how well it can motivate adoption of emission abatement technologies among polluting manufacturers. The world has seen numerous advancements in abatement technology developments since the 1970s, such as ‘Top gas recycling’, ‘Sorption enhanced water gas shift’, and ‘Rectisol’.[15] Krass et al. (2013)[16] emphasizes Carbon

Capture and Storage (CCS) as a key technology in reducing emissions in cement manufacturing. IPCC (2005) explains that CCS contains 3 essential steps: separate CO_2 from sources, transport CO_2 to an appropriate location, and finally store CO_2 securely. CCS realizes 90% efficiency[17] (proportion of emissions that a technology can remove) of reducing CO_2 from the atmosphere. According to the World Energy Outlook 2011, current CCS technology is capable of completing 3.5 Gtons of GHG reduction by 2035, which is almost 22% of the global emissions it takes to reach the 2˚C temperature rise limit.[18] Global CCS Institute has identified 38 safe, reliable, and adaptable large-scale CCS projects around the world before 2017; more than 20 will be operational before 2018. In case study of Chapter 6, the impact of PTX and CTX on a power generator is discussed with option to invest in CCS technology.

1.4 Contributions

This thesis focuses the effect of emission tax design (PTX and CTX) on manufacturers' production, pricing and emission abatement decisions. The manufacturer is considered as a profit-maximizing monopolistic manufacturer producing a single product, who is either directly subject to a tax for emissions it emits during production (i.e., PTX) or indirectly affected by a CTX through consumer demand. Under each tax scheme, the manufacturer maximizes its profit by choosing its production quantity, product price and whether to invest in an emission abatement technology to reduce the emission content associated with a unit product. Demand for the product is price-sensitive and subject to uncertainty.

The contributions of this work are as follows. First, this work is the first to consider demand uncertainty in studying the impact of PTX versus CTX. This provides feasibility to generate insights and observe effects that would have been absent had a deterministic demand had been used (see Rosič et al. (2013)[19] and Benjaafar et al. (2013)[20] for examples of papers considering deterministic demand). In fact, it is not difficult to show that PTX and CTX are equivalent under deterministic demand. In contrast, I show that when demand uncertainty is present, PTX and CTX may lead to different production quantity, price and abatement decisions, and in turn result in differing manufacturer profits and emission levels. These results highlight the importance of accounting for demand uncertainty in evaluating the effectiveness of emission tax designs. Second, this thesis contributes to the discussion on the tradeoff between PTX and CTX, which has predominantly been placed in settings of different emission policy level (i.e. emission tax rate) between locations of production and consumption (e.g. emission policy is only implemented at location of consumption but not production) to illustrate the leakage effect, by shedding light on when and how the impact of PTX versus CTX may vary when emission policy levels are comparable under the two taxes. I also analyze the impact of tax rate, technology efficiency and demand uncertainty on manufacturer profit, product price, optimal production quantity, and abatement technology investment decision respectively. Perhaps surprisingly, the effect of tax rate maybe non-monotone under either scheme: while an initial increase in tax motivates the manufacturer to invest in abatement technology, further taxes increase may have an opposite effect, leading manufacturer to revert to not investing in abatement. Krass et al. (2013) points out a similar effect that high tax increases may motive the manufacturer to choose “dirty technology” over “clean technology”. However, they do not consider demand uncertainty or consumption-based tax, and this thesis observes more complex investment behavior as a result of demand uncertainty. Third, the comparison between PTX and CTX is analyzed in several dimensions through a case study of an electricity generator. Interestingly, CTX is the dominating scheme (in terms of manufacturer profit and emissions) when tax rates are either low or high, while PTX becomes the dominating scheme for intermediate tax rates.

The rest of the thesis is structured as follows. Related literature is reviewed in Chapter 2, the model formulation is illustrated in Chapter 3, the manufacturer's optimal solutions analysis under PTX and CTX are provided in Chapter 4 and 5. A case study using real world data shows in Chapter 6. And concluding remarks lie in Chapter 7.

Chapter 2: Literature Review

The literature on sustainability is extensive, see for example Costanza (1992)[21] and Adams (2006) [22] for reviews. Both Costanza (1992) and Adams (2006) emphasize that "Ecological Economics" must be built in which human are responsible to coordinate the relationship between anthropogenic activities and the environment. Within this literature, there is a growing stream focusing on climate change and global warming, see Cox et al. (2000) [23], Meinshausen et al. (2009) [24], and Rezai et al. (2016)[25] for recent reviews. As the key contributor of global warming is GHG emission, there are extensive literature on mitigating GHG emissions with varying focuses. An important topic that has drawn great attention from both the research community and practitioners is the understanding of available policy instruments for encouraging emission abatement (See Avi-Yonah et al. (2009) [26]). In what follows, the literature related to emission regulations that are most relevant to this thesis is reviewed. This thesis lies in the intersection of economics literature and operations management literature.

2.1 Economics Literature

In the economics literature, Avi-Yonah et al. (2009) analyze leading alternatives for reducing CO_2 emission in a clear framework. Although manufacturers' voluntary emission reduction efforts have produced some success (e.g. Walmart's Sustainability Index program, Coca Cola's emission reduction targets), mandatory regulation is still necessary to motivate broader involvements. Current emission regulations around the world can be mainly categorized into two types:

regulatory limit and market-based policy instruments. Regulation limit is also called command-and-control (CAC), whose basic mechanism is to set the quantitative emission upper limit for specific sources in certain timeframes, and to punish carbon emitters who emit over the limit. Examples of emission regulations using Regulation Limit include the Clean Air Act (CAA) set by United States Environmental Protection Agency (EPA) and the Clean Power Plan (CPP), which limits CO_2 emission from chemical plants, utilities, and steel mills etc.[27] Market-based policy instruments mainly involve carbon pricing mechanisms such as in emission tax or cap-and-trade. World Bank Group and OECD (2015)[28] stress the advantages of carbon pricing over regulatory limit in terms of fairness, stability and predictability, transparency, efficiency, cost-effectiveness, reliability and environmental integrity etc. Similarly, Climate Reality Carbon Pricing Handbook (2017)[29] states that carbon pricing stimulates the market to mitigate emissions, showing the potential to "decarbonize" anthropogenic activities and facilitate emission abatement technology innovation. Mankiw (2007)[30] points out the superiority of an emission tax (a carbon tax in GHG emission focused programs) over cap-and-trade in international dimension. Shurtz (2016)[31] regards emission tax as the most effective method of reducing GHG since it provides the clearest price signal, and is unencumbered by factors as credits, allowance allocation, etc. Avi-Yonah et al. (2009) also mention that emission tax has advantages over cap-and-trade in terms of its simplicity, revenue creation and cost certainty. This research contributes to the literature on market-based policy instruments by examining the impact of emission tax design under the presence of demand uncertainty.

Within economics literature, there is extensive literature studying the impact of an emission tax in the environmental economics community. Hoeller & Markku (1991) [32], and Pearce (1991)[33] clarify the definition, function and mechanism of carbon tax in the early period of its implementation. Summers (1991)[34] takes the first attempt to quantify the efficiency of emission taxes of several countries. Based upon their work, Shah & Bjorn (1992) [35] provide numerical calculations on the revenue potential of emission tax under differential scenarios. There are also a number of papers in environmental ecomomics that study the optimal design of environmental policies from the perspective of a social planner (e.g., Baumol (1972), Barnett (1980), and Katsoulacos and Xepapadeas (1995)). They show that taxing emissions always increases efforts in emission abatement and thus reduces total emissions. Other results include that a Pigouvian tax (taxing emissions using the true social cost of emissions) is socially-optimal under perfect competition but may not be otherwise. In fact, imposing a Pigouvian tax on a monopolist is shown to be not socially optimal and could hurt consumption by increasing price and shrinking demand.

All above literature default that emission tax should be imposed on emission production, however, there has been some discussions of alternative methods. For example, some have contemplated the impact of using production and consumption-based emission accounting methods in an international context, e.g., Peters (2008)[36] and Jakob et al. (2013)[37]. Liu et al. (2015)[38] study these two accounting methods in China by both methods through an interregional input-output model. Huo et al.(2014)[39] compare the two methods through an empirical study based in China. In the above papers, the key issue is the leakage effect due to separated targets or different emission regulations at locations of production versus consumption. In contrast, this thesis focuses on illustrating the impact of PTX and CTX on production, pricing, and emission abatement decisions where production and consumption are within the same region or different regions sharing the same emission policy.

In addition, there is very limited literature on emission tax that account for consumers' response to emission tax or demand uncertainty. Symons et al. (1994) [40] first take demand into account in studying the effect carbon tax. They use an input-output simulation model to examine the possibility of achieving a 20% CO_2 mitigation in line with the 'Toronto target' via a carbon tax in a UK case. However, this paper only provides numerical results and does not consider demand uncertainty. This thesis not only considers the impact of emission tax on consumption, but also demand uncertainty. Both analytical solutions and a case study based on a real world electricity generator are provided.

2.2 Operations Management Literature

There is also growing literature in operations management concerning emissions and emission regulations. Most related ones are reviewed below. Krass et al. (2013) [41] consider a problem where a central planner sets a tax rate to maximize social welfare while anticipating the manufacturer's decisions regarding the optimal emission-abatement technology, production quantity and product price. In contrast to their paper, which assumes tax is imposed on production,, this paper consider both production-based and consumption-based emission tax. In addition, they assume a deterministic demand while I consider the impact of demand uncertainty. Drake et al. (2016) [42] explore technology choice and capacity decisions for new plants facing stochastic demand under cap-and-trade versus emission tax regulations. However, they do not consider pricing decisions of the manufacturer, or consumption-based emission tax.

This work utilizes the classical Newsvendor model. Khouja (1999) [43] offers an excellent review of the newsvendor model. Various extensions of the basic newsvendor model have been studied (e.g. Extensions to different supplier pricing policies, discounting structures, multi-location, etc.). Harrison et al.(1999) [44] consider a newsvendor model for a manufacturing manufacturer to make the optimal investment decision under multiple resources and multiple products, which is also regarded as "multidimensional newsvendor model". Mieghem et al. (2003)[45] extend properties of optimal newsvendor network solutions in Harrison et al. (1999) to a dynamic setting under several conditions. Yu et al. (2013) [46] discuss an example of newsvendor model with fuzzy price-dependent demand. However, no one is designed to address regulation problems, of course no one is related to emission tax. A random variable is introduced to classic demand function to present uncertainty of demand, which will influence every decision of the manufacturer in multiple dimensions, such as pricing, deciding production quantity, investment to abatement technology, even the comparison of two taxes. Jiang et al. (2012) [47] study joint production capacity and investment decisions under command and control and market-based regulations using the newsvendor model. Four dimensions of performance comparison are discussed in their paper: profit, emission, investment amount and investment timing, and they identify conditions under which either cap-and-trade or command and control would be preferred. However, Jiang et al. (2012) only analyze cap-and-trade under market-based regulations and do not consider the impact of production-based or consumption-based emission accounting.

Also related to this thesis are discussions of emission allocation among manufacturers in supply chains. Caro et al. (2013) show that over-allocating emissions, or double-counting, is necessary for manufacturers to exert their first-best emission reduction efforts. Cox et al. (2014) study emission allocation in a setting where manufacturers are accountable for their own emissions as well as the emissions from all upstream suppliers. They show that an emission responsibility sharing scheme where the direct emissions of one manufacturer is allocated equally among all its downstream manufacturers is in the core of the cooperative game and corresponds to the Shapley value. Mansur (2011)[48] examines the tradeoff between imposing the emission tax on upstream versus downstream entities, with upstream being manufacturers producing or importing raw materials (coal, natural gas, etc) and downstream being manufacturers that are direct sources of GHG emission (motor vehicles, farms, and power plants, etc).

Chapter 3: Model Formulation

This thesis considers an emission-intensive manufacturer (e.g. coal-fired power plant) who sells a single product (e.g. electricity) to consumers. The production of a unit of product costs w, and generates e units of emissions. The market is subject to an emission tax. There are two configurations of this emission tax: a production-based emission tax (PTX) and a consumption-based emission tax (CTX). Under a production-based emission tax, the manufacturer is subject to an emission tax for each unit of emissions it emits. Under a consumption-based emission tax, the consumers are required to pay an emission tax for each unit of product they purchase. Let t denote the tax rate per unit of emissions. The manufacturer can choose to invest in emission abatement technology at cost I, which works to reduce the unit product emission to $(1-\alpha)e$, where α indicates the efficiency of the abatement technology. I denote the manufacturer's technology investment decision as δ, which is a binary variable with $\delta = 1$ denoting the decision to invest and $\delta = 0$ to not invest.

It is reasonable to assume linear demand $D = a - bp' + \xi$, where p' is the effective price that consumers need to pay to purchase a unit of product and ξ is a random variable representing demand uncertainty. Note that the value of the effective price p' depends on the type of emission tax and does not necessarily equal to the price of the product p. Specifically, $p' = p$ under PTX, whereas $p' = p + te(1 - \alpha\delta_C)$ under CTX. ξ follows a Bernoulli distribution, where ξ takes the value of ϵ and $-\epsilon$ with equal probability, where ϵ is a non-negative constant. That is

$$\xi = \begin{cases} \epsilon, & with\ probability\ 0.5, \\ -\epsilon, & with\ probability\ 0.5. \end{cases} \tag{1}$$

Therefore, the manufacturer expect either of two demand outcomes. One high demand scenario with $D = a - bp' + \epsilon$, and one low demand scenario with $D = a - bp' - \epsilon$. Table 1 provides a summary of all notations in this thesis. Therefore, given emission tax type τ ($\tau \in \{P, C\}$), rate t, product price p_τ and the manufacturer's investment decision δ_τ, the customer demand function is given as:

$$D_\tau(p_\tau, \delta_\tau; t) = \begin{cases} a - bp_P + \xi, & if\ \tau = P, \\ a - b[p_C + te(1 - \alpha\delta_C)] + \xi, & if\ \tau = C. \end{cases} \tag{2}$$

As a result, the sales of the product can be computed as

$$S_\tau(p_\tau, \delta_\tau, q_\tau; t) = min\{D_\tau(p_\tau, \delta_\tau; t), q_\tau\}. \tag{3}$$

It is not difficult to show that it is never optimal to order over $a - bp' + \epsilon$ or under $a - bp' - \epsilon$. Therefore,

$$E[S_\tau(p_\tau, \delta_\tau, q_\tau; t)] = E[min\{D_\tau(p_\tau, \delta_\tau; t), q_\tau\}] = \frac{1}{2}q_\tau + \frac{1}{2}(a - b\mathrm{p}' - \epsilon). \tag{4}$$

Table 3.1: Notation

Parameter	Definition
t	Emission tax rate
P	Subscript denoting production-based emission tax
C	Subscript denoting consumption-based emission tax
τ	Type of emission tax, i.e., $\tau \in \{P,C\}$
w	Unit cost of production
e	Emission quantity per unit product
I	Cost of emission abatement technology
α	Emission abatement technology efficiency
ξ	Systematic uncertainty of customer demand (Random Variable)
ϵ	A non-negative constant representing the highest value of ξ
$\delta_\tau(t)$	Emission abatement technology investment decision given government regulation of t, τ; $\delta_\tau(t) \in \{0,1\}$
p_τ	Product selling price under certain tax type τ
p'_τ	Final price to customer under certain tax type τ
q_τ	Production quantity under certain tax type τ
$D_\tau(p_\tau, \delta_\tau; t)$	Customer demand given manufacturer's decision of p_τ, δ_τ and government regulation of t, τ
$S_\tau(p_\tau, q_\tau, \delta_\tau; t)$	Sales quantity given manufacturer's decision of p_τ, q_τ, δ_τ, and government regulation of t, τ
$\Pi_\tau(p_\tau, q_\tau, \delta_\tau; t)$	Manufacturer's profit given manufacturer's decision of $p_\tau, q_\tau, \delta_\tau$ and government regulation of t, τ
$\psi_\tau(p_\tau, q_\tau, \delta_\tau; t)$	Manufacturer's emission given manufacturer's decision of $p_\tau, q_\tau, \delta_\tau$ and government regulation of t, τ
t_b	Upper boundary of t
$\Pi_\tau^*(t)$	Optimal profit of optimal solution under certain t, τ
$\Delta\widehat{\Pi}_\tau(t)$	Difference of optimal profit with investment and no investment under certain t, τ

Substituting (2) into the above equation gives

$$E[S_\tau(p_\tau,\delta_\tau,q_\tau;t)] = \begin{cases} \frac{1}{2}q_P + \frac{1}{2}(a - bp_P - \epsilon), & if\ \tau = P \\ \frac{1}{2}q_C + \frac{1}{2}\left[a - b\left(p_C + bte(1-\alpha\delta_C)\right) - \epsilon\right], & if\ \tau = C \end{cases} \quad (5)$$

Under a given emission tax policy, the manufacturer chooses its product price, order quantity, and emission abatement decisions to maximize its (after-tax) profit, which is given as follows:

$$\Pi_\tau(p_\tau, q_\tau, \delta_\tau; t) =$$

$$\begin{cases} p_P E[min\{D_P(p_P,\delta_P;t), q_P\}] - [w + te(1-\alpha\delta_P)]q_P - I\delta_P, & for\ \tau = P, \\ p_C E[min\{D_C(p_C,\delta_C;t), q_C\}] - wq_C - I\delta_C, & for\ \tau = C. \end{cases} \quad (6)$$

It is reasonable to make the following assumptions for the rest of analysis.

Assumption 1. $$a > 5bw. \quad (7)$$

Assumption 2. $$t_b = \frac{a-bw-2\epsilon}{be}. \quad (8)$$

Assumption 1 and 2 ensure that the demand function remains nonnegative for the range of emission taxes[2]. Next two chapters analyze the manufacturer's optimal solution under PTX and CTX respectively.

[2] t_b is set to ensure even when the manufacturer chooses price and production quantity according to high demand realization but real demand realization turns out to be low, demand will still be positive even under the initial emission leval. Specifically, let $q_P = a - bp_P + \epsilon$ with the corresponding profit maximizing price being p_P. Solving for the largest t such that $D = a - bp_P - \epsilon \geq 0$ under both PTX and CTX gives $t \leq t_b$.

Chapter 4: Manufacturer Performance Analysis under PTX

4.1 Optimal Solution

Under PTX, the manufacturer is directly taxed for each unit of emissions generated from its production. The manufacturer chooses its product price p_P, production quantity q_P, and emission abatement decision δ_P to maximize

$$\max_{p_P,\ q_P,\ \delta_P} \Pi_P(p_P, q_P, \delta_P; t) = p_P\left[\frac{1}{2}q_P + \frac{1}{2}(a - bp_P - \epsilon)\right] - [w + te(1 - \alpha\delta_P)]q_P - I\delta_P$$

$$\begin{aligned} s.t.\ & q_P > a - bp_P - \epsilon \\ & q_P \le a - bp_P + \epsilon \\ & p_P, q_P \ge 0, \\ & \delta_P \in \{0,1\} \end{aligned} \tag{9}$$

The first and second constraints in (9) guarantee that the manufacturer neither produces more than the high demand realization nor lower than the low demand realization. The following lemma provides the optimal price and order quantity for given investment decision.

***Lemma* 1.** *For a given δ_P, the optimal price and order quantity $\left(\hat{p}_P(\delta_P; t), \hat{q}_P(\delta_P; t)\right)$ are given as*

$$\left(\hat{p}_P(\delta_P;t),\hat{q}_P(\delta_P;t)\right)$$
$$=\begin{cases}\left(\frac{(a+b[w+te(1-\alpha\delta_P)]}{2b},\frac{a+2\epsilon-b[w+te(1-\alpha\delta_P)]}{2}\right), & if\ 0\le t< Min(t'^P,t_b),\\ \left(\frac{(a-\epsilon+b[w+te(1-\alpha\delta_P)]}{2b},\frac{a-\epsilon-b[w+te(1-\alpha\delta_P)]}{2}\right), & if\ t'^P\le t\le t_b,\end{cases} \quad (10)$$

$where\ t'^P=\frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha\delta_P)}$.

Define $\left(\hat{p}_P(\delta_P;t),\hat{q}_P(\delta_P;t)\right)$ result under $0\le t< Min(t'^P,t_b)$ as solution I, result under $t'^P\le t\le t_b$ as solution II. All proofs are provided in the appendix. Lemma 1 shows for each given δ_P, the optimal production quantity $\hat{q}_P(\delta_P;t)$ is higher when t is small (solution I) than when t is large (solution II). This is because when t is small, the profit margin of selling a product is high and thus the manufacturer produces more to capture this high margin. It is also apparent that the product price increase when t is small ($0\le t< Min(t'^P,t_b)$) and when t is large ($t'^P\le t\le t_b$) respectively. However, the price may have a drop inbetween the two cases for the manufacturer may slash production when $t=Min(t'^P,t_b)$, and it lowers price to reduce the cost of lostsale.

Next step is to solve for the optimal investment decision $\delta_P^*(t)$. $\delta_P^*(t)$ can be obtained by comparing the profit with investment ($\delta_P=1$) and without investment ($\delta_P=0$), and choosing the one leading to higher profit. I denote the difference of manufacturer profit between the two investment decisions by $\Delta\widehat{\Pi}_P(t)=\Pi_P[\hat{p}_P(1;t),\hat{q}_P(1;t),1;t]-\Pi_P[\hat{p}_P(0;t),\hat{q}_P(0;t),0;t]$. Then $\delta_P^*(t)$ can be determined by comparing $\Delta\widehat{\Pi}_P(t)$ and I, that is, $\delta_P^*(t)=1$ if $\Delta\widehat{\Pi}_P(t)\ge I$ and $\delta_P^*(t)=0$ otherwise. Figure 4.1.1 illustrates for an example how $\delta_P^*(t)$ can be determined. The following theorem charaterizes the optimal solution to the manufacturer's problem under production-based emission tax.

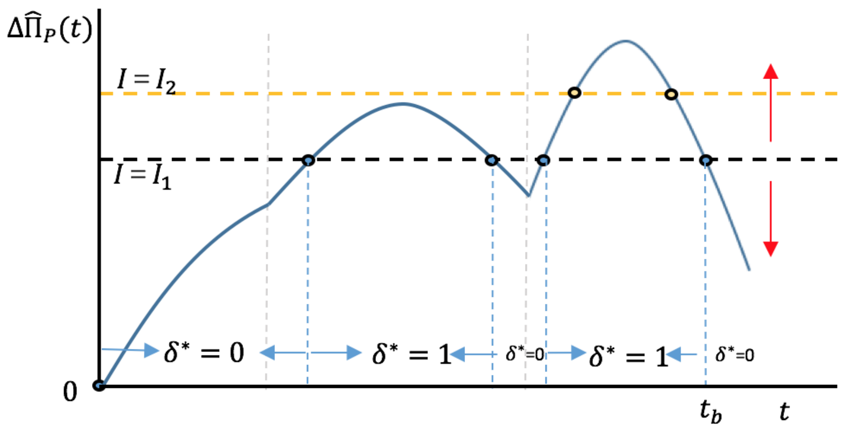


Figure 4.1.1: Profit Difference Curve

Theorem 1*. The optimal abatement decision under production-based emission tax is given as follows.*

$\delta_P^*(t) = 1$ *if and only if one of the following conditions hold:*

- $\epsilon \leq \frac{4}{11}a,\ 0 < \alpha \leq \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)},\ 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{3be}$, *and* $I \leq t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$;
- $\epsilon \leq \frac{4}{11}a,\ 0 < \alpha \leq \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)},\ \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)}$, *and* $I \leq t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$;
- $\epsilon \leq \frac{4}{11}a,\ 0 < \alpha \leq \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)},\ \frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)} < t \leq \frac{a-bw-2\epsilon}{be}$, *and* $I \leq t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw-\epsilon}{2})$;
- $\epsilon \leq \frac{4}{11}a,\ \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)} < \alpha \leq 1,\ 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{3be}$, *and* $I \leq t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$;

- $\epsilon \le \frac{4}{11}a, \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)} < \alpha \le 1,\ \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \le \frac{a-bw-2\epsilon}{be}, I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b};$

- $\frac{4a}{11} < \epsilon \le \frac{a-bw}{2},\ 0 < t \le \frac{a-bw-2\epsilon}{be}, and\ \ I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2}).$

$\delta_P^*(t) = 0$ *if and only if one of the following conditions hold:*

- $\epsilon \le \frac{4}{11}a,\ 0 < \alpha \le \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)},\ 0 < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be}, and\ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te\alpha(\frac{a-bw+2\epsilon}{2});$

- $\epsilon \le \frac{4}{11}a,\ 0 < \alpha \le \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)}, and\ \ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b};$

- $\epsilon \le \frac{4}{11}a,\ 0 < \alpha \le \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)} < t \le \frac{a-bw-2\epsilon}{be}, and\ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te\alpha(\frac{a-bw-\epsilon}{2});$

- $\epsilon \le \frac{4}{11}a,\ \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)} < \alpha \le 1,\ 0 < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be}, and\ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te\alpha(\frac{a-bw+2\epsilon}{2});$

- $\epsilon \le \frac{4}{11}a, \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)} < \alpha \le 1,\ \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \le \frac{a-bw-2\epsilon}{be}, I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) +$

  $te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b};$

- $\frac{4a}{11} < \epsilon \le \frac{a-bw}{2},\ 0 < t \le \frac{a-bw-2\epsilon}{be}, and\ \ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2}).$

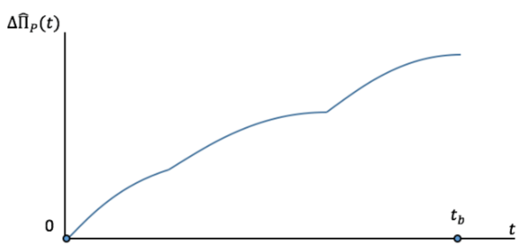
The optimal price $p_P^*(t)$ and production quantity $q_P^*(t)$ are given as

$$\left(p_P^*(t), q_P^*(t)\right) =$$

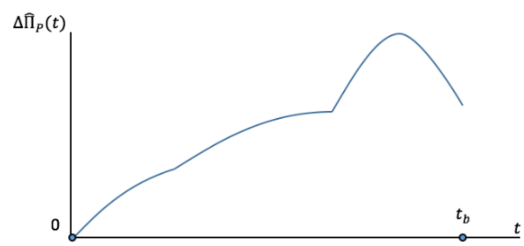
$$\begin{cases} \left(\dfrac{(a + b[w + te(1 - \alpha\delta_P^*(t))]}{2b}, \dfrac{a + 2\epsilon - b\left[w + te\left(1 - \alpha\delta_P^*(t)\right)\right]}{2}\right), if\ 0 \le t < Min(t'^P, t_b), \\ \left(\dfrac{(a - \epsilon + b[w + te(1 - \alpha\delta_P^*(t))]}{2b}, \dfrac{a - \epsilon - b[w + te(1 - \alpha\delta_P^*(t))]}{2}\right), \quad if\ t'^P \le t \le t_b. \end{cases} \quad (11)$$

4.2 Analysis

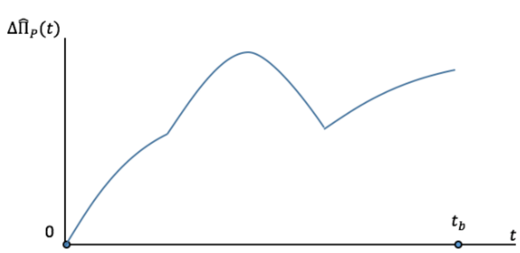
As discussed in Section 4.1, profit difference $\Delta\widehat{\Pi}_P(t)$ and investment cost I jontly determine $\delta_P^*(t)$. $\Delta\widehat{\Pi}_P(t)$ alone determines the first-order effect of the emission tax t on the willingness of the manufacturer to invest in abatement technology. Specifically, when slope of $\Delta\widehat{\Pi}_P(t)$ is positive, the manufacturer's willingness to invest the abatement technology increases with t ,and otherwise the willingness decreases with t. Interestingly, the effect of t is nonmonotone, i.e., the slope of $\Delta\widehat{\Pi}_P(t)$ may change directions at one or more values of t. In fact, the number of times the slope of $\Delta\widehat{\Pi}_P(t)$ changes directions can take values of 0, 1, 2, 3 which are denoted by scenarios C_0, C_1, C_2, C_3 respectively. Figure 4.2.1 illustrates these four scenarios.



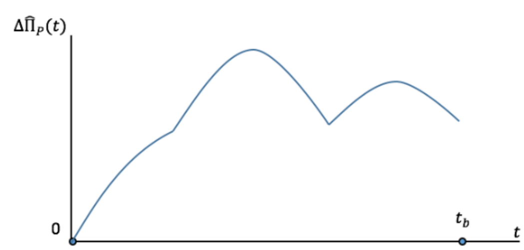
$(a) C_0$



(b) C_1



$(c) C_2$



(d) C_3

Furthermore, it is shown that the number of times the slope of $\Delta\widehat{\Pi}_P(t)$ change directions is determined by the customer demand uncertainty ϵ and the technology efficiency α. This result is summarized in the following proposition.

Proposition 1. The number of times the slope of $\Delta\widehat{\Pi}_P(t)$ switch directions during $0 \le t \le t_b$ is:

1) 0 (case C_0) if and only if one of the following conditions hold:

   a) $\frac{4}{11}a < \epsilon \le \frac{a-bw}{2}$ and $\alpha > \alpha_1$;

   b) $\frac{2a-6bw}{7} < \epsilon \le \frac{4}{11}a$ and $Max(\alpha_5, \alpha_8) < \alpha \le Min(\alpha_6, \alpha_2)$;

   c) $\frac{2a-6bw}{7} < \epsilon \le \frac{4}{11}a$ and $Max(\alpha_2, \alpha_3) < \alpha \le 1$;

   d) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $Max(\alpha_2, \alpha_3) < \alpha \le 1$;

2) 1 (case C_1) if and only if one of the following conditions hold:

   a) $\frac{4}{11}a < \epsilon \le \frac{a-bw}{2}$ and $0 < \alpha \le \alpha_1$;

   b) $\frac{2a-6bw}{7} < \epsilon \le \frac{4}{11}a$ and $\alpha_5 < \alpha \le Min(\alpha_6, \alpha_8, \alpha_2)$;

   c) $\frac{2a-6bw}{7} < \epsilon \le \frac{4}{11}a$ and $\alpha_2 < \alpha \le Max(\alpha_2, \alpha_3)$;

   d) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $\alpha_5 < \alpha \le Min(\alpha_6, \alpha_7, \alpha_2)$;

   e) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $\alpha_7 < \alpha \le Min(\alpha_4, \alpha_2)$;

   f) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $Max(\alpha_4, \alpha_7) < \alpha \le Min(\alpha_5, \alpha_2)$;

   g) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $Max(\alpha_5, \alpha_7) < \alpha \le Min(\alpha_6, \alpha_2)$;

   h) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $Max(\alpha_6, \alpha_7) < \alpha \le \alpha_2$;

   i) $0 < \epsilon \le \frac{2a-6bw}{7}$ and $\alpha_2 < \alpha \le Max(\alpha_2, \alpha_4)$;

j) $0 < \epsilon \leq \frac{2a-6bw}{7}$ and $Max(\alpha_2, \alpha_4) < \alpha \leq Max(\alpha_2, \alpha_3)$.

3) 2 (case C_2) if and only if one of the following conditions hold:

a) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $\alpha_8 < \alpha \leq Min(\alpha_4, \alpha_2)$;

b) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $Max(\alpha_4, \alpha_8) < \alpha \leq Min(\alpha_5, \alpha_2)$;

c) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $\alpha_6 < \epsilon \leq Min(\alpha_8, \alpha_2)$;

4) 3 (case C_3) if and only if one of the following conditions hold:

a) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $0 < \alpha \leq Min(\alpha_4, \alpha_8, \alpha_2)$;

b) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $\alpha_4 < \alpha \leq (\alpha_5, \alpha_8, \alpha_2)$;

c) $\frac{2a-6bw}{7} < \epsilon \leq \frac{4}{11}a$ and $\alpha_6 < \alpha \leq Min(\alpha_8, \alpha_2)$;

d) $0 < \epsilon \leq \frac{2a-6bw}{7}$ and $0 < \alpha \leq Min(\alpha_4, \alpha_7, \alpha_2)$;

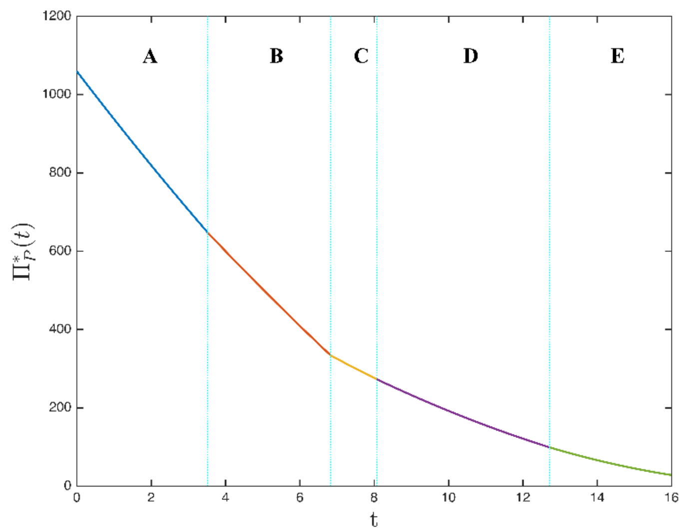
e) $0 < \epsilon \leq \frac{2a-6bw}{7}$ and $\alpha_4 < \alpha \leq (\alpha_5, \alpha_7, \alpha_2)$;

f) $0 < \epsilon \leq \frac{2a-6bw}{7}$ and $\alpha_6 < \alpha \leq Min(\alpha_7, \alpha_2)$.

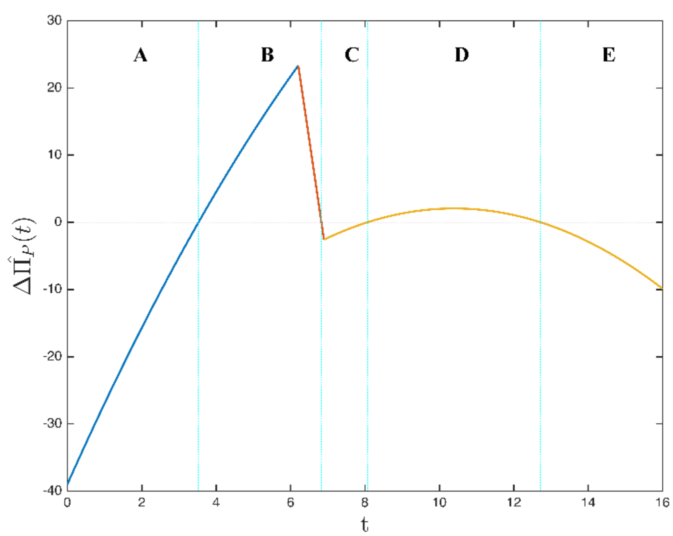
where the $\alpha_1 = \frac{a-bw-6\epsilon}{a-bw-2\epsilon}$, $\alpha_2 = \frac{4a-11\epsilon}{6(a-bw-2\epsilon)}$, $\alpha_3 = \frac{a-bw-6\epsilon+\sqrt{a^2-2abw+b^2w^2+12\epsilon^2}}{2(a-bw-2\epsilon)}$, $\alpha_4 = \frac{a+7\epsilon\pm\sqrt{a^2+50a\epsilon+6abw+9b^2w^2-66b\epsilon w+31\epsilon^2}}{-2a+6bw+\epsilon}$, $\alpha_5 = \frac{a+3bw+16\epsilon-\sqrt{a^2+6abw+9b^2w^2-40a\epsilon+96bw\epsilon+22\epsilon^2}}{4a+13\epsilon}$, $\alpha_6 = \frac{a+3bw+16\epsilon+\sqrt{a^2+6abw+9b^2w^2-40a\epsilon+96bw\epsilon+22\epsilon^2}}{4a+13\epsilon}$, $\alpha_7 = \frac{2(a+3bw-2\epsilon)}{4a-5\epsilon}$, $\alpha_8 = \frac{a-bw-3\epsilon}{a-bw-2\epsilon}$.

Proposition 1 suggests, perhaps surprisingly, that it is possible (in cases C_1, C_2, C_3) for an increase in the emission tax to lead the manufacturer to be less willing to invest in emission abatement. With certain investment costs, this would imply that the manufacturer may switch from investing in emission abatement to not investing as the emission tax increase. In what follows, I explain the mechanisms driving this result.

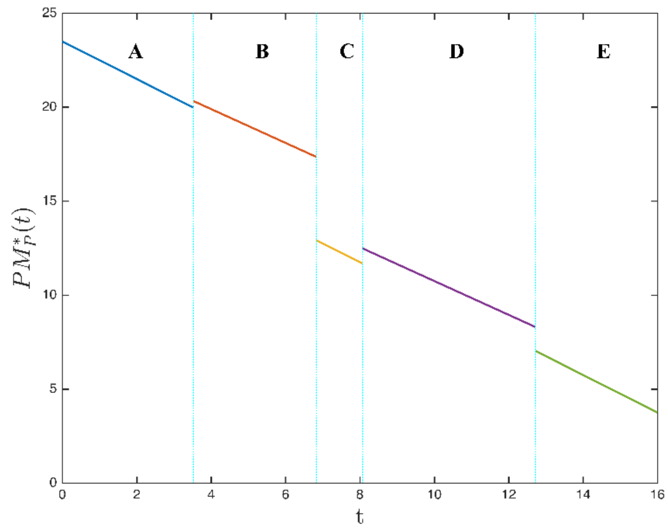
The effect with an example is illustrated in Figure 4.2.1, which corresponds to scenario C_3.



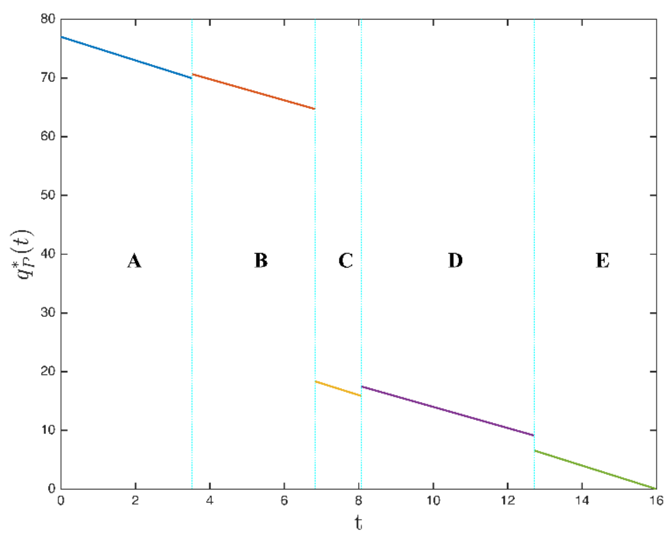
(a) Optimal profit



(b) Optimal profit difference



(c) Optimal profit margin



(d) Optimal production quantity

Figure 4.2.2: Effect of emission tax rate t

(Parameters: a=100;b=2;e=2;w=3;α=0.1;I=39;ϵ=15.)

Table 4.2.1: Solution of figure 4.2.2

Segment	A	B	C	D	E
Preferred solution	I	I	II	II	II
Investment Decision	0	1	0	1	0

Under either PTX or CTX, there are two methods for the manufacturer to reduce total emissions. One is to invest in the abatement technology, which serves to reduce emission tax per unit of product from te to $te(1-\alpha)$. The other method is to slash down the production quantity q_τ. These two methods can be used seperately or together.

From Section 4.1, it is obvious that small t results in low overage cost and high profit margin, and the manufacturer is then motivated to produce in large quantity (solution I). On the other hand, large t leads to high overage cost and low profit margin, and the manufacturer as a result produces in small quantity (solution II).

When t is zero, the manufacturer never invest in the abatement technology, since it would lead added investment cost I. When t is in region A, the profit margin is relatively high, and thus the manufacturer produces at high quantity (solution I) to capture this high margin. The manufacturer does not want to invest abatement technology unless the emission tax savings from abatement is greater than the investment cost, which occurs at the right boundary of region A. At the same time, the manufacturer produces to match high demand realization while $q_P^*(t)$ slowly decreases with t. When t is in region B, the manufacturer invests abatement technology. However, as t increases, both the production quantity declines due to lower profit margin, which reduces the emission tax savings from the abatement technology. At the right boundary of region B, the emission tax savings reduce to the cost of the abatement investment, and the manufacturer is indifferent between investing and no investing. In addition, at this point, t has become relatively large, resulting in a large overage cost. Starting from region C, the manufacturer changes its production quantity to match low demand realization (this is why $q_P^*(t)$ drops significantly between regions B and C). As a result, the manufacturer chooses to not invest in region C as the effectiveness of emission tax reduction significantly reduces. When technology efficiency α is relatively low (this is the case in scenario C_3), investment decisions may experience additional changes when t is large, because the technology abatement effect is insufficient to handle high tax rate. Following that, as t increases further, the value of abating emissions increases, leading the manufacturer to invest once again in abatement in region D. However, in region E, the tax becomes so high that the production quantity is too low to justify investment. Therefore, the manufacturer does not invest in region E.

The impact of techonology efficiency α on profit is examined as follows,

Proposition 2. $\frac{\partial \Pi_P^*}{\partial \alpha} > 0$.

Proposition 2 suggest that the manufacturer's optimal profit Π_P^* is monotonically increasing with α. That is, more efficient emission abatement technology benefits the manufacturer (see Figure 4.2.3).

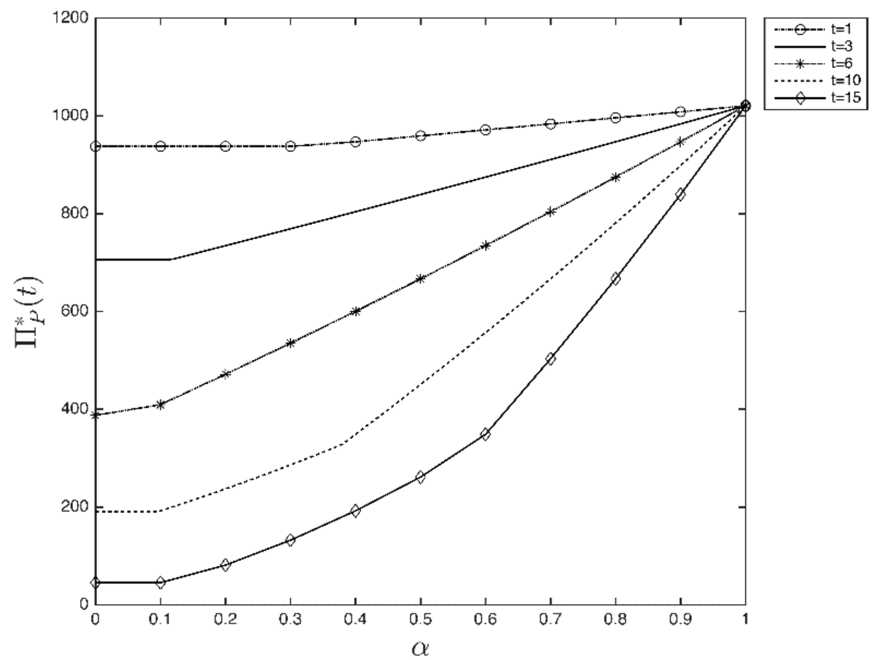


Figure 4.2.3: Impact of abatement technology efficiency on manufacturer profit

(a=100; b=2; e=2; w=3; I=39; ϵ=15)

Proposition 3. $\frac{\partial^2 \Pi_P^*}{\partial \alpha \, \partial t} > 0$.

Proposition 3 suggests that $\frac{\partial \Pi_P^*}{\partial \alpha}$ is monotonously increasing with t. That is, the higher the tax, the more having more efficient abatement technology will benefit the manufacturer's profitability.

Proposition 4. $\frac{\partial \Delta \widehat{\Pi}_P}{\partial \alpha} > 0$.

Proposition 4 suggests that higher technology efficiency α motivates the manufacturer to invest in abatement technology.

The following proposition illustrates the impact of the emission tax rate t. Note that (a.e.) denotes *almost everywhere*. This property can be provided as,

Proposition 5. $\frac{\partial \Pi_P^*}{\partial t} < 0$, $\frac{\partial \Pi_P^{*\,2}}{\partial t^2} > 0$ (a.e.).

Proposition 5 suggests that Π_P^* is concave decreasing in t almost everywhere. That is, an increase in the emission tax leads to less manufacturer profit. Furthermore, the reduction in manufacturer profit decreases with the tax rate. This is because, as previously pointed out, production quantity decreases with the emission tax. See diagram 4.3.1(a) for an example.

Now it is important to examine the impact of demand uncertainty ϵ.

Proposition 6 $\frac{\partial \Pi_P^*}{\partial \epsilon} < 0$.

Proposition 6 shows that the manufacturer's optimal profit Π_P^* is monotonically decreasing in ϵ (see Figure 4.6.1 for an example illustration).

The following proposition explains the relationship between ϵ and $\Delta\widehat{\Pi}_P(t)$.

Proposition *7.* $\frac{\partial \Delta\widehat{\Pi}_P}{\partial \epsilon} \geq 0$ *if and only if* $0 < \epsilon \leq Min\left(\frac{4a}{11}, 2a - 6bw - 6bet,\ a - bte(3 - 2\alpha) - 3bw,\ \frac{a-bw-bte}{2}\right)$. $\frac{\partial \Delta\widehat{\Pi}_P}{\partial \epsilon} < 0$ *otherwise.*

It is not difficult to derive the following insights from Proposition 7. When the emission tax is low, more demand uncertainty ϵ encourages the manufacturer to invest in emission abatement. This is because in this case the manufacturer's overage cost is relatively low, which motivates the manufacturer to produce in large quantities. An increase in ϵ increases the benefit of meeting demand, thus compelling the manufacturer to reduce the production and overage cost further by investing in emission abatement technology. When the emission tax is high, the overage cost is relatively high leading the manufacturer to be conservative in production. In this case, an increase in ϵ reduces the minimum demand and discourages emission abatement investment because overage cost is high, and increasing ϵ can strengthen this effectmotivates the manufacturer to reduce production quantity even further, which renders emission abatement less valuable. Therefore, an increase in ϵ discourages investment.

Chapter 5: Manufacturer Performance Analysis under CTX

5.1 Optimal Solution

CTX is directly imposed on customers instead of the manufacturer for each unit of emissions generated from their consumption. The manufacturer chooses its product price p_C, production quantity q_C, and emission abatement decision δ_C to maximize

$$\max_{p_C,\ q_C,\ \delta_C} \Pi_P(p_P, q_P, \delta_P; t) = p_C\{\frac{1}{2}q_C + \frac{1}{2}[a - b(p_C + bte(1 - \alpha\delta_C) - \epsilon]\} - wq_C - I\delta_C$$

$$\begin{aligned} s.t.\ q_C &> a - b[p_C + bte(1 - \alpha\delta_C)] - \epsilon \\ q_C &\leq a - b[p_C + bte(1 - \alpha\delta_C)] + \epsilon \\ p_C, q_C &\geq 0, \\ \delta_C &\in \{0,1\} \end{aligned} \tag{12}$$

The first and second constraints in (12) guarantee that the manufacturer neither produces more than the high demand realization nor lower than the low demand realization. The following lemma provides the optimal price and order quantity for given investment decision.

***Lemma* 2 .** *For a given* δ_C *, the optimal price and order quantity* $(\hat{p}_C(\delta_C;t), \hat{q}_C(\delta_C;t))$ *are given as*

$$(\hat{p}_C(\delta_C;t),\hat{q}_C(\delta_C;t))$$
$$= \begin{cases} \left(\dfrac{(a + b[w - te(1-\alpha\delta_C)]}{2b}, \dfrac{a + 2\epsilon - b[w + te(1-\alpha\delta_C)]}{2}\right), & if\ 0 \le t < Min(t'^C, t_b), \\ \left(\dfrac{(a - \epsilon + b[w - te(1-\alpha\delta_C)]}{2b}, \dfrac{a - \epsilon - b[w + te(1-\alpha\delta_C)]}{2}\right), & if\ t'^C \le t \le t_b, \end{cases} \tag{13}$$

where $t'^C = \frac{a - \frac{1}{2}\epsilon - 3bw}{be(1-\alpha\delta_C)}$.

Define $(\hat{p}_C(\delta_C;t),\hat{q}_C(\delta_C;t))$ result under $0 \le t < Min(t'^C, t_b)$ as solution I, result under $t'^C \le t \le t_b$ as solution II. All proofs are provided in the appendix. Lemma 2 provides that for each given δ_C, the optimal production quantity $\hat{q}_C(\delta_C;t)$ is higher when t is small (solution I) than when t is large (solution II). This is because when t is small, the profit margin of selling a product is high and thus the manufacturer produces more to capture this high margin. It can also be seen that the product price increase when t is small ($0 \le t < Min(t'^C, t_b)$) and when t is large ($t'^C \le t \le t_b$) respectively. However, the price may have a drop inbetween the two cases for the manufacturer may slash production when $t = Min(t'^C, t_b)$, and it lowers price to reduce the cost of lostsale.

Next step is to solve for the optimal investment decision $\delta_C^*(t)$. $\delta_C^*(t)$ can be obtained by comparing the profit with investment ($\delta_C = 1$) and without investment ($\delta_C = 0$), and choosing the one leading to higher profit. Denote the difference of manufacturer profit between the two investment decisions by $\Delta\widehat{\Pi}_C(t) = \Pi_C[\hat{p}_C(1;t), \hat{q}_C(1;t), 1; t] - \Pi_C[\hat{p}_C(0;t), \hat{q}_C(0;t), 0; t]$, then $\delta_C^*(t)$ can be determined by comparing $\Delta\widehat{\Pi}_C(t)$ and I, that is, $\delta_C^*(t) = 1$ if $\Delta\widehat{\Pi}_C(t) \ge I$ and $\delta_C^*(t) = 0$ otherwise. Same as PTX, figure 1 illustrates for an example how $\delta_C^*(t)$ can be determined. The following theorem charaterizes the optimal solution to the manufacturer's problem under consumption-based emission tax.

Theorem 2. *The optimal abatement decision under consumption -based emission tax is given as follows.*

$\delta_C^*(t) = 1$ *if and only if one of the following conditions hold:*

- $\epsilon \leq \frac{4}{3}bw,\ 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)},\ 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be}$, *and* $I \leq t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$;
- $\epsilon \leq \frac{4}{3}bw, 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{be} < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be(1-\alpha)}$, *and* $I \leq t^2\frac{be^2\alpha(\alpha-2)}{4} + te\frac{\alpha(a-bw)-\epsilon}{2} + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$;
- $\epsilon \leq \frac{4}{3}bw,\ 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{be(1-\alpha)} < t \leq \frac{a-bw-2\epsilon}{be}$, *and* $I \leq t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw-\epsilon}{2})$;
- $\epsilon \leq \frac{4}{3}bw,\ \alpha < \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)} \leq 1, 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be}$, *and* $I \leq t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$;
- $\epsilon \leq \frac{4}{3}bw,\ \alpha < \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)} \leq 1, \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \leq \frac{a-bw-2\epsilon}{be}$, *and* $I \leq t^2\frac{be^2\alpha(\alpha-2)}{4} + te\frac{\alpha(a-bw)-\epsilon}{2} + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$;
- $\frac{4}{3}bw < \epsilon \leq \frac{a-bw}{2}, 0 < t \leq \frac{a-bw-2\epsilon}{be}$, *and* $I \leq t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$

$\delta_C^*(t) = 0$ *if and only if one of the following conditions hold:*

- $\epsilon \leq \frac{4}{3}bw,\ 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)},\ 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be}$, *and* $I > t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$;
- $\epsilon \leq \frac{4}{3}bw, 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{be} < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be(1-\alpha)}$, *and* $I > t^2\frac{be^2\alpha(\alpha-2)}{4} + te\frac{\alpha(a-bw)-\epsilon}{2} + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$;

- $\epsilon \leq \frac{4}{3}bw,\ 0 < \alpha \leq \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}, \frac{a-\frac{1}{2}\epsilon-3bw}{be(1-\alpha)} < t \leq \frac{a-bw-2\epsilon}{be},\ and\ I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw-\epsilon}{2})$;

- $\epsilon \leq \frac{4}{3}bw,\ \alpha < \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)} \leq 1, 0 < t \leq \frac{a-\frac{1}{2}\epsilon-3bw}{be},\ and\ I > t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$;

- $\epsilon \leq \frac{4}{3}bw,\ \alpha < \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)} \leq 1, \frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \leq \frac{a-bw-2\epsilon}{be},\ and\ I > t^2\frac{be^2\alpha(\alpha-2)}{4} + te\frac{\alpha(a-bw)-\epsilon}{2} + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$;

- $\frac{4}{3}bw < \epsilon \leq \frac{a-bw}{2}, 0 < t \leq \frac{a-bw-2\epsilon}{be}, and\ I > t^2\frac{be^2\alpha(\alpha-2)}{4} + te\alpha(\frac{a-bw}{2})$

The optimal price $p_C^*(t)$ and production quantity $q_C^*(t)$ are given as

$$\left(p_C^*(t), q_C^*(t)\right) =$$

$$\begin{cases} \left(\frac{(a+b[w-te(1-\alpha\delta_C^*(t))]}{2b}, \frac{a+2\epsilon-b\left[w+te\left(1-\alpha\delta_C^*(t)\right)\right]}{2}\right), if\ 0 \leq t < Min(t'^C, t_b), \\ \left(\frac{(a-\epsilon+b[w-te(1-\alpha\delta_C^*(t))]}{2b}, \frac{a-\epsilon-b[w+te(1-\alpha\delta_C^*(t))]}{2}\right), \quad if\ t'^C \leq t \leq t_b. \end{cases} \quad (14)$$

5.2 Analysis

Same as PTX, profit difference $\Delta\widehat{\Pi}_C(t)$ and investment cost I jointly determine $\delta_C^*(t)$. $\Delta\widehat{\Pi}_C(t)$ alone determines the first-order effect of the emission tax t on the willingness of the manufacturer to invest in abatement technology. Specifically, when slope of $\Delta\widehat{\Pi}_C(t)$ is positive, the manufactuer's willingess to invest the abatement technology increases with t ,and otherwise the willingness decreases with t. Interestingly, the effect of t is nonmonotone. The number of times the slope of $\Delta\widehat{\Pi}_C(t)$ changes directions can also take values of 0, 1, 2, 3 which are denoted by scenarios C_0, C_1, C_2, C_3 respectively.

Furthermore, the number of times the slope of $\Delta\widehat{\Pi}_C(t)$ changes directions is determined by the customer demand uncertainty ϵ and the technology efficiency α. This result is summarized in the following proposition.

Proposition 8. The number of times the slope of $\Delta\widehat{\Pi}_C(t)$ switch directions during $0 \leq t \leq t_b$ is:

1) 0 (case C_0) if and only if one of the following conditions hold:

   $a)$ $\frac{4}{3}bw < \epsilon \leq \frac{a-bw}{2}$ and $\alpha_1 < \alpha \leq 1$.

2) 1 (case C_1) if and only if one of the following conditions hold:

   $a)$ $\frac{4}{3}bw < \epsilon \leq \frac{a-bw}{2}$ and $0 < \alpha \leq \alpha_1$;

   b) $0 < \epsilon \leq \frac{4}{3}bw$ and $\alpha_6 < \alpha \leq Min(\alpha_2, \alpha_3, \alpha_7)$;

   c) $0 < \epsilon \leq \frac{4}{3}bw$ and $\alpha_3 < \alpha \leq Min(\alpha_2, \alpha_5)$;

   d) $0 < \epsilon \leq \frac{4}{3}bw$ and $Max(\alpha_3, \alpha_5) < \alpha \leq Min(\alpha_2, \alpha_6)$;

   e) $0 < \epsilon \leq \frac{4}{3}bw$ and $Max(\alpha_3, \alpha_5, \alpha_7) < \alpha \leq \alpha_2$;

   f) $0 < \epsilon \leq \frac{4}{3}bw$ and $Max(\alpha_3, \alpha_6) < \alpha \leq Min(\alpha_7, \alpha_2)$.

3) 2 (case C_2) if and only if one of the following conditions hold:

   a) $0 < \alpha \leq \frac{4}{3}bw$ and $0 < \alpha \leq \frac{4}{3}Min(\alpha_2, \alpha_3, \alpha_5)$.

4) 3 (case C_3) if and only if one of the following conditions hold:

   a) $0 < \alpha \leq \frac{4}{3}bw$ and $\alpha_5 < \alpha \leq \frac{4}{3}Min(\alpha_2, \alpha_3, \alpha_6)$;

   b) a) $0 < \alpha \leq \frac{4}{3}bw$ and $Max(\alpha_5, \alpha_7) < \alpha \leq \frac{4}{3}Min(\alpha_2, \alpha_3)$.

where the $\alpha_1 = \frac{a-bw-4\epsilon}{a-bw-2\epsilon}$, $\alpha_2 = \frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}$, $\alpha_3 = \frac{a-5bw-\epsilon}{a-3bw-\frac{1}{2}\epsilon}$, $\alpha_4 =$

$\frac{a-bw-4\epsilon+\sqrt{(a-bw-4\epsilon)^2+4\varepsilon(a-bw-2\epsilon)}}{2(a-bw-2\epsilon)}$, $\alpha_5 = \frac{a-5bw-\epsilon-\sqrt{(a-5bw-\epsilon)^2+4\varepsilon(a-3bw-\frac{1}{2}\epsilon)}}{2(a-3bw-\frac{1}{2}\epsilon)}$, $\alpha_6 =$

$\frac{a-5bw-2\epsilon-\sqrt{(a-5bw-2\epsilon)^2-4\varepsilon(2bw+\frac{1}{2}\epsilon)}}{-2(2bw+\frac{1}{2}\epsilon)}$, $\alpha_7 = \frac{a-5bw-2\epsilon+\sqrt{(a-5bw-2\epsilon)^2-4\varepsilon(2bw+\frac{1}{2}\epsilon)}}{-2(2bw+\frac{1}{2}\epsilon)}$, $\alpha_8 = \frac{a-5bw}{\frac{1}{2}\epsilon-2bw}$.

Proposition 8 suggests, perhaps surprisingly, that it is possible (in cases C_1, C_2, C_3) for an increase in the emission tax to lead the manufacturer to be less willing to invest in emission abatement. With certain investment costs, this would imply that the manufacturer may switch from investing in emission abatement to not investing as the emission tax increase. In what follows, the mechanisms driving this result is explained.

This effect is shown with an example in Figure 4.2.1, which corresponds to scenario $C_3(see\ Chapter\ 4.2\ for\ PTX\ C_3\ analysis; CTX\ is\ similar)$.

In the following, the impact of techonology efficiency α on profit is examined,

Proposition 9. $\frac{\partial \Pi_C^*}{\partial \alpha} > 0$.

Proposition 9 suggest that the manfacturer's optimal profit Π_C^* is monotonically increasing with α. That is, more efficient emission abatement technology benefits the manufacturer.

Proposition 10. $\frac{\partial^2 \Pi_C^*}{\partial \alpha \partial t} > 0$.

Proposition 10 suggests that $\frac{\partial \Pi_C^*}{\partial \alpha}$ is monotonously increasing with t. That is, the higher the tax rate, the more efficient abatement technology will benefit the manufacturer's profitability.

Proposition 11. $\frac{\partial \Delta\hat{\Pi}_C}{\partial \alpha} > 0$.

Proposition 11 suggests that higher technology efficiency α motivates the manufacturer to invest in abatement technology.

The following proposition illustrates the impact of the emission tax rate t. Note that (a.e.) denotes *almost everywhere*. This property can be provided as,

Proposition 12. $\frac{\partial \Pi_C^*}{\partial t} < 0$, $\frac{\partial {\Pi_C^*}^2}{\partial t^2} > 0$ (a.e.).

Proposition 12 suggests that Π_P^* is concave decreasing in t almost everywhere. That is, an incease in the emission tax leads to less manufacturer profit. Furthermore, the reduction in manufacturer profit decreases with the tax rate. This is because, as previously pointed out, production quantity decreases with the emission tax.

Now it is important to examine the impact of demand uncertainty ϵ.

Proposition 13 $\frac{\partial \Pi_C^*}{\partial \epsilon} < 0$.

Proposition 13 shows that the manufacturer's optimal profit Π_C^* is monotonically decreasing in ϵ.

The following proposition explains the relationship between ϵ and $\Delta\widehat{\Pi}_C$.

Proposition 14. $\frac{\partial \Delta\widehat{\Pi}_C}{\partial \epsilon} = 0$ *if and only if* $0 < \epsilon \leq Min(\frac{4a}{11}, 2a - 6bw - 2bet, \frac{a - bw - bte}{2})$. $\frac{\partial \Delta\widehat{\Pi}_C}{\partial \epsilon} < 0$ *otherwise.*

The following insights can be derived from Proposition 14. When the emission tax is low, the manufacturer produces at high quantity. More demand uncertainty ϵ doesn't influence the manufacturer's technology investment decision. This is because in this case, if the manufacturer invests to the technology, the final price to customer decreases and quantity is higher. By basic model, in profit difference function, uncertainty has been offset. When the emission tax is high, an increase in ϵ discourages emission abatement investment because of high overage cost.

Chapter 6: Case Study

In this chapter, I compare the effects of PTX versus CTX in several dimensions: optimal profit, minimum tax rate for investment, emissions. I study the case of American Electric Power (AEP), which is a major investor-owned electric public utility in the United States, and one of the nation's largest generators of electricity, delivering electricity to more than five million customers in 11 states[49]. AEP is also a pioneer of emission mitigation in the industry. It has tested and adopted many emission abatement technologies in the past 15 years. The model parameters are calibrated using data from several publicly available databases, including Energy Information administration (EIA) Databases, American Electric Power (AEP) Annual Fact Books and Annual Reports.

Table 6.1: Parameter values

Parameter	Description	Value	Unit	Source
ϵ	AEP's customer demand uncertainty	30,171	Thousand MWh	AEP (2016)[50] EIA(2010-2016)[51]
a	Intercept of demand function	218,446	Thousand MWh	EIA(2010-2016)
b	Slope of demand function	1.64	Thousand MWh	EIA(2010-2016)
e	Emission quantity per unit electricity	0.971	Ton /MWh	AEP(2017)
w	Unit cost of production	24.4	Dollar/MWH	EIA (2016) AEP(2016)
I	Cost of emission abatement technology(CCS)	1.5	Billion Dollars	CC&ST(2017)[52]
α	Emission abatement technology(CCS) efficiency	0.9	-	CRS(2017)[53]

According to U.S. Energy Information Administration (EIA) (2017), the annual total electricity sales to ultimate customers in U.S. during 2010-2016 are: 3,754,841 (year 2010), 3,749,846 (year 2011), 3,694,650 (year 2012), 3,724,868 (year 2013), 3,764,700 (year 2014), 3,758,992 (year 2015), 3,710,779 (year 2016) thousand megawatt hours. U.S. Energy Information Administration (EIA) (2017) also provides U.S. total generation of electricity: 4,125,060 (year 2010), 4,100,141 (year 2011), 4,047,765 (year 2012), 4,065,964 (year 2013), 4,093,606 (year 2014), 4,077,601(year 2015), and 4079079 (year 2016), in which the coal-generated part: 1,847,290 (year 2010), 1,733,430 (year 2011), 1,514,043 (year 2012), 1,581,115 (year 2013), 1,581,710 (year 2014), 1,352,398 (year 2015), 1,240,108 (year 2016) thousand megawatt hours. It is easy to divide U.S. total coal-generated electricity by U.S. total generation of electricity to calculate the coal-generated rate. The total coal-generated electricity sales of the whole U.S.

electricity industry are obtained when multiplying the annual total electricity sales to ultimate customers in U.S. by coal-generated rate. Multiplying the total coal-generated electricity sales of the whole U.S. electricity industry by the average market share (AEP2016) of AEP 3.7% , AEP annual coal-generated electricity sales are obtained, which estimate the customer demand as: 62,091 (year 2010), 58,540 (year 2011), 51,031(year 2012), 53,487 (year 2013), 53,714 (year 2014), 46,037 (year 2015), 41,658 (year 2016) thousand megawatt hours. Demand uncertainty is estimated using the absolute residuals of demand, which is 30,171 thousand megawatt hours.

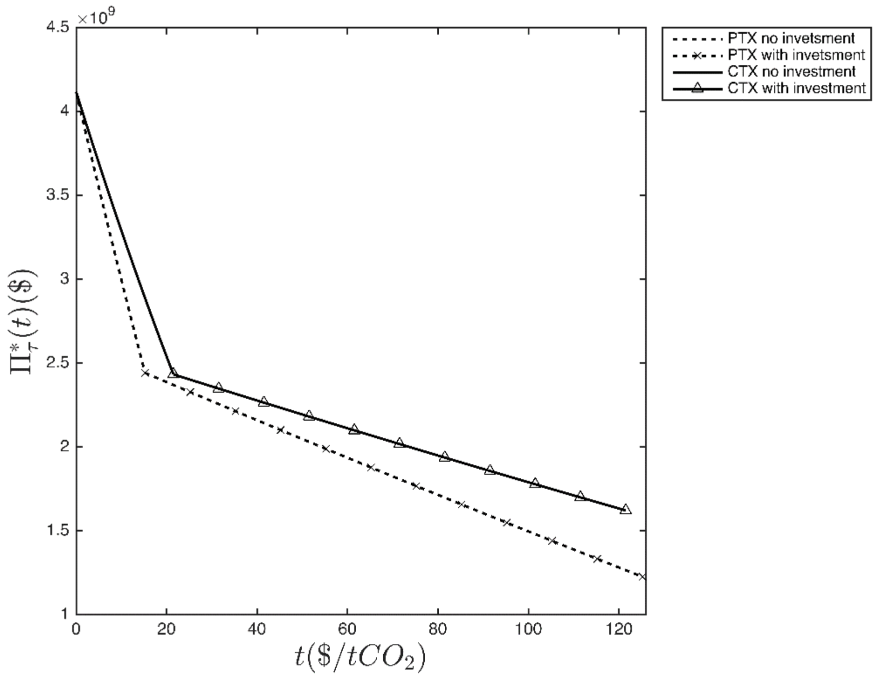
According to U.S. Energy Information Administration (EIA) (2017), the annual average prices of electricity to ultimate customers are 9.83 (year 2010), 9.90 (year 2011), 9.84 (year 2012), 10.07 (year 2013), 10.44 (year 2014), 10.41 (year 2015), 10.28 (year 2016) cents per kilowatt hour. Parameter a and b are fitted in linear demand function by the series of estimated demand of AEP and annual average prices: a=218,446 and b=1.64. Based on AEP Sustainability (2016), average coal price is $47.08/ton in 2016. The Office of Natural Resources Revenue (2017) provides that 1,927 Kilowatt hour of electricity is generated by a ton of coal[54]. Therefore, the cost of coal per Kwh is 2.44 (=47.08/1927 *100) cents, presenting the unit cost of production w.

AEP has been dedicated to decrease the CO_2 released from coal for years, yet it still has not achieved the ideal result. According to AEP Climate Change Information Request Report (2017), AEP hard coal emissions intensity in 2016 is 0.971 (ton CO_2/Mwh), regarded as emission quantity per unit electricity e; while EPA (2016) shows federal published standards of fossil stream emissions intensity is 1,400 pounds of CO_2/Mwh (equals to 0.635 ton CO_2/mwh)[55], suggesting that AEP still has a long way to go on emission abatement.

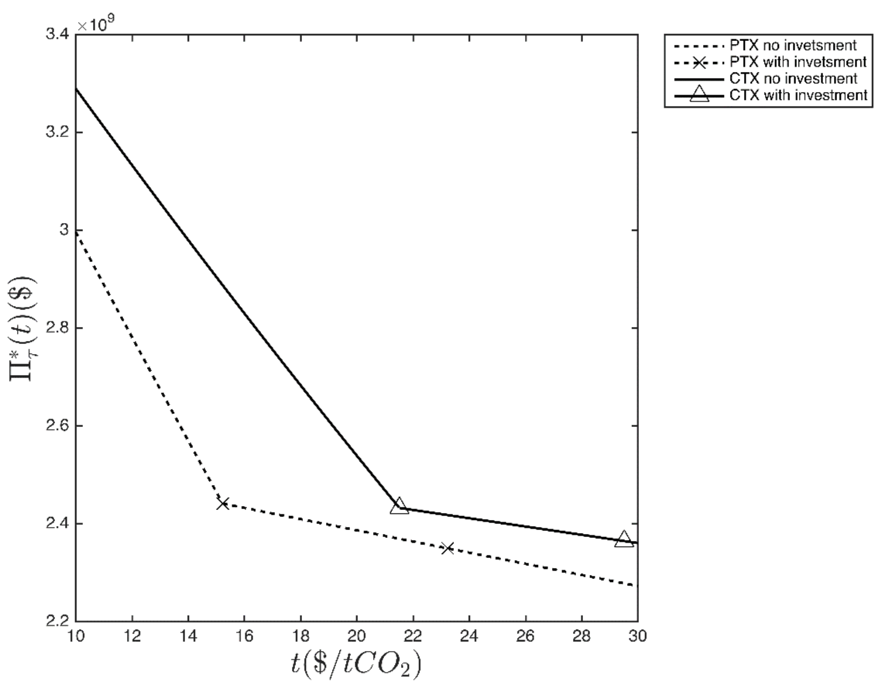
Carbon Capture and Storage Association (CCSA) (2017) stresses that Carbon Capture and Storage (CCS) is a key technology that can capture up to 90% of CO_2 produced from the use of fossil fuels, and store CO_2 permanently underground.[56] Thus emission abatement technology (CCS) efficiency α is 0.9. CCS is one of the few carbon abatement technologies that can be used in a 'carbon-negative' mode -– actually taking CO_2 out of the atmosphere. Currently, CCS is the only technology with large-scale abatement potential for many industrial sources, especially for electricity power plants.

AEP has been testing CCS technology for 15 years. According to AEP (2002), AEP's first CCS project started in Mountaineer Plant in New Haven, West Virginia in 2002 with research funding from the United States Department of Energy's (DOE) and National Energy Technology Laboratory (NETL)[57]. In October 2017, Battelle (2017) announced that the 15-Year CO_2 Storage Project at AEP Mountaineer Power Plant had been concluded successfully.[58] It is reasonable to project that AEP is ready for further CCS commercial-scale applications in the recent future. Since the data of AEP Mountaineer Project has not been published yet, I use the investment cost from an existing commercial-scale CCS project – Boundary Dam. The Boundary Dam project in Canada was the first commercial-scale power plant with CCS in the world. Boundary Dam retrofits post-combustion capture technology to units of existing plants and the total cost of the project is currently $1.5 billion, which is regarded as the Investment cost I. In what follows, it is important to use the parameter estimated above as model inputs to compare the performances of PTX and CTX.

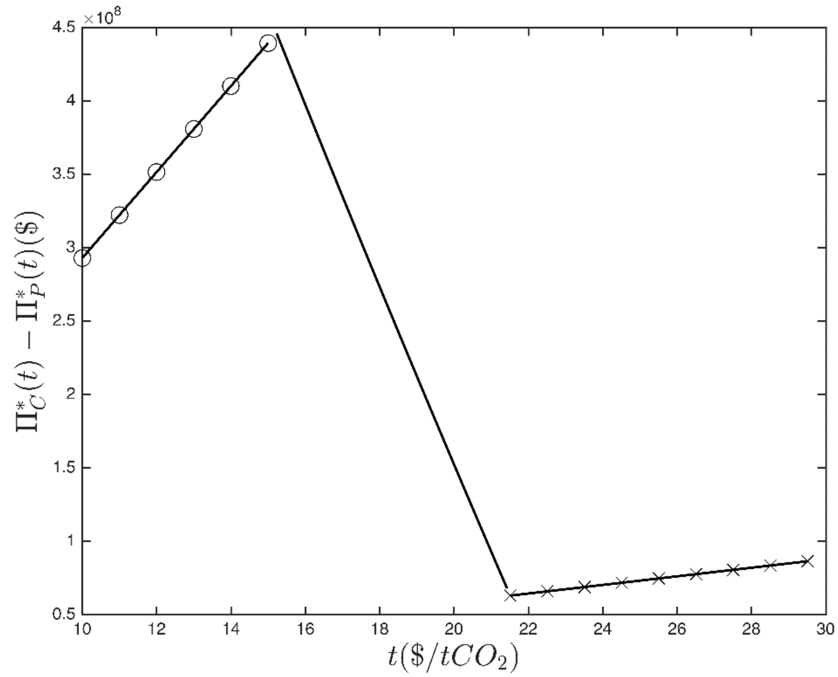
Relationship between optimal profit and tax rate



(a): $\Pi_P^*(t)$ vs. $\Pi_C^*(t)$



(b) $\Pi_P^*(t)$ vs. $\Pi_C^*(t)$ for $10 \leq t \leq 30$



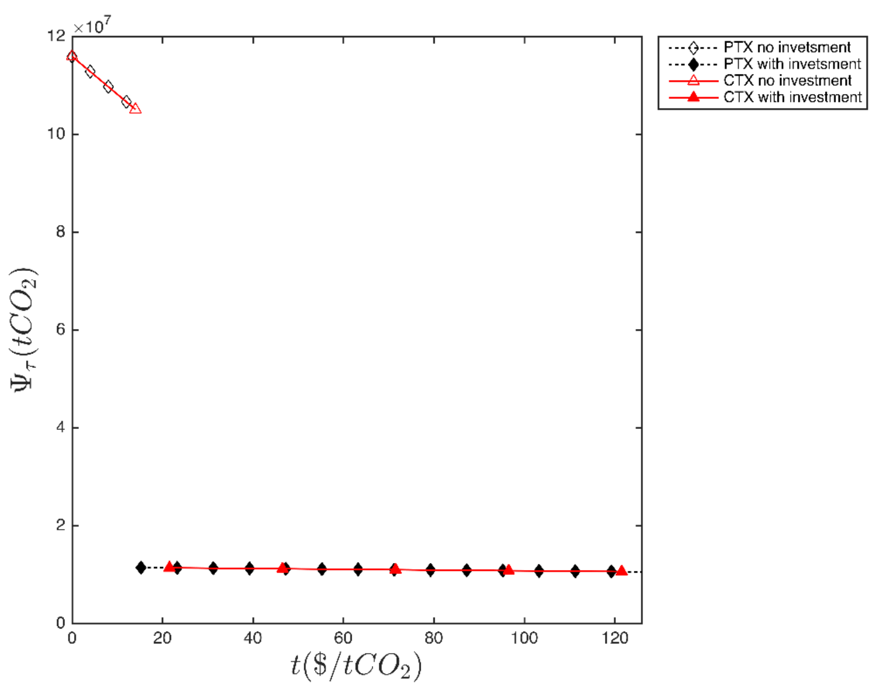
(c) $\Pi_C^*(t)$ - $\Pi_P^*(t)$) for $10 \leq t \leq 30$

Figure 6.1: Optimal profit-t

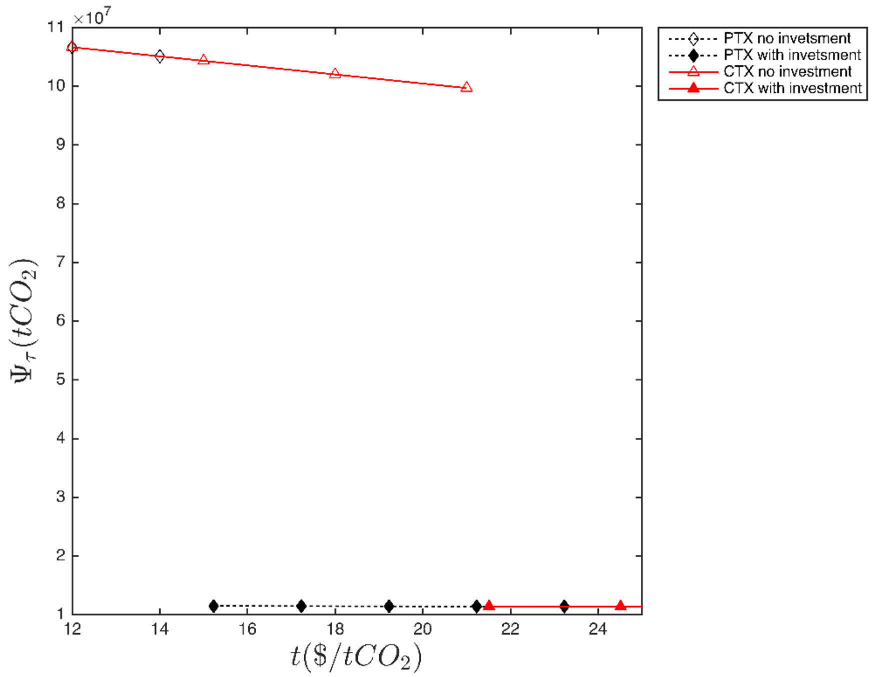
World Bank (2017) releases that current emission tax worldwide is 1~126 \$/tCO_2, which will be used as the t boundary in all following t figures. Figure 6.1(a) illustrates the optimal profit $\Pi_\tau^*(t)$. Several observations can be made based on this figure. First, it is apparent that for both of the taxes, when the manufacturer invests in emission abatement technology, the optimal profit $\Pi_\tau^*(t)$ is decreasing in t but at a much lower rate than the case without investment. This is because of the emission-abatement technology reduces unit emissions and thus the impact of emission tax. Second, for each given t, the manufacturer obtains a higher profit under CTX policy ($\Pi_P^*(t) < \Pi_C^*(t)$). This is because under CTX the manufacturer's production may not be entirely taxed. Third, under PTX, the manufacturer chooses to invest abatement technology at a smaller t than under CTX, which indicates that the manufacturer is under higher pressure to invest in abatement when PTX is imposed.

When t is quite small, the manufacturer declines to invest abatement technology under either tax, because the cost of the technology cannot be justified by the profit margin benefit; and in this case, $\Pi_C^*(t)$ is significantly higher than $\Pi_P^*(t)$ with their difference increasing in t. When t is around \$15.55/tCO_2, as discussed before, the manufacturer starts to invest under PTX but still not invest under CTX. The advantage of abatement technology investment increase at a faster rate than CTX's profit advantages. When t is around \$22/tCO_2, the manufacturer chooses to invest in abatement technology (CCS in this case) under either of the tax. CCS is a very effective abatement technology with $\alpha = 0.9$, then almost all emission has been captured, thus the profit difference under PTX and CTX becomes small, with CTX yielding higher profit.

Relationship between emissions and tax rate



(a) Emission -t



(b) Emission – t for $12 \leq t \leq 25$

Figure 6.2: Emission-t

When t is relatively small and relatively large, the manufacturer always takes the same measures and produce same emission under both taxes. Note when $15.55 \leq t \leq 21.51$, the manufacturer chooses to invest under PTX while chooses not to invest under CTX, resulting in strictly lower emissions under PTX than under CTX.

Relationship between optimal profit and demand uncertainty

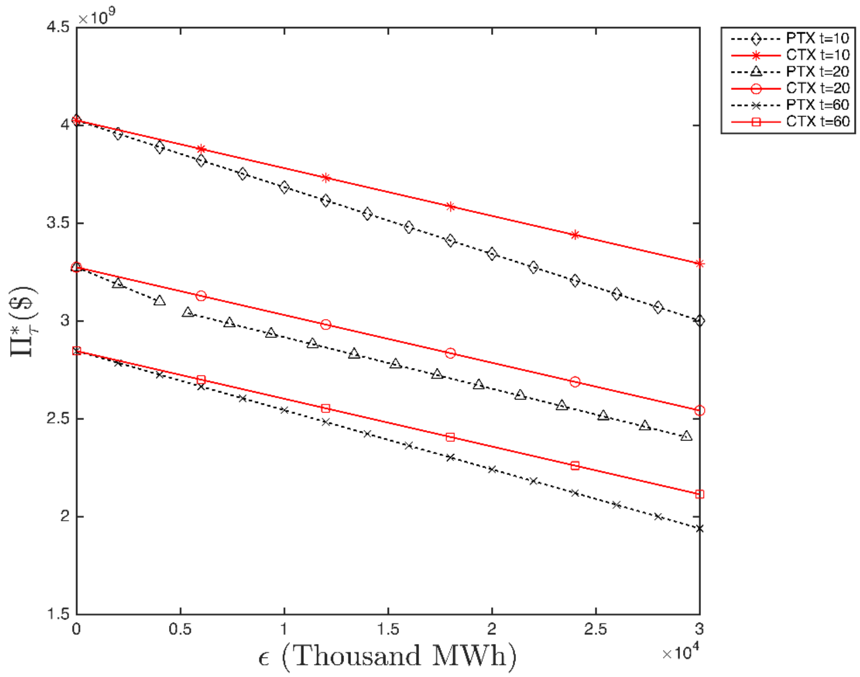
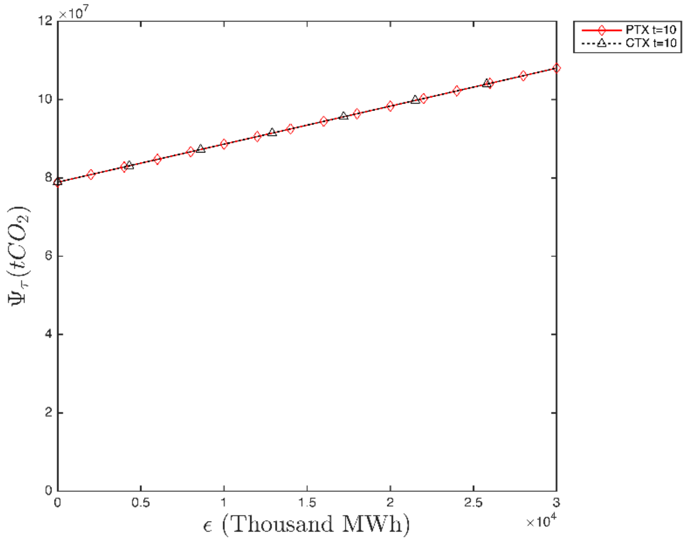


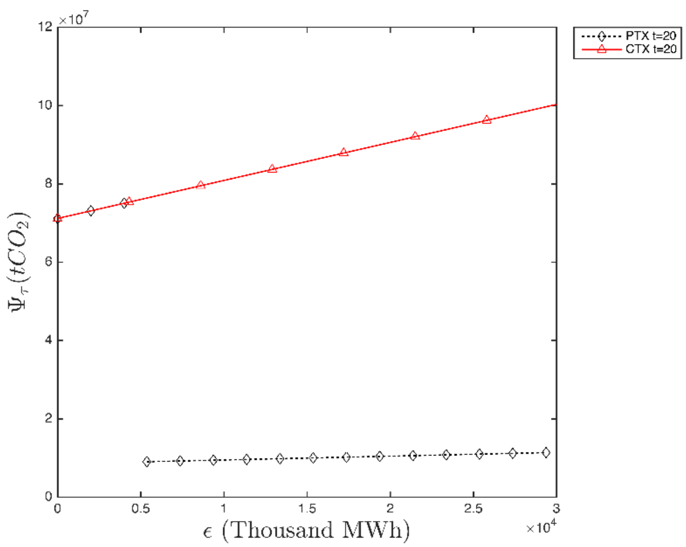
Figure 6.3: Relationship between optimal profit and demand uncertainty

The optimal profit $\Pi^*_\tau(t)$ is decreasing in demand uncertainty ϵ. Given each ϵ, $\Pi^*_P(t) < \Pi^*_C(t)$, and $\Pi^*_C(t) - \Pi^*_P(t)$ is increasing in ϵ. When t=10 or 60, the manufacturer does either always chooses to invest or always chooses not to invest for all ϵ. When t=20, the manufacturer always chooses not to invest under CTX, however, it first chooses to invest and then not to invest under PTX. It can be seen that when the manufacturer invests in abatement when t=20, the profit decreases at a slower rate than that when it does not invest in abatement.

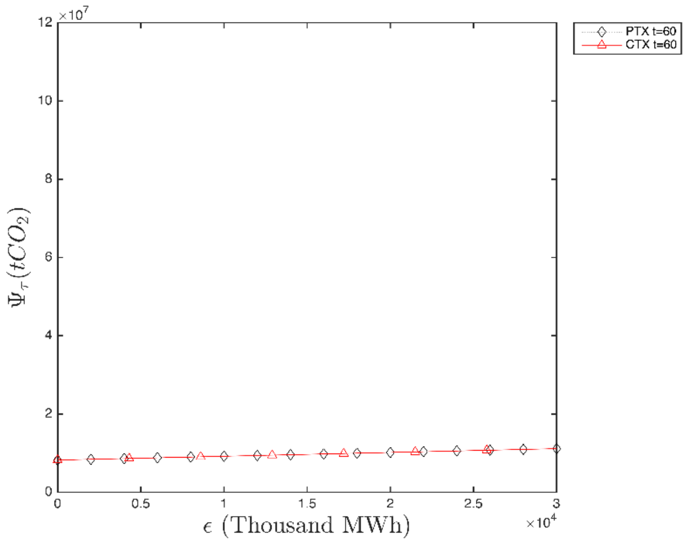
Relationship between emission and demand uncertainty



(a) t=10 \$/tCO_2



(b) t=20 \$/tCO_2



(c) t=60 \$/t$\mathbf{CO_2}$

Figure 6.4: Relationship between emission and demand uncertainty

Emissions are increasing in demand uncertainty ϵ. Consistent with figure 6.3, it is obvious that abatement investment decisions remain the same for all ϵ when t is either relatively small or or relatively large. When t is medium (t=20), the manufacturer does not invest when $\epsilon \leq 0.5$ and invest when $\epsilon > 0.5$ under PTX.

Relationship between optimal profit and emission

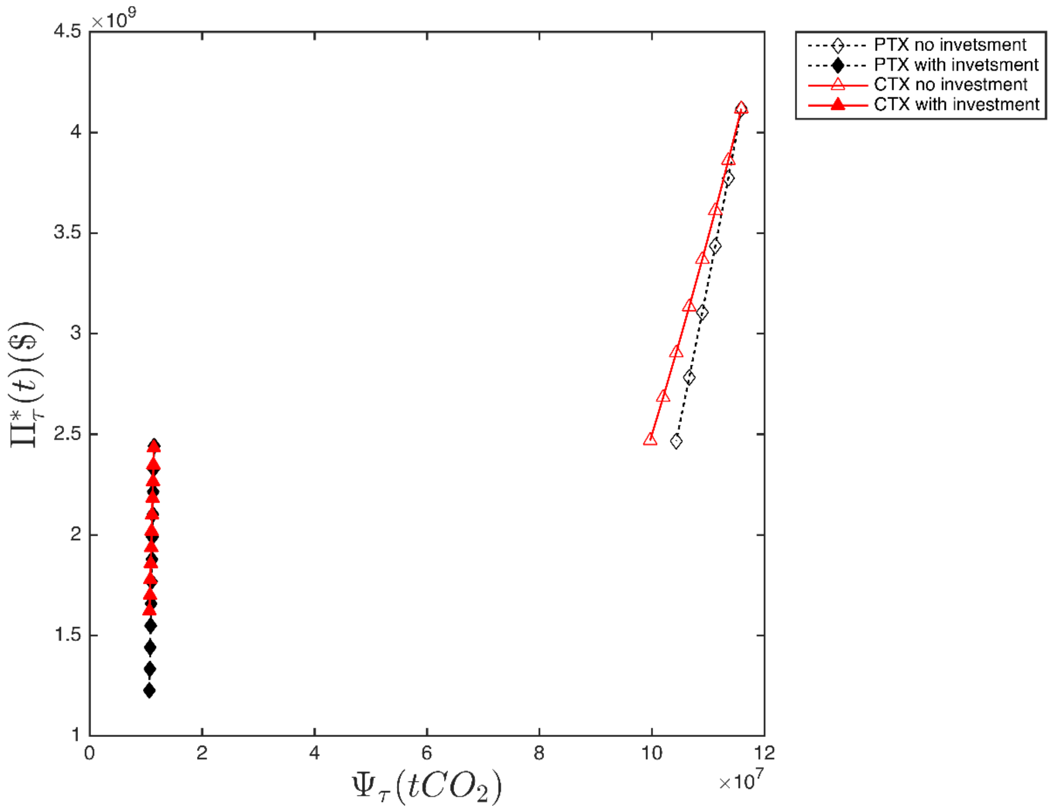


Figure 6.5: Relationship between optimal profit and emission

The optimal profit increases as emissions increase. The curves can be separated into two groups. When t is small, the manufacturer's concern for emissions and emission tax is low, and as a result it does not invest in abatement leading to high profit and high emission. (when t=0, both profit and emission reach the maximum values). When t is relatively big, the manufacturer slashes down the emission by investing in abatement technology (and reducing production quantity), which also drags the optimal profit down (when t=t_b, both profit and emission reach the minimum values.)

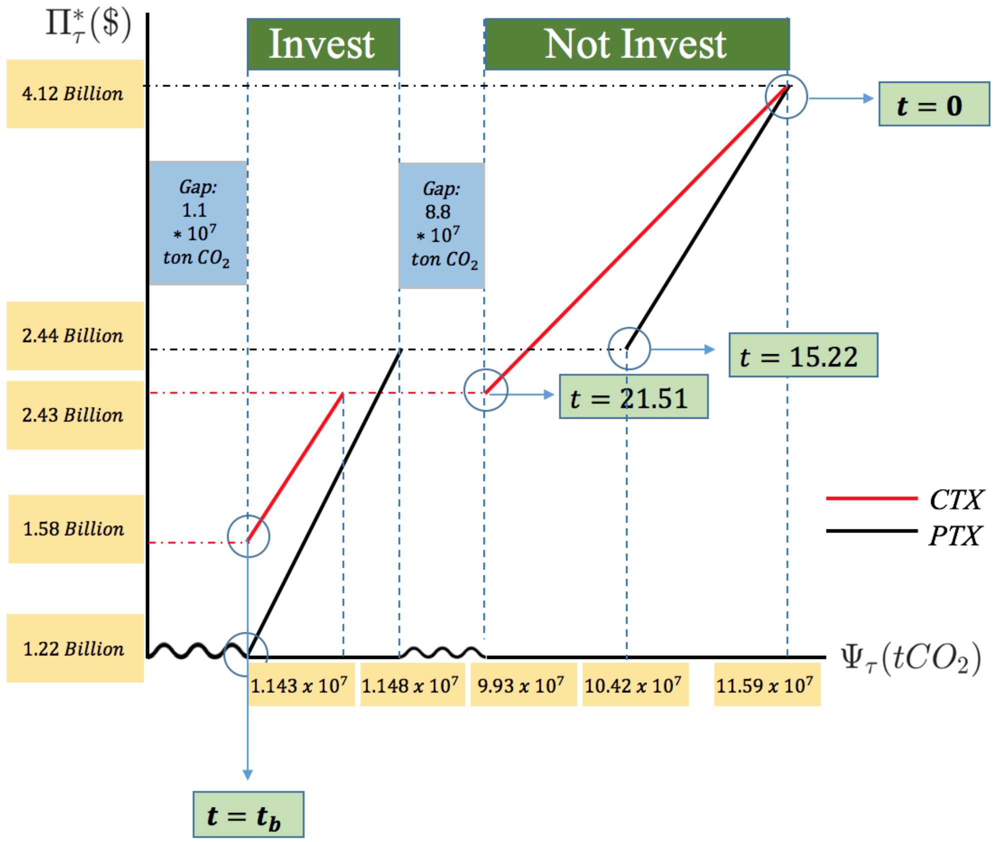


Figure 6.6: Analysis between optimal profit and emission

It is notable that, the manufacturer's investment decisions change at t=\$15.55/tCO_2, with $\Pi^*_P = \$2.4415$ Billion, and $\psi_P = 11475$ thousand tCO_2 under PTX; while this change happens at t=\$21.51/tCO_2 under CTX, with $\Pi^*_C = \$2.4325$ Billion, and $\psi_C = 11426$ thousand tCO_2. It can be seen from the figure that when the profits are medium (\$2.4415 Billion~\$2.4325 Billion), PTX induces much lower emissions than CTX for the same profit. When the profits are higher or lower, CTX induce lower emissions than PTX for same profit.

In addition, after the investment, the two profit-emission curves are more parallel than before, which is because the result difference between the two taxes has been reduced significantly by the high efficiency technology (CCS removes 90% of the emission).

Sensitivity Analysis for minimum tax rate for investment (unit: $\$/tCO_2$)

Variation in Parameter		% change value in parameter						
		-50	-25	-10	0	10	25	50
α	*PTX*	**Not invest.**[3]	**53.66**[4]	17.14	15.22	13.70	-	-
	CTX	**Not invest**[5]	31.53	24.59	21.51	19.14	-	-
I	*PTX*	7.39	11.25	13.62	15.22	16.86	**21.21**[6]	**30.44**[7]
	CTX	10.12	15.63	19.11	21.51	23.99	27.86	34.81
ϵ	*PTX*	17.78	16.40	15.67	15.22	14.81	14.22	13.34
	CTX	21.51	21.51	21.51	21.51	21.51	21.51	21.51

[3] No investment. The manufacturer chooses to slash down production quantity (when t= 17.44) to abate emission and tax.

[4] Three reverses cases. The manufacturer chooses to slash down production quantity (when t= 17.44) at first and then draw back the high production quantity with investment (when t=31.19) to abate emission and tax. (Same as case in chapter 4.3)

[5] No investment. The manufacturer chooses to slash down production quantity (when t= 64) to abate emission and tax.

[6] The manufacturer chooses to slash down production quantity (when t= 17.44) at first and then draw back the high production quantity with investment (when t=21.21) to abate emission and tax.

[7] The manufacturer chooses to slash down production quantity (when t= 17.44) at first and then draw back the high production quantity with investment (when t=30.44) to abate emission and tax.

Chapter 7: Discussion and Conclusion

This paper demonstrates solutions for a profit-maximizing monopolistic manufacturer facing demand uncertainty to maximize its profit by selecting its production quantity, product price and whether to invest in an emission abatement technology under two tax schemes: production-based emission tax (PTX) or consumption-based emission tax (CTX). Differing from previous discussion on different emission accounting methods which focuse on the emission leakage effect due to varying emission tax levels between locations of production and consumption, this thesis explores the different effects of PTX and CTX in the presence of demand uncertainty.

The result of the paper highlights the importance of including demand uncertainty into evaluating the effects of emission tax schemes. It has been found that under demand uncertainty, PTX and CTX leads to different decisions of the manufacturer and the corresponding profits and emissions. Contrary conventional wisdom, under either PTX or CTX, higher emission tax may discourage the manufacturer from investing in emission abatement technology in some cases, suggesting that the government should not always pursue higher tax rate to incentivize more emission abatement. Interestingly, an increase of uncertainty may can motivate the manufacturer to invest in emission abatement when tax rate is relatively low.

Finally in this paper, I took the case of a major electricity generator American Electric Power to analyze the comparison between PTX and CTX in several dimensions. The results shows that CTX is the dominating scheme (in terms of manufacturer profit and emissions) when tax rates are either low or high, while PTX becomes the dominating scheme for intermediate tax rates.

This work can be extended in several directions. Demand uncertainty is verified to be an essential parameter to be included in the discussion to understand the impact of an emission tax. It would be interesting to check the manufacturer's optimal solutions if the demand certainty is subject to different distribution other than Bernoulli distribution. It is predicted that similar conclusion will still hold, but the solution is more likely to be continuous. One can also change the linear demand function into other forms, albeit that would likely make the mathematics more cumbersome. In addition, it will be worthwhile to study the socially optimal tax rate of the government under either tax scheme and the corresponding impact on the economy and the environment.

Appendix I. Proofs

Proof of Proposition 2.

Given other parameters fixed, next ste is to explore what impact that technology efficiency α brings. By lemma 1, there are two eligible solutions for the manufacturer to apply, solution I and solution II. Denote optimal profit under the two solutions by Π_{PI}^* and Π_{PII}^* repectively. Per *Lemma 1*,

$if\ 0 \le t < Min(t''^P, t_b)$,solution I is preferred,

$$\frac{\partial \Pi_P^*}{\partial \alpha} = \frac{\partial \Pi_{PI}^*}{\partial \alpha} = \frac{te}{2}(a + 2\epsilon - b[w + te(1 - \alpha\delta_p)]) > 0.$$

$if\ t''^P \le t \le t_b$, solution II is preferred,

$$\frac{\partial \Pi_P^*}{\partial \alpha} = \frac{\partial \Pi_{PII}^*}{\partial \alpha} = \frac{te}{2}(a + \epsilon - b[w + te(1 - \alpha\delta_p)]) > 0.$$

It is obvious that under each solution, optimal profit Π_P^* increases with α raises. Consider that $\Pi_P^* = max(\Pi_{PI}^*,\ \Pi_{PII}^*)$ and Π_P^* is continuous in α.

Proof of Proposition 3.

There is another important principle that can be observed easily.

$if\ 0 \le t < Min(t'^P, t_b)$,solution I is preferred,

$$\frac{\partial^2 \Pi_{PI}^*}{\partial \alpha \partial t} = \frac{e}{2}(a + 2\epsilon - bw - 2bte(1 - \alpha\delta_p)) > 0.$$

$if\ t''^P \le t \le t_b$, solution II is preferred,

$$\frac{\partial^2\Pi_{PII}^*}{\partial\alpha\partial t} = \frac{e}{2}(a - \epsilon - bw - 2bte(1 - \alpha\delta_p)) > 0.$$

Therefore, $\frac{\partial^2\Pi_{PI}^*}{\partial\alpha\partial t}$ and $\frac{\partial^2\Pi_{PII}^*}{\partial\alpha\partial t}$ are both monotonously increasing in t. In addition, $\Pi_P^* = max(\Pi_{PI}^*, \Pi_{PII}^*)$ and Π_P^* is continuous in α, thus $\frac{\partial^2\Pi_P^*}{\partial\alpha\partial t}$ is monotonously increasing in t. In other words, when t increases, Π_P^* becomes more sensitive to α, indicating that when t is greater, the effect of given abatement technology will be stronger.

Proof of Proposition 4.

Next, the property of relationship between α and $\Delta\widehat{\Pi}_P$ shows as follows. There are three possible senarios for $\frac{\partial\Delta\widehat{\Pi}_P}{\partial\alpha}$, as follows,

(1) $(\partial\Pi_{PI}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PI}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t])/\partial\alpha = \frac{te}{2(a+2\epsilon-b[w+te(1-\alpha\delta_p)])} > 0$

(2) $(\partial\Pi_{PI}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PII}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t])/\partial\alpha 0; t])/\partial\alpha = \frac{te}{2(a+2\epsilon-b[w+te(1-\alpha\delta_p)])} > 0$

(3) $(\partial\Pi_{PII}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PII}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t])/\partial\alpha 0; t])/\partial\alpha = \frac{te}{2(a-\epsilon-b[w+te(1-\alpha\delta_p)])} > 0$

Thus no matter in whichever senario, $\frac{\partial\Delta\widehat{\Pi}_P}{\partial\alpha} > 0$.

Proof of Proposition 5.

$if\ 0 \le t < Min(t'^P, t_b)$, solution I is preferred,

$$\frac{\partial\Pi_{PI}^*}{\partial t} = \frac{e}{2}(\alpha - 1)(a + 2\epsilon - b[w + te(1 - \alpha\delta_p)]) < 0.$$

$if\ t'^P \leq t \leq t_b$, solution II is preferred,

$$\frac{\partial \Pi_{PII}^*}{\partial t} = \frac{e}{2}(\alpha - 1)(a - \epsilon - b[w + te(1 - \alpha\delta_p)]) < 0.$$

With t increasing, Π_{PI}^* and Π_{PII}^* are monotonically decreasing. $\Pi_P^* = max(\Pi_{PI}^*,\ \Pi_{PII}^*)$ and Π_P^* is continuous in t, thus $\frac{\partial \Pi_P^*}{\partial t} < 0$. It is notable that for second derivative, there are:

$$\frac{\partial^2 \Pi_{PI}^*}{\partial t^2} = \frac{\partial^2 \Pi_{PII}^*}{\partial t^2} = \frac{be^2}{2}(1 - \alpha) > 0,$$

thus $\frac{\partial^2 \Pi_P^*}{\partial t^2} > 0$ (a. e.).

Proof of Proposition 6.

Refer Lemma 1, transform t conditions of solution I and II into ϵ conditions:

$if\ 0 \leq \epsilon < Min(2a - 6bw - 6bte(1 - \alpha\delta_p), \frac{4a}{11}, \frac{a-bw-bte}{2})$ or $\frac{4a}{11} \leq \epsilon <\ Min(\frac{a-bw}{2}, \frac{a-bw-bte}{2})$, solution I is preferred.

$$\frac{\partial \Pi_{PI}^*}{\partial \epsilon} = te(\alpha - 1) - w < 0$$

$if\ 2a - 6bw - 6bte(1 - \alpha\delta), \leq \epsilon < Min(\frac{a-bw-bte}{2}, \frac{4a}{11})$, solution II is preferred.

$$\frac{\partial \Pi_{PII}^*}{\partial \epsilon} = \frac{\epsilon - a + bw + bte - bte\alpha}{2b} < 0$$

It is obvious that under each solution, optimal profit decreases with ϵ raises. Next let's consider two solutions together. With ϵ increasing, Π_{PI}^* and Π_{PII}^* are continuous and monotonically decreasing, Π_P^* is also continuous and monotonically decreasing, since $\Pi_P^* = max(\Pi_{PI}^*,\ \Pi_{PII}^*)$.

Proof of Proposition 7.

There are three possible senarios for $\frac{\partial \Delta \hat{\Pi}_P}{\partial \epsilon}$, as follows,

(1) $(\partial \Pi_{PI}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PI}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t]) / \partial \epsilon = te\alpha > 0$

(2) $(\partial \Pi_{PI}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PII}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t]) / \partial \epsilon =$

$\frac{-(\epsilon - a + 3bw + 3bet - 2bet\alpha)}{2b}$

when $t \leq \frac{a - \epsilon - 3bw}{be(3 - 2\alpha)}, \frac{\partial \Delta \hat{\Pi}_P}{\partial \epsilon} \geq 0;$

when $t > \frac{a - \epsilon - 3bw}{be(3 - 2\alpha)}, \frac{\partial \Delta \hat{\Pi}_P}{\partial \epsilon} < 0;$

(3) $(\partial \Pi_{PII}[\hat{p}_P(1;t), \hat{q}_P(1;t), 1; t] - \Pi_{PII}[\hat{p}_P(0;t), \hat{q}_P(0;t), 0; t]) / \partial \epsilon = \frac{-te\alpha}{2} < 0$

Please note t period keeps increasing in order of (1)(2)(3).

Summarize all senarios:

$\frac{\partial \Delta \hat{\Pi}_P}{\partial \epsilon} \geq 0$ *if and only if one of the following conditions hold:*

$$0 < \epsilon \leq Min(\frac{4a}{11}, 2a - 6bw - 6bet, \quad a - bte(3 - 2\alpha) - 3bw, \quad \frac{a - bw - bte}{2})$$

$\frac{\partial \Delta \hat{\Pi}_P}{\partial \epsilon} < 0$ *otherwise.*

Proof of Proposition 8~13.

All properties proof methods under PTX are also applicable to methods under CTX. Please refer to proof of Proposition 2~6.

Proof of Proposition 14.

There are three possible senarios for $\frac{\partial \Delta \hat{\Pi}_C}{\partial \epsilon}$, as follows,

(3) If $0 \leq t < \frac{a - \frac{1}{2}\epsilon - 3bw}{be}$,

$(\partial \Pi_{CI}[\hat{p}_C(1;t), \hat{q}_C(1;t), 1; t] - \Pi_{CI}[\hat{p}_C(0;t), \hat{q}_C(0;t), 0; t]) / \partial\epsilon = 0;$

(4) $(\partial \Pi_{CI}[\hat{p}_C(1;t), \hat{q}_C(1;t), 1; t] - \Pi_{CII}[\hat{p}_C(0;t), \hat{q}_C(0;t), 0; t]) / \partial\epsilon =$

$\frac{-(\epsilon - a + 3bw + 3bet - 2bet\alpha)}{2b}$

when $t \leq \frac{a-\epsilon-3bw}{be}, \frac{\partial\Delta\hat{\Pi}_C}{\partial\epsilon} \geq 0;$

when $t > \frac{a-\epsilon-3bw}{be}, \frac{\partial\Delta\hat{\Pi}_C}{\partial\epsilon} < 0;$

(3) $(\partial \Pi_{CII}[\hat{p}_C(1;t), \hat{q}_C(1;t), 1; t] - \Pi_{CII}[\hat{p}_C(0;t), \hat{q}_C(0;t), 0; t]) / \partial\epsilon = \frac{-te\alpha}{2} < 0$

Please note t period keeps increasing in order of (1)(2)(3).

Summarize all senarios:

$\frac{\partial\Delta\hat{\Pi}_C}{\partial\epsilon} = 0$ *if and only if one of the following conditions hold:*

$$0 < \epsilon \leq Min(\frac{4a}{11}, 2a - 6bw - 2bet, \frac{a - bw - bte}{2})$$

$\frac{\partial\Delta\hat{\Pi}_C}{\partial\epsilon} < 0$ *otherwise.*

Appendix II. Optimal Investment Decision

Table Appendix 3.1: Optimal investment decision under PTX

ϵ and α	t	I	$\delta_P^*(t)$
$\epsilon \le \frac{4}{11}a$, $0 < \alpha \le \frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)}$	$0 < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	0
	$\frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$	0
	$\frac{a-\frac{1}{2}\epsilon-3bw}{3be(1-\alpha)} < t \le \frac{a-bw-2\epsilon}{be}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw-\epsilon}{2})$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw-\epsilon}{2})$	0
$\epsilon \le \frac{4a}{11}$, $\frac{a-\frac{11}{2}\epsilon}{3(a-bw-2\epsilon)} < \alpha \le 1$	$0 < t \le \frac{a-\frac{1}{2}\epsilon-3bw}{3be}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	0
	$\frac{a-\frac{1}{2}\epsilon-3bw}{3be} < t \le \frac{a-bw-2\epsilon}{be}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te(\frac{\alpha(a-bw+2\epsilon)-3\epsilon}{2}) + \frac{\epsilon(2a-6bw-\epsilon)}{4b}$	0
$\frac{4a}{11} < \epsilon \le \frac{a-bw}{2}$	$0 < t \le \frac{a-bw-2\epsilon}{be}$	$I \le t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	1
		$I > t^2(\frac{be^2\alpha(\alpha-2)}{4}) + te\alpha(\frac{a-bw+2\epsilon}{2})$	0

Table Appendix 3.2: Optimal investment decision under CTX

ϵ **and** α	t	I	$\delta_C^*(t)$
$\epsilon \leq \frac{4}{3}bw$, $0 < \alpha \leq \frac{4bw - 3\epsilon}{2(a - bw - 2\epsilon)}$	$0 < t \leq \frac{a - \frac{1}{2}\epsilon - 3bw}{be}$	$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	1
		$I > t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	0
	$\frac{a - \frac{1}{2}\epsilon - 3bw}{be} < t \leq \frac{a - \frac{1}{2}\epsilon - 3bw}{be(1 - \alpha)}$	$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\frac{\alpha(a - bw) - \epsilon}{2} + \frac{\epsilon(2a - 6bw - \epsilon)}{4b}$	1
		$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\frac{\alpha(a - bw) - \epsilon}{2} + \frac{\epsilon(2a - 6bw - \epsilon)}{4b}$	0
	$\frac{a - \frac{1}{2}\epsilon - 3bw}{be(1 - \alpha)} < t \leq \frac{a - bw - 2\epsilon}{be}$	$I \leq t^2(\frac{be^2\alpha(\alpha - 2)}{4}) + te\alpha(\frac{a - bw - \epsilon}{2})$	1
		$I > t^2(\frac{be^2\alpha(\alpha - 2)}{4}) + te\alpha(\frac{a - bw - \epsilon}{2})$	0
$\epsilon \leq \frac{4}{3}bw$, $\alpha < \frac{4bw - 3\epsilon}{2(a - bw - 2\epsilon)} \leq 1$	$0 < t \leq \frac{a - \frac{1}{2}\epsilon - 3bw}{be}$	$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	1
		$I > t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	0
	$\frac{a - \frac{1}{2}\epsilon - 3bw}{3be} < t \leq \frac{a - bw - 2\epsilon}{be}$	$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\frac{\alpha(a - bw) - \epsilon}{2} + \frac{\epsilon(2a - 6bw - \epsilon)}{4b}$	1
		$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\frac{\alpha(a - bw) - \epsilon}{2} + \frac{\epsilon(2a - 6bw - \epsilon)}{4b}$	0
$\frac{4}{3}bw < \epsilon \leq \frac{a - bw}{2}$	$0 < t \leq \frac{a - bw - 2\epsilon}{be}$	$I \leq t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	1
		$I > t^2 \frac{be^2\alpha(\alpha - 2)}{4} + te\alpha(\frac{a - bw}{2})$	0

Appendix III. The Number of Times The Slope of Profit Difference Switches Directions

Table Appendix4.2.1: Number of times profit difference switches slope directions under PTX

$(\alpha_4 < \alpha_5 < \alpha_6; \alpha_4 < \alpha_3)$

Case Type	$\boldsymbol{\epsilon}$	$\boldsymbol{\alpha}$
C_0	$(\frac{4}{11}a, \frac{a-bw}{2}]$	$(\alpha_1, 1]$
	$(\frac{2a-6bw}{7}, \frac{4}{11}a]$	$(Max(\alpha_5, \alpha_8), Min(\alpha_6, \alpha_2)] \cup (Max(\alpha_2, \alpha_3), 1]$
	$([0, \frac{2a-6bw}{7}]$	$(Max(\alpha_2, \alpha_3), 1]$
C_1	$(\frac{4}{11}a, \frac{a-bw}{2}]$	$(0, \alpha_1]$
	$(\frac{2a-6bw}{7}, \frac{4}{11}a]$	$(\alpha_5, Min(\alpha_6, \alpha_8, \alpha_2)] \cup (\alpha_2, Max(\alpha_2, \alpha_3)]$
	$([0, \frac{2a-6bw}{7}]$	$(\alpha_5, Min(\alpha_6, \alpha_7, \alpha_2)] \cup (\alpha_7, Min(\alpha_4, \alpha_2)]$ $\cup (Max(\alpha_4, \alpha_7), Min(\alpha_5, \alpha_2)]$ $\cup (Max(\alpha_5, \alpha_7), Min(\alpha_6, \alpha_2)]$ $\cup (Max(\alpha_6, \alpha_7), \alpha_2] \cup (\alpha_2, Max(\alpha_2, \alpha_4)]$ $\cup (Max(\alpha_2, \alpha_4), Max(\alpha_2, \alpha_3)]$
C_2	$(\frac{2a-6bw}{7}, \frac{4}{11}a]$	$(\alpha_8, Min(\alpha_4, \alpha_2)] \cup (Max(\alpha_4, \alpha_8), Min(\alpha_5, \alpha_2)]$ $\cup (\alpha_6, Min(\alpha_8, \alpha_2)]$
C_3	$(\frac{2a-6bw}{7}, \frac{4}{11}a]$	$(0, Min(\alpha_4, \alpha_8, \alpha_2)) \cup ((\alpha_4, Min(\alpha_5, \alpha_8, \alpha_2)]$ $\cup (\alpha_6, Min(\alpha_8, \alpha_2)]$
	$[0, \frac{2a-6bw}{7}]$	$((0, Min(\alpha_4, \alpha_7, \alpha_2)] \cup (\alpha_4, Min(\alpha_5, \alpha_7, \alpha_2)]$ $\cup (\alpha_6, Min(\alpha_7, \alpha_2)]$

Table Appendix4.2.2: α values under PTX

$\boldsymbol{\alpha}$	**Value**
α_1	$\frac{a - bw - 6\epsilon}{a - bw - 2\epsilon}$
α_2	$\frac{4a - 11\epsilon}{6(a - bw - 2\epsilon)}$
α_3	$\frac{a - bw - 6\epsilon + \sqrt{a^2 - 2abw + b^2w^2 + 12\epsilon^2}}{2(a - bw - 2\epsilon)}$
α_4	$\frac{a + 7\epsilon \pm \sqrt{a^2 + 50a\epsilon + 6abw + 9b^2w^2 - 66b\epsilon w + 31\epsilon^2}}{-2a + 6bw + \epsilon}$
α_5	$\frac{a + 3bw + 16\epsilon - \sqrt{a^2 + 6abw + 9b^2w^2 - 40a\epsilon + 96bw\epsilon + 22\epsilon^2}}{4a + 13\epsilon}$
α_6	$\frac{a + 3bw + 16\epsilon + \sqrt{a^2 + 6abw + 9b^2w^2 - 40a\epsilon + 96bw\epsilon + 22\epsilon^2}}{4a + 13\varepsilon}$
α_7	$\frac{2(a + 3bw - 2\epsilon)}{4a - 5\epsilon}$
α_8	$\frac{a - bw - 3\epsilon}{a - bw - 2\epsilon}$

Table Appendix4.2.3: Number of times profit difference switches slope directions under CTX

Case Type	ϵ	α
C_0	$(\frac{4}{3}bw, \frac{a-bw}{2}]$	$(\alpha_1, 1]$
C_1	$(\frac{4}{3}bw, \frac{a-bw}{2}]$	$(0, \alpha_1]$
	$(0, \frac{4}{3}bw]$	$(\alpha_6, Min(\alpha_2, \alpha_3, \alpha_7)] \cup (\alpha_3, Min(\alpha_2, \alpha_5)]$ $\cup (Max(\alpha_3, \alpha_5), Min(\alpha_2, \alpha_6)] \cup (Max(\alpha_3, \alpha_5, \alpha_7), \alpha_2]$ $\cup (Max(\alpha_3, \alpha_6), Min(\alpha_7, \alpha_2)]$
C_2	$(0, \frac{4}{3}bw]$	$(0, Min(\alpha_2, \alpha_3, \alpha_5)]$
C_3	$(0, \frac{4}{3}bw]$	$(\alpha_5, Min(\alpha_2, \alpha_3, \alpha_6)) \cup (Max(\alpha_5, \alpha_7), Min(\alpha_2, \alpha_3)]$

Table Appendix4.2.4: α values under CTX

α	Value
α_1	$\frac{a-bw-4\epsilon}{a-bw-2\epsilon}$
α_2	$\frac{4bw-3\epsilon}{2(a-bw-2\epsilon)}$
α_3	$\frac{a-5bw-\epsilon}{a-3bw-\frac{1}{2}\epsilon}$
α_4	$\frac{a-bw-4\epsilon+\sqrt{(a-bw-4\epsilon)^2+4\varepsilon(a-bw-2\epsilon)}}{2(a-bw-2\epsilon)}$
α_5	$\frac{a-5bw-\epsilon-\sqrt{(a-5bw-\epsilon)^2+4\varepsilon(a-3bw-\frac{1}{2}\epsilon)}}{2(a-3bw-\frac{1}{2}\epsilon)}$
α_6	$\frac{a-5bw-2\epsilon-\sqrt{(a-5bw-2\epsilon)^2-4\varepsilon(2bw+\frac{1}{2}\epsilon)}}{-2(2bw+\frac{1}{2}\epsilon)}$
α_7	$\frac{a-5bw-2\epsilon+\sqrt{(a-5bw-2\epsilon)^2-4\varepsilon(2bw+\frac{1}{2}\epsilon)}}{-2(2bw+\frac{1}{2}\epsilon)}$
α_8	$\frac{a-5bw}{\frac{1}{2}\epsilon-2bw}$

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