

Carbon Tax Based on the Emission Factor

by

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Abstract

In response to growing concerns about the negative impact of GHG emissions, several countries such as the European Union have adopted a cap-and-trade policy to limit the overall emissions levels. Alternatively, other countries including Argentina, Canada, the United Kingdom, and United States have proposed an intensity-based cap-and-trade system that targets emission intensities, measured in emissions per dollars or unit of output. Arguably, intensity regulations can accommodate future economic growth, reduce cost uncertainty, engage developing countries in international efforts to mitigate climate change, and provide incentives to improve energy efficiency and to use less carbon-intensive fuels.

This work models and studies a carbon tax scheme where policy makers set a target emission factor, which is used as an intensity measure, for a specific industry and tax firms if they exceed that limit. The policy aims to promote energy efficiency, alleviate the impact on low emitters, and allow high emitters some flexibility to comply. We examine the effectiveness of the policy in reducing the emission factor due to manufacturing and transportation. The major objective of this research is to provide policy makers with a decision support tool that can aid in investigating the impact of an intensity-based carbon tax on regulated sectors and in finding the tax rate that achieves a target reduction. Therefore, we first propose a social-welfare maximizing model that can serve as a tool to evaluate the economic and environmental impacts of the policy. We compare the outcomes of the intensity-based tax and other existing environmental policies; namely, carbon tax imposed on overall emissions, cap-and-trade systems, and mandatory caps using case studies that are built within the context of the cement industry. The effectiveness of the policy is measured by achieving a balance between the target emission factor and the social welfare.

To find the optimal tax rate that achieves a target reduction, we propose a bilevel programming model where at the upper level, the government sets a target emission factor for the industry and taxes firms if they exceed that target, and at the lower level, the industry sets output levels that maximize social welfare. In the design of the policy, the government takes into account the decisions of the producers regarding fuel types and production quantities as well as the decisions of the market regarding demand. To evaluate the effectiveness of the policy, we build case studies in the context of cement industry. The policy is found to be effective in reducing the CO₂ emissions by opting for a less carbon-intensive fuel with a little impact on social welfare. To examine the effectiveness of the intensity-based carbon tax on reducing CO₂ emissions from transportation, which is a major supply chain activity, we finally propose a bilevel program where at the upper level the government decides on the tax rate and at the lower level firms decide on the design of their supply chain and truck types. The policy is found to be effective in inducing firms to reduce their emission factors and consequently reducing the overall emissions.

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Dedication

This thesis is dedicated to my parents who always believe in me.

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Chapter 1

Introduction

Global concerns are growing over climate change which is mostly attributed to the high concentrations of greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2), in the earth's atmosphere. CO_2 is released naturally into the air from natural processes and from the burning of fossil fuels. According to Treut et al., (2007), worldwide CO_2 emissions have increased by about 35% since the Industrial Revolution and are on trend to increase by 1.9% annually if no action is taken. Breaking down worldwide CO_2 emissions by sector reveals that the majority of the world's CO_2 emissions in 2005 can be attributed to four end-use sectors: manufacturing industry (38%), transportation (25%), households (21%), and services (12%) (International Energy Agency [IEA], 2008). During the last three decades the global industrial energy consumption has grown by 61%, making the sector one of the major sources of GHG emissions; and consequently, one of the target sectors to reduce CO_2 emissions. About two-thirds of CO_2 emissions from manufacturing industries are attributed to six major manufacturing industries; namely, petroleum refining, chemical production, iron and steel, cement, paper and pulp, and other minerals and metals (IEA, 2007).

Global transport-related CO_2 emissions in 2007 have increased by 45% from the 1990 level with road transport accounting for nearly three-quarters of the sector's

CO₂ emissions. Given current trends, transport-related CO₂ emissions are likely to continue to rise by 40% above 2007 levels by 2030 if no action is taken (The International Transport Forum, 2010). In Canada, the transportation sector is responsible for about 24% of Canada's GHG emissions, of which 79.4% are from road transport (see Figure 1.1) (Environment Canada, 2013). Despite the fact that Canada's contribution to the world's GHG emissions is about 2%, it is considered one of the highest per capita emitters. Under the Kyoto Protocol, Canada has agreed to reduce its 1990 emission levels by 6% by 2012. Yet, Canada's GHG emissions in 2008 exceeded 1990 levels by 24%, corresponding to an increase of 31.5% above the Kyoto target (Environment Canada, 2010).

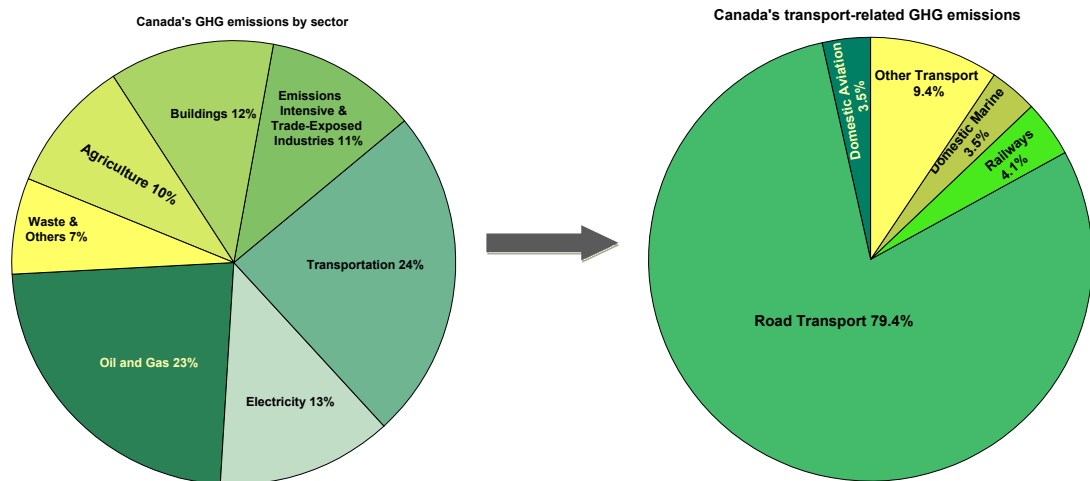


Figure 1.1: The contribution of economic sectors and transportation to Canada's GHG emissions

Given the anticipated future increase in CO₂ levels and the growing concerns about the negative impacts of GHG emissions, substantial efforts have been devoted to limit the increase of CO₂ concentration through market-based environmental

policies. Stavins (2003) defines market-based mechanisms as regulations that rely on market forces to encourage behavior; e.g., increasing the price of emissions-intensive goods would decrease demand for such products and thus reduce emission level. Policy makers can employ two market-oriented instruments to control GHG emissions: a price-based mechanism (e.g., carbon tax) or a quantity-based policy (e.g., cap and trade) (Ramseur and Parker, 2009). An alternative approach to market-based environmental policies is command and control mechanism which relies on setting specific standards for firms to comply with environmental regulations, often including technology and performance standards (Mäler and Vincent, 2003). According to economic theory, market-based policies have the potential to reduce GHG emissions at the least cost to society compared to using command and control mechanism (Robb et al., 2010).

A carbon tax is a direct charge on CO₂ emissions that requires companies to pay fees proportional to their CO₂ emission levels. In general, the tax policy provides price stability, but the primary concern is the uncertainty of the emission level. Thus, the government is interested in estimating the tax rate that achieves the GHG emissions reduction target. In the literature, the proposed tax rates range widely from \$30/tonne of Carbon (tC) to \$400 or more. Pizer's (2002) simulation results show that the cost of achieving the 1990 emission level by 2010 ranges between \$0 and \$30. Cline (2006) reports that a meaningful cutback in GHG emissions would target a 40% reduction in the early stages compared to 1990 levels and rise to 50% by 2100. To achieve this reduction, a carbon tax should be about \$170/tC by 2005 and increased to \$367 by 2055. Nordhaus (1993) estimates that a carbon tax of \$30/tC is expected to result in a reduction of 10 to 40% in emission level. The challenge of determining a carbon tax rate lies in setting the lowest tax rate that achieves the desirable long-term reduction in emission levels (Winkler

and Marquard, 2009). Although firms are expected to take actions to reduce their emission levels if the tax rate is higher than their marginal abatement costs, setting the tax too high may cause financial difficulties. In contrast, setting the carbon tax too low might be ineffective; e.g., some companies may decide to pay the tax rather than investing in new technologies (Ramseur and Parker, 2009).

On the other hand the cap-and-trade program, one of the Kyoto Protocol outcomes, can hold the emission level at a predetermined absolute target but the cost of the program is uncertain. Under the cap-and-trade policy, governments issue a limited number of carbon permits, each allowing its holder to emit one tonne of carbon. Regulated entities holding carbon credits in excess of their emissions are allowed to trade them in a secondary market (Koutstaal, 1996, and Paltsev et al., 2007). Given the uncertainty surrounding economic growth, setting a cap on the total emissions would limit the economic developments and increase the reduction costs if the economic growth is higher than expected (Herzog et al., 2006). Moreover, provided that the number of permits is fixed and the policy is inflexible in supplying additional allowances, the permit price is likely to fluctuate. For instance, in the European Union's Emissions Trading Scheme, carbon permit price has fluctuated from €30/tC in 2008 to €8/tC in 2009 (Ramseur and Parker, 2009). Under permit price volatility, planning investment in new technologies would present more of a challenge for firms. The cap-and-trade policy would have negative impacts on some industries if the cost of obtaining carbon permits or the cost of reducing CO₂ internally turns out to be higher than expected. Thus, policy makers would have to weigh the benefits of holding emissions at a predetermined level against the economic impact on the regulated sectors.

1.1 Motivation

A variation of the cap-and-trade policy that sets a limit on the emission intensity, measured in emissions per dollars or unit of output, is proposed in several countries such as Argentina, Canada, the United Kingdom, and United States to overcome some of the limitations of the aforementioned cap-and-trade system (Herzog et al., 2006). Under the intensity-based cap-and-trade scheme, firms reducing their emission intensity below the target obtain credits that can be traded in a secondary market (Rivers and Jaccard, 2010). Throughout this thesis, we use the terms intensity and emission factor interchangeably to refer to CO₂ emission per unit produced. In 2007, the government of Canada introduced its national climate change action plan, entitled *Turning the Corner*, to reduce the emission intensity of pollution-intensive sectors and companies. The policy requires regulated entities to reduce their emissions per unit of production by 18% below 2006 levels by 2010 and to decrease their emission intensity by an additional 2% every subsequent year. Emitters exceeding their intensity targets can comply by purchasing permits from efficient firms or by contributing to a technology fund (\$15/tC) (Environment Canada, 2007 and 2008). Arguably, the emission-intensity cap-and-trade policy can accommodate future economic growth, reduce cost uncertainty, encourage the involvement of developing countries in climate change prevention, and provide incentives to improve energy efficiency and to use less carbon-intensive fuels (Herzog et al., 2006, Jotzo and Pezzey, 2007, Pizer, 2005). However, a major criticism for the policy is the uncertainty of the resulting emission level (Rivers and Jaccard, 2010).

Although one of the key drivers behind adopting the intensity cap-and-trade policy is to reduce cost uncertainty, the effect of the policy on cost uncertainty is

found to be ambiguous and depends on uncertain parameter values (Dudek and Golub, 2003, Marschinski and Edenhofer, 2010, Newell and Pizer, 2008, Pizer, 2005, Webster et al., 2010). On the other hand, the carbon tax is argued to provide predictable costs and is found to be preferable to quantity instruments for GHG mitigation (Jotzo and Pezzey, 2007, Newell and Pizer, 2008, Pizer, 2002, Weitzman, 1974). However, most of the work on the intensity regulations has focused on the intensity-based cap-and-trade policy with no attention paid to an intensity-based carbon tax. Imposing a carbon tax on the emission factors would provide price stability and help regulated entities in anticipating the costs of complying with the target emission while providing them with a higher incentive to invest in new technologies and thereby reduce their emission levels. The administration of the policy is no more complicated than the administration of the intensity caps since trading of carbon credits among firms is not allowed. However, in light of the reviewed literature, models that examine the effectiveness of the policy seem to be missing in the existing literature. There is a need for models that can aid policy makers in investigating the impacts of such policy on regulated sectors and estimating the tax rate that achieves a target reduction.

1.2 Research Scope, Objectives, and Contribution

This thesis models and analyses a carbon tax scheme based on the emission factor due to production or transportation activities. Specifically, we study a carbon tax scheme where policy makers set a target emission factor for a specific industry and tax firms if they exceed that limit. Emission factors vary by firm to reflect

the differences in technologies and production or transportation efficiencies. Generally, firms can reduce their emission factors through investing in energy efficient technology and cleaner fossil fuels or renewable energy sources and making some operational adjustments. However, regulated entities would have to weigh the costs of investing in carbon reduction technologies against the costs of obtaining carbon credits. The key concept behind such a policy is to induce high emitters to reduce their emission factors while alleviating the burden on low emitters. The policy aims to provide firms with an incentive to invest in new technologies while allowing them more flexibility to comply in case of unexpectedly high internal mitigation costs. Therefore, the regulatory authority is interested in finding the tax rate that achieves the target reduction with the least impacts on the industries.

The major objectives of this research are:

- Develop models for the intensity-based carbon tax that can aid in examining the impact of the policy on regulated sectors.
- Investigate the impact of different tax rates on regulated sectors.
- Examine the effectiveness and the efficiency of the policy by comparing its outcomes to those of other existing environmental policies.
- Find the optimal tax rate that achieves a target reduction.

The main contribution of this thesis is the modeling and analyses of an intensity-based carbon tax where a mathematical model is presented to find the tax rate that maximizes social welfare. We equally use the same modelling framework to model other environmental policies such as carbon tax imposed on total emissions, cap-and-trade systems, and mandatory caps to evaluate the proposed tax policy. In

addition, we construct several case studies in the context of cement industry and green supply chain design to test the proposed models.

The thesis has three main parts. In Chapter 3, we model and analyze an intensity-based carbon tax that targets the production emission factor of manufacturing industries. We use the cement industry as a case study. Assuming a competitive market with a linear demand curve, the chapter proposes a social-welfare maximizing model that can serve as a tool to evaluate the economic and environmental impacts of the policy. With some modifications, the model is applicable to other manufacturing industries. The model can be used to assess the effects of different tax rates on the industry-specific emission factors, the overall emissions, the product price, and the social welfare. The chapter also shows how to modify the proposed formulation to model other environmental policies; namely, absolute carbon tax, cap-and-trade systems, and mandatory caps. The effectiveness of the policy is measured by achieving a balance between the target emission factor and the social welfare. To find the best tax rate, we solved the model for different tax rates and picked the one that achieves the target reduction; however, this approach does not find the optimal tax rate.

In Chapter 4, we formulate the problem of designing an intensity-based carbon tax that targets the production emission factor, presented in Chapter 3, as a bilevel programming problem. Designing effective environmental policies that reduce the negative impacts of industries on the ecosystems cannot be undertaken in isolation from the strategic and the operational decisions of the regulated entities. The problem of designing a carbon tax can be viewed as a hierarchical process where the leader, the government, determines the tax rate and the follower, the industry, decides on production quantities and fuel types. Firms can reduce their emission intensities by switching to less carbon-intensive fuels. The model is applied to

manufacturing industries represented by cement industry; however, with appropriate modifications, the model can be applied to other manufacturing industries.

In Chapter 5, we propose an intensity-based carbon tax that targets the transportation emission factor of multiple supply chains. The proposed model examines the effect of the intensity-based carbon tax on designing supply chain networks and selecting transportation modes. Each supply chain network consists of existing suppliers, potential geographical sites for locating distribution centers (DCs), and customer zones at fixed locations. Customers and suppliers are connected to DCs by different types of trucks. Customer demand over a given long-term period is assumed to be known. The primary source of CO₂ emissions is fossil fuel combustion for transport and electricity generation. Firms can reduce their emission factors by changing the design of their supply chain networks, reducing shipment frequency, and using electric trucks. The objective function of each supply chain is to minimize the total costs including the cost of carbon credits, whereas the regulatory authority is looking for the minimum tax rate that achieves the target level.

1.3 Organization of the Thesis

The thesis is organized as follows. Chapter 2 provides an overview of the basic features of some market-based instruments: cap and trade, carbon tax, and intensity-based cap-and-trade policies and summarizes the literature related to the intensity-based cap-and-trade policy. Chapter 3 presents a nonlinear programming (NLP) formulation that maximizes social welfare under a carbon tax policy based on the emission factor, describes how to modify the proposed formulation to model other environmental policies, and describes a case study built within the context of the cement industry. Chapter 4 proposes a bilevel formulation for designing a

carbon tax policy based on the production emission factor. Chapter 5 proposes a bilevel formulation for designing a carbon tax policy based on the transportation emission factor. Chapter 6 concludes the thesis and discusses future research directions.

Chapter 2

Related Background

The research conducted in this thesis draws upon the literature from two distinct disciplines: environmental economics and operations research (OR). Although market-based policies put prices on carbon so companies take cost into account when making decisions, there is little OR literature on incorporating environmental costs into companies' strategic and operational decisions. An extensive literature review by Benjaafar et al. (2010) highlights the absence of operations management and operations research models that address issues related to carbon emissions and operational and strategic decisions. Yet, considerable efforts have been made to address sustainability and environmental impacts of supply chains, which we will talk about it in more details in Chapter 5, (e.g. Cruz and Matsypura, 2009, Nagurney and Yu (2012), and Sundarakani et al., 2010). On the other hand, a significant amount of work had been performed on climate-change control policies in the economics literature (see Aldy et al., 2003, Anderson, 2008, Goers et al., 2010, Newell and Pizer, 2008, Nordhaus, 1993, Pizer, 2002, 2005, Sue Wing et al., 2006). Most of these attempts are centered on addressing issues related to the efficiency of carbon tax, cap-and-trade, and intensity-based cap-and-trade policies. Moreover, many discussion papers and reports investigate the design and the implementation of each policy (Ramseur et al., 2009; Robb et al., 2010). Table 2.1

summarizes the focus of some of the work that has been reviewed in this chapter and the next two chapters. This chapter provides an overview of the basic features of four market-based instruments: cap and trade, carbon tax, hybrid, and intensity-based cap-and-trade policies and summarizes the related literature in the area of OR and environmental economics.

2.1 Carbon Tax

A carbon tax is a direct charge on CO₂ emissions that obliges companies to pay fees proportional to their CO₂ emission levels. Currently, adopted carbon taxes are applied to fossil fuels (e.g., coal, gasoline, and natural gas) based on their carbon content. As a result, the cost of the fossil-fuel-based energy would increase and consequently the cost of the energy-intensive products and services. The carbon tax is intended to reduce CO₂ emissions by creating an incentive to use less fossil fuels and invest in renewable energy and low-carbon fuels. However, the key question facing the regulatory authority is at what rate fossil fuels would be taxed (Ramseur and Parker, 2009).

Since the early 1990s, several European countries, including Denmark, Finland, Norway, and Sweden have adopted carbon taxes. At a later time, at the end of 1990s, Germany, Italy, the Netherlands, and the United Kingdom have introduced carbon taxes. However, the tax rates vary by country and differ among sectors within a country (Hahn, 2009). Anderson (2008) examined the impact of carbon taxes on six European countries and concluded that the carbon taxes reduced fuel consumptions and consequently lowered the GHG emissions for the periods 1994 to 2004. North America's experience in implementing carbon taxes is limited to the ones introduced by two Canadian provinces: British Columbia and Quebec. In

Carbon Tax	Cap-and-Trade	Intensity-based Cap-and-Trade
Fischer & Springborn (2011) Goers et al. (2010) Anderson (2008) Newell & Pizer (2008) Pezzey (2003) Pizer (2002) Pizer (1999) Weitzman (1974) efficiency of a tax imposed on total emissions	Fischer & Springborn (2011) Goers et al. (2010) Goeree et al. (2009) Newell & Pizer (2008) Pezzey (2003) Springer (2003) Pizer (2002) Pizer (1999) Weitzman (1974) efficiency	Bruneau & Renzetti (2009) Kolstad (2005) Kim & Baumert (2002) impact on total emissions
Zhou et al. (2011) Galinato & Yoder (2010) Bard et al., (2000) Kainuma et al. (1999) tax imposed on total emissions & subsidy	Plambeck & Taylor (2013) Szabó et al. (2006) Lund (2007) Brännlund et al. (1998) impacts on industries	Fischer & Springborn (2011) Marschinski & Edenhofer (2010) Webster et al. (2010) Newell & Pizer (2008) Jotzo & Pezzey (2007) Sue Wing et al. (2006) Quirion (2005) Pizer (2005) Dudek & Golub (2003) Ellerman & Sue Wing (2003) impact on cost uncertainty
Choi (2013) Hoen et al. (2011a) Gomes et al. (2009) impact on strategic decisions	Ramudhin et al.(2010) impact on strategic decisions	Rivers & Jaccard (2010) Kuik & Mulder (2004) impact on firms' competitiveness
Chen et al. (2011) Benjaafar et al. (2010) impact on operational decisions	Chen et al. (2011) Hua et al. (2011) Benjaafar et al. (2010) impact on operational decisions	Fischer & Springborn (2011) Jotzo & Pezzey (2007) Pizer (2005) impact on economic growth
Gemechu et al. (2012) tax imposed on carbon footprint		Marschinski & Edenhofer (2010) Fischer (2003) integration with other environmental policies

Table 2.1: Summary of the focus of the literature on market-based environmental policies

2008, British Columbia started the carbon tax at a rate of \$10 per metric ton of CO₂ emissions and planned to increase it annually by \$5 until it reaches \$30 in 2012. Quebec imposed a low rate carbon tax of 0.8 cents per litre of gasoline and 0.93 cents per litre of diesel in 2007 (Duff, 2008).

Galinato and Yoder (2010) develop a constrained tax and subsidy regime to tax energy sources with high emissions and use the revenue to subsidize energy sources with low emissions. The proposed policy provides welfare gains relative to a no-tax case. Gomes et al. (2009) evaluate the impact of a linear carbon tax on new refinery configurations in Brazil. The optimum configuration is compared before and after the tax using a linear programming model that minimizes the production costs and the carbon tax. The model is solved under different fixed tax rate each time. Results show that refineries reduce their emission levels when the tax rate is higher than \$100/tC. Benjaafar et al. (2010) integrates a linear carbon tax into firms' operational decisions using a single multi-stage lot-sizing model. The objective function minimizes firm's total costs including the CO₂ emissions cost. The results show that the carbon tax policy is a reliable mechanism for achieving a quick reduction in emission level.

2.1.1 Design Considerations of a Carbon Tax Policy

Several decisions need to be considered when designing a carbon tax: (1) setting the tax level; (2) the point of taxation; and (3) distribution of the tax revenue (Aldy et al., 2008; Ramseur and Parker, 2009).

Setting the Tax Level

As we mentioned earlier, setting the tax rate at a high level would induce some firms to reduce their emission levels; however, it also could have costly effects on some firms. To mitigate the impacts on industries, some countries such as Denmark, Germany, and Sweden exempted some sectors or differentiated the tax rates across sectors (Böhringer and Rutherford, 1997). A gradual increase in the tax rate (slow ramp-up) and baseline level exemptions (grandfathering) are alternative options proposed to reduce the tax burden (Metcalf and Weisbach, 2008).

The Point of Taxation

In designing a carbon tax policy, policy makers have to determine which GHG emissions and sectors would be regulated and where to impose the carbon tax in the economy. Including all sectors would yield the maximum possible environmental benefits; however, this would increase the implementation complexity. Hence, the government has to balance the full-coverage benefits with the implementation costs. To decide where to impose the carbon tax in the economy, the regulators can consider three options: upstream where carbon enters the economy (i.e., coal mines), downstream where GHGs are emitted (i.e., power plants), and a combination of both (Ramseur and Parker, 2009).

Distribution of the Tax Revenue

Carbon taxes are likely to generate significant revenue. For example, in its first year, the British Columbia carbon tax is anticipated to raise \$880 million in 2010/11 (Duff, 2008). The carbon tax revenue can be used to fund various objectives such as reducing other existing taxes and developing or subsidization of clean technology

(Ramseur and Parker, 2009).

2.2 Cap and Trade

Cap-and-trade mechanism is one of the Kyoto Protocol outcomes under which each participant country commits to a reduction of at least 5% in its GHG emissions by 2012 relative to its 1990 level (Springer, 2003). Therefore, a regulatory authority in each country determines which sectors are regulated by the program and sets an emissions cap on the acceptable release of CO₂ emissions in a specified period (e.g., annually). Usually, the imposed caps are equivalent to the regulated entities current emission level and is gradually reduced over time to reach the overall target reduction (Goers et al., 2010). Following the emission level decision, in each period, carbon caps are translated into a limited number of permits issued by government regulating bodies. Each permit allows producers to emit one tonne of carbon and remains valid until the holder burns a quantity of fossil fuels that contains one tonne of carbon. Permit holders are allowed to trade their allowances in a secondary market where firms who were able to reduce their emissions below the cap can sell their credits to the ones who exceed their caps. At the end of each period, companies are obliged to report their emission levels and to demonstrate sufficient permits that cover their total emissions (Koutstaal, 1996, and Paltsev et al., 2007).

Early experience with a cap-and-trade policy to control pollution has begun in the United States in 1995 to reduce sulfur dioxide (SO₂) (Klaassen and Nentjes 1995). The implemented system succeeded in reducing SO₂ emission level from 19 million tonnes in 1980 to 9 million tonnes in 2000. However, the existing cap-and-trade systems for GHG emissions are still in their early stages. The world largest carbon trading system is the European Union's Emissions Trading Scheme (EU-

ETS) which has been put into operation since 2005. The EU ETS covers about 46% of the European CO₂ emissions from four broad sectors: building materials, energy activities, ferrous metals, and pulp and paper (Ellerman, 2008; Hahn, 2009). In the United States, the first mandatory cap-and-trade policy for CO₂ emissions is the Regional Greenhouse Gas Initiative (RGGI). The program imposes a cap on CO₂ emissions from power plants in ten Northeastern and Mid-Atlantic states and aims to reduce emission level by 10% by 2018 (Hahn, 2009). Other examples of developed trading systems includes: Western Climate Initiative, California and the west, and the Midwestern Greenhouse Gas Reduction Accord (Hahn, 2009; Climate Change, 2009).

Springer (2003) reviews 25 models of the market of GHG emissions permits. The models are classified into four categories: emissions trading, macroeconomic, integrated assessment, and the energy system models. All the results of the reviewed models indicate the efficiency of the emissions trading program in reaching the target reduction at the lowest cost to society. Szabó et al. (2006) develop a global dynamic simulation model of the cement industry to quantify the effect of three carbon trading markets, which differ in the geographical coverage of the emission trading markets (EU15, EU27 and Annex B), on the cement industry. Results indicate that the permit price decreases if the market enlarges to the EU27 or to Annex B. Brännlund et al. (1998) compares the Swedish pulp and paper industry profits with and without emissions trading. The results show that the industry can achieve the same target reduction in emission level at a higher profit if an aggregate emission level is used for the entire industry instead of individual levels.

2.2.1 Design Considerations of a Cap-and-Trade Policy

The cost and the effectiveness of the cap-and-trade policy are determined by several design decisions which include the first allocation of permits, coverage and the point of regulation, safety valve, and banking and borrowing of permits. These elements are discussed below.

Initial Allocation

A key decision in designing the cap-and-trade policy is the first distribution of permits to regulated entities. The most common alternatives for initial allocation are grandfathering, auctioning, or a combination of both. If governments employ the grandfathering approach, carbon permits would be freely allocated to companies based on their past emission levels (Goers et al., 2010). Although the grandfathering procedure could help in reducing the impact of the program on firms and consumers, it could result in some windfall profits. The initial phase of EU ETS required the participating countries to auction at most 5% of the carbon permits. As a result, the Germany based RWE which is one of Europe's largest carbon emitters, collected windfall profits of about \$6.4 billion (Goeree et al., 2009). Alternatively, companies can bid to purchase carbon permits. The auctioning procedure eliminates windfall profits and generates revenue that could be used to investment in low-carbon technology or to reduce tax burdens. However, in a high competitive environment, auctioning could hurt the business of some firms who lack the fund to buy permits. A combination of grandfathering and auctioning might overcome each policy's disadvantages (Climate Change, 2009).

Coverage and the Points of Regulation

Primary decisions in designing a cap-and-trade policy is deciding what sectors and GHG emissions are covered by the program and the point of regulation. Some programs such as RGGI focuses on power generation, whereas EU-ETS includes other sectors such as iron, steel, glass, oil, coal mines, natural gas, refineries, and cement. The proposed approaches regarding the point of regulation range from upstream where fossil fuels enter the economy (e.g., oil wells and coal mines) to downstream where GHG emissions are emitted (e.g., manufacturer). Choosing the point of regulation has been influenced by many factors such as monitoring emissions and the administrative complexity. Upstream regulation is considered to be more efficient when emissions cannot be easily or cheaply monitored (Ellerman, 2008).

Safety Valve

In order to control price volatility of carbon permits, policy makers can design a cap-and-trade policy that allows for supplying unlimited additional permits at a fixed price known as the trigger price. Companies who exceed their caps can buy the required credits from the government if the market price of the emissions allowances exceeds the trigger price. This safety valve provides flexibility for the regulated sectors to comply with the imposed caps and places an upper bound on the allowance price. However, since the safety valve allows for exceeding the caps, achieving the target reduction would be unguaranteed (Ellerman, 2008; Paltsev et al., 2007).

Banking and Borrowing of Permits

A cap-and-trade policy can be designed to allow for banking and borrowing mechanisms which add flexibility to the system and reduce the program cost. Banking refers to the ability to save excess credits to use in future periods, whereas borrowing involves using future year's allowances in the current period. With the banking option, the cumulative emissions at any point will not exceed the issued permits even if the system allows firms to shift their obligations across periods (Stavins, 2003; Paltsev, 2007). The borrowing mechanism has been implemented in the EU-ETS and limited to using the next period allowances. On contrast, banking has been successfully implemented in the U.S. in the context of SO₂ trading system (Ellerman, 2008).

2.3 A Comparison between Carbon Tax and Cap-and-Trade Policies

Carbon tax and a cap-and-trade systems are both market-based environmental policies that place a price on carbon. Although the design and the implementation of the carbon tax and the cap-and-trade policy demonstrate some similarities in terms of the point of regulation, there are some differences between the two policies which lie in the source of uncertainty. The carbon tax policy controls the carbon price but the emission levels remain uncertain, whereas the cap-and-trade policy caps the emission level but the cost is uncertain. While each policy has its supporters, both policies are argued to possess some advantages and disadvantages that are summarized in Table 2.2 (Climate Change, 2009; Ellerman, 2008; Ramseur and Parker, 2009).

	Carbon Tax	Cap-and-Trade
Advantages	1-Provide a stable price. Hence, predictable costs can help in planning the investment in new technologies. 2-Easier to implementation because of the existing tax collection rules. 3-Raise revenue that can be used to finance several objectives.	1-Imposes a direct cap on GHG emissions. Thus, the target reduction would be achieved if the policy implemented correctly. 2-Encourages the development of cleaner technologies. 3-Proves its effectiveness in reducing other pollutant such as sulfur dioxide and nitrogen oxides in the U.S.
Disadvantages	1-Would yield uncertain emissions levels. 2-Would face political challenges because of the word "tax." 3-Would receive less support from industries and environmental groups.	1-Potential windfall profits with free allocation. 2-Price is very likely to fluctuate. 3-The program may lose its ability to control emissions if too many permits are issued. 4-Implementation complexity; the efficiency of the program depends on the accuracy of monitoring emissions.

Table 2.2: Advantages and disadvantages of carbon tax and cap-and-trade system

The efficiency and the effectiveness of both policies are investigated and analyzed in the literature. Weitzman (1974) analyzed price and quantity policies and provided conditions in which each instrument would lead to the best social welfare outcome. If the marginal benefit curve is relatively flat, Weitzman's analyses demonstrate that a tax policy would be preferred over the quantity policy. In contrast, Weitzman's analyses show that a quantity policy is suitable when the marginal cost curve is relatively flat. Newell and Pizer (2008) and Pizer (2002 and 1999) find that the marginal costs of reduction are relatively steeper than the marginal benefits leading to favouring a carbon tax over a cap-and-trade policy. Wittneben (2009) supports Exxon Mobil's Chairman and CEO Rex Tillerson statement that favour carbon tax policy over cap-and-trade policy. The author lists seven differences between the two market-based policies and argues that carbon market constructed under the Kyoto Protocol and EU ETS failed to reduce emission level albeit the high costs of the program. Pizer (2002) analyzes the social welfare associated with tax and cap-and-trade policies and show that the tax system is more efficient than the cap-and-trade system by a factor of five. Pezzey (2003) compares the long run efficiencies of three views about the initial allocation of emissions permits under the trading system and the exempted emission level under the emissions tax system. The analyses show that the emissions tax with a grandfathering achieves the long run efficiency if the baseline is treated as property right; i.e., existing firms get the exemption right but any new firm does not. However, the paper calls for further investigation before adopting this policy. Lund (2007) evaluates the cost impacts of EU ETS on energy-intensive manufacturing industries. The results show that the highest impact is on steel and cement industries which is found to be 3-4 fold compared to the impacts on oil refining and pulp and paper industries. Therefore, the author suggests considering some correcting mechanisms to alleviate the impacts on some

industries; for example, using different taxation schemes.

2.4 Hybrid Policies

To utilize the advantages of the cap-and-trade policy and the carbon tax, hybrid policies were proposed in the literature. One such policy is the safety valve which sets an upper bound on permits prices. Essentially, the system works as a trading system until the trigger price is reached, then the system changes to a carbon tax with a fixed price (Goers et al., 2010). Pizer (2002) examines the efficiency of using the trigger price and concludes that the hybrid policy is slightly more efficient than the emissions tax. However, both policies are more efficient than the trading system which makes the hybrid policy an attractive alternative to either carbon tax or cap-and-trade policy. Lee et al. (2008) examines the effects of combining a carbon tax policy with a cap-and-trade policy on several industry sectors in Taiwan. A fuzzy goal programming model is used to simulate the potential reduction in CO₂ emissions. The permits price is determined by the marginal reduction cost which is calculated by introducing the carbon tax to the fuzzy goal programming model. Adopting the hybrid system is found to be more efficient than using the carbon tax alone.

2.5 An Intensity-Based Cap and Trade

The intensity-based cap-and-trade policy is a variation of the cap-and-trade policy which sets a limit on the emission intensity, measured in emissions per dollars or unit of output. Firms reducing their emission intensity below the target obtain

credits that can be traded in a secondary market (Rivers and Jaccard, 2010). Regulations limiting the emission intensity are introduced in Argentina, the United Kingdom, and United States (Herzog et al., 2006). In 2007, the government of Canada introduced its national climate change action plan, entitled *Turning the Corner*, to reduce the emission intensity of pollution-intensive sectors and companies. The policy requires regulated entities to reduce their emissions per unit of production by 18% below 2006 levels by 2010 and to decrease their emission intensity by an additional 2% every subsequent year. Emitters exceeding their intensity targets can comply by purchasing permits from efficient firms or by contributing to a technology fund (\$15/tC). Since the focus of the policy is to encourage the adoption of cleaner production technology, firms will not be given credits for shutting down production for economic reasons or moving the production out of Canada. Given that firms cannot comply with the regulation by simply reducing their production quantities, the policy would provide an incentive for firms to improve their production processes (Environment Canada, 2007 and 2008).

Intensity regulations have been advocated as a means to accommodate future economic growth, reduce cost uncertainty, provide incentives to improve energy efficiency, and engage developing countries in the international efforts to mitigate climate change (Herzog et al., 2006, Jotzo and Pezzey, 2007, Pizer, 2005). Yet, a major criticism for the policy is that it would allow overall emissions to rise as production increases (Rivers and Jaccard, 2010). The literature on intensity regulations focuses primarily on evaluating the intensity-based cap-and-trade policy in terms of its impact on the overall emissions, performance under uncertainty, impact on companies' competitiveness, and ability to integrate with other existing environmental policies. Bruneau and Renzetti (2009) investigate the Canadian government's proposed policy in light of historical trends between 1990 and 2002.

The results indicate that targeting emission intensity would push Canadian companies to reduce their emission intensities; however, the overall emissions will be higher than 1990 levels. Kim and Baumert (2002) conclude that the total emissions with intensity regulations is uncertain; however, the intensity-based policies make the mitigation of GHG emissions feasible and efficient by reducing cost uncertainty and facilitating the participation of developing countries in the international efforts to combat climate change. Kolstad (2005) examines the intensity regulations and concludes that in order to achieve a meaningful reduction in GHG emissions, the emission intensity must be decreased by a rate that is equal to the growth rate of GDP.

Pizer (2005) finds that the intensity-based policies accommodate future economic growth especially for developing countries and relatively not difficult to administer but not the best policy to handle cost uncertainty. Jotzo and Pezzey (2007) find that optimal intensity target reduce cost uncertainty, achieve higher expected welfare, and perform better than absolute target. Fischer and Springborn (2011) employ a dynamic stochastic general equilibrium model to compare three environmental policies: a carbon tax, an emission cap, and an intensity target. The results show that although the intensity targets allow for economic growth when compared to the tax and the cap policies, the carbon tax has the lowest welfare cost. However, the volatility levels of the output are lower with the absolute target, higher with the carbon tax, and the same as the no environmental policy case with intensity target. Ellerman and Sue Wing (2003) study the effect of the absolute and the intensity cap-and-trade policies on costs and emissions when the future GDP is uncertain. The analyses show that the reduction cost is uncertain under both policies because the uncertainty in GDP translates in either uncertainty in emission intensity or total emissions depending on the used policy. Sue Wing et al. (2006)

find that a small GDP variance and high correlation between emissions and GDP are required in order to favour intensity caps over absolute caps, a conclusion that is shared by Quirion (2005) and Newell and Pizer (2008) based on maximizing social welfare. Quirion (2005) compares the expected welfare under three environmental policies: a cap on the total emissions, a cap on the intensity of emissions, and a price instrument (tax or subsidy). In most cases, the expected welfare obtained under the cap on the total emissions or under the price instrument is found to be higher than the one obtained under the intensity target. Newell and Pizer (2008) extend Weitzman's (1974) work to compare intensity caps and absolute caps and find that neither policy dominates the other. Webster et al. (2010) build on the Weitzman's (1974) model to compare the intensity targets to hybrid policies and show that a high correlation between GDP and emissions favours intensity targets.

Rivers and Jaccard (2010) employed a dynamic general equilibrium model to evaluate three environmental policies: emission intensity, cap-and-trade, carbon tax. The analysis suggests that the emission-intensity policy could have less impact on the international competitiveness of the regulated entities if the environmental policies of other countries are less aggressive. Furthermore, the results imply that the emission intensity policy has some advantages over the cap-and-trade policy and the carbon tax if there are pre-existing tax distortions and only some sources of emissions are regulated. Kuik and Mulder (2004) assess the impacts of three trading schemes: trading under absolute caps, trading under intensity caps, and trading under mixed caps. The results demonstrate that the intensity caps have less negative impact on the competitiveness of the regulated entities, but it needs to be combined with other environmental policy, such as energy tax, in order to achieve a certain reduction. Fischer (2003) examines the effects of allowing trading of emission permits between two sectors: one is regulated by an intensity cap

and the other is regulated by an absolute cap. The results indicate that in the absence of cross-price effect, allowing trading between the two sectors increases the combined emissions. Marschinski and Edenhofer (2010) use some criteria to assess potential merits of intensity caps including compatibility with other existing trading systems, reducing cost uncertainty, ease of implementation, and providing incentive to innovate. The analyses show that the effect of the intensity caps on the cost uncertainty is ambiguous and trading between the absolute cap and the intensity cap would increase the permit price. Dudek and Golub (2003) argue that the intensity targets have no advantages over the absolute targets based on some criteria including reducing cost uncertainty, ease of implementation, and providing incentive to innovate.

2.6 Summary

From the preceding review of market-based environmental policies, several key points can be concluded. First, although the intensity cap-and-trade policy is advocated as a tool to reduce cost uncertainty, the effect of the policy on cost uncertainty is found to be ambiguous and depends on some parameter values such as the correlation between emissions and GDP (Marschinski and Edenhofer, 2010, Newell and Pizer, 2008, Pizer, 2005, Sue Wing et al., 2006, Webster et al., 2010). Second, while the carbon tax is argued to provide predictable costs and is found to be preferable to quantity instruments for GHG mitigation, most of the work on the intensity regulations has focused on the intensity cap-and-trade policy with no attention paid to a carbon tax based on the emission intensity. Third, the cap-and-trade policy increases business risk and consequently the risk of bankruptcy if the compliance costs turn out to be higher than expected. Fourth, operations

research models that address the design of climate-change control policies seem to be missing in the existing OR literature.

We attempt to address some of the previous points in the next chapters. In Chapter 3, we propose a social-welfare maximizing model that can serve as a tool to evaluate the economic and environmental impacts of the intensity-based carbon tax. In Chapter 4, we propose a bilevel formulation to find the optimal tax rate that achieves a target reduction. In Chapter 5, we propose a bilevel formulation to examine the effectiveness of the intensity-based carbon tax on reducing CO₂ emissions from transportation.

Chapter 3

Modeling and Analysis of an Intensity-Based Tax Policy

In this chapter we model and analyze a tax policy based on the emission factor, which is used as an intensity measure. Specifically, we model a situation where policy makers set a limit on the production emission factor of a regulated industry and tax firms if they exceed that limit. We evaluate the efficiency of the policy against other existing environmental policies using a social welfare mathematical programming model. In particular, we are interested in assessing the impacts of the intensity-based carbon tax and other environmental policies on the emission factors, overall emissions, product price, productions, consumers' and producers' surpluses, and social welfare. We test the proposed models on two case studies that are built within the context of the cement industry. In Section 3.1, we present a nonlinear programming (NLP) formulation that maximizes social welfare under the intensity-based carbon tax and show how to modify the proposed formulation to model other environmental policies. In Section 3.2, we describe a case study built within the context of the cement industry. In Section 3.3, we discuss the results of the case studies and provide policy recommendations. In Section 3.4, we summarize the chapter.

3.1 Problem Formulation

We consider a polluting industry with N firms producing a single homogeneous product, q_i , and generating CO₂ emissions in proportion to their output levels. CO₂ emissions are primarily due to burning fossil fuels to produce energy that is required for production. Each firm $i = 1, \dots, N$ requires a certain amount of energy b_i to produce a single unit of output. Thus, the amount of fossil fuels required by firm i to produce a quantity q_i is

$$\sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i,$$

where l is the index of fuel types, w_{il} is the amount of fuel l used at firm i , and $\hat{b}_{il}$ is the energy content in fuel l when used by firm i (GJ/tonne, m³, ...). Please refer to the Appendices for notation used throughout this thesis.

CO₂ emissions can be calculated using emission factors which convert energy consumption (in energy units: kilowatt hour (kWh), or British thermal unit (BTU)) to the associated CO₂ emissions. A CO₂ emission factor of production is an average value that reflects the level of CO₂ emissions per unit of production. Hence, the production emission factor, x_i , of firm i can be calculated as

$$x_i = \frac{\text{total CO}_2 \text{ emissions}}{\text{total production}}$$

The production emission factors vary by firm to reflect the differences in production efficiencies and technologies. When the source of CO₂ emissions is fossil fuels, the total CO₂ emissions is given by $\sum_{l=1}^L e_{il} w_{il}$, where e_{il} is the CO₂ emission factor of fuel type l at firm i . Therefore, the production emission factor of firm i is

$$x_i = \frac{\sum_{l=1}^L e_{il} w_{il}}{q_i} \quad (3.1)$$

Policy makers are interested in reducing the production emission factor of a specific industry by designing effective and efficient carbon tax that reaches the target reduction at the least cost. Assuming that regulatory bodies set a target production emission factor for the industry, β , use an output-based allocation, and freely allocate each firm certain number of carbon credits, βq_i , a regulated firm is required to pay tax only if its production emission factor exceeds the target (see Figure 3.1). Therefore, firm i pays $\alpha_2 q_i (x_i - \beta)$ if its emission factor x_i exceeds β , where α_2 is the tax rate. Hence, the CO₂ emissions cost for firm i is:

$$g(x_i) = \begin{cases} 0 & \text{for } 0 \leq x_i \leq \beta \\ \alpha_2 q_i (x_i - \beta) & \text{for } x_i > \beta. \end{cases} \quad (3.2)$$

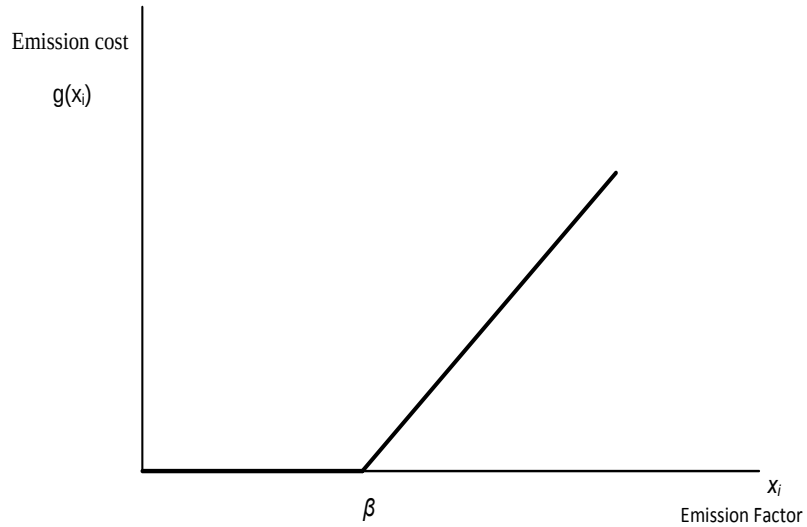


Figure 3.1: Emission Cost

The problem faced by the government is to determine the optimal tax rate that induces firms to reduce their emission factors and consequently reduces the emission factor of the industry to the target level. We consider a competitive market whose inverse demand curve is given by $p = \gamma - \delta q^d$, where γ and δ are the intercept and the slope of the inverse demand function, respectively, and q^d is the demand corresponding to price p . We assume that each firm has a production capacity limit, d_i , and the firm's production cost function is convex quadratic of the form $C_i(q_i) = c_i q_i + t_i q_i^2$, where c_i and t_i are known constants. Firms can reduce their emission intensities by using less carbon-intensive fuels. The fuel cost of firm i is given by $\sum_{l=1}^L h_{il} w_{il}$, where h_{il} is the variable cost associated with using fuel w_{il} . Given the market price and the carbon tax, firms would like to determine production levels and fossil fuel types that maximize their surplus. On the other hand, the government agency seeks to evaluate the impact of the tax rate on the emission factor of the industry, the total CO₂ emissions generated by all firms in the industry, the demand, the product price, the social welfare, and the cost of reaching a certain production emission factor.

The equilibrium model of a competitive market where consumers and producers are price takers can be represented by combining two models that maximize the consumers' and the producers' surplus as well as the market clearing condition (Gabriel et al., 2012, Hazell and Norton, 1986). The producer's surplus maximization model for firm i is:

$$\max pq_i - \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - g(x_i) \quad (3.3)$$

$$\text{s.t. } q_i \leq d_i \quad (3.4)$$

$$\sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i \quad (3.5)$$

$$x_i q_i = \sum_{l=1}^L e_{il} w_{il} \quad (3.6)$$

$$q_i, w_{il}, x_i \geq 0 \quad l = 1, \dots, L \quad (3.7)$$

The objective function (3.3) maximizes the surplus of firm i which is a profit measure, the difference between the revenue from selling products to consumers and the variable production cost, the variable fuel cost, and the CO₂ emission cost. Constraint (3.4) is the production capacity limit. Constraint (3.5) is the energy balance. Constraint (3.6) calculates the CO₂ emission factor. Constraints (3.7) are the nonnegativity constraints.

From (3.2) and (3.6), the taxed CO₂ emission level can be represented by the maximum of $(\sum_{l=1}^L e_{il} w_{il} - \beta q_i, 0)$. Defining $\theta_i = \max(\sum_{l=1}^L e_{il} w_{il} - \beta q_i, 0)$, the CO₂ emission cost for firm i can be represented as $\alpha_2 \theta_i$. Therefore, the surplus maximization problem for each firm i can be written as

$$\begin{aligned} [\text{PS}_i]: \max pq_i - \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - \alpha_2 \theta_i \\ \text{s.t. } q_i \leq d_i \\ \sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i \\ \theta_i \geq \sum_{l=1}^L e_{il} w_{il} - \beta q_i \\ q_i, w_{il}, \theta_i \geq 0 \end{aligned} \quad l = 1, \dots, L \quad (3.8)$$

After solving the model and obtaining the values for w_{il} and q_i , equation (3.1) is used to calculate the emission factor of firm i .

The consumers problem is

$$[\text{CS}]: \max_{q^d \geq 0} \gamma q^d - \frac{1}{2} \delta (q^d)^2 - p q^d$$

which maximizes consumers' surplus, the difference between the amount of money that consumers are willing to pay for products and the revenue paid to the firms (Baron and Myerson, 1982, and Gabriel et al., 2012). Given that $p = \gamma - \delta q^d$, the consumers' surplus can be also written as $\gamma q^d - \frac{1}{2} \delta (q^d)^2 - (\gamma - \delta q^d) q^d$, which is equivalent to $\frac{1}{2} \delta (q^d)^2$.

The market clearing condition is

$$q^d - \sum_{i=1}^I q_i \leq 0 \quad (3.9)$$

which ensures that the total demand of the industry is satisfied.

The equilibrium model of a competitive market can be formulated as the following social-welfare maximization problem that maximizes the sum of consumers' and producers' surpluses, subject to the constraints of the consumers and the producers as well as the market clearing condition (3.9). After solving the problem, the market price can be retrieved from the dual variable of the market clearing constraint (Gabriel et al., 2012).

$$\begin{aligned}
[\text{SW}]: \max \quad & \gamma q^d - \frac{1}{2} \delta (q^d)^2 - \sum_{i=1}^I \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - \sum_{i=1}^I \alpha_2 \theta_i \\
\text{s.t.} \quad & q_i \leq d_i & i = 1, \dots, N \\
& \sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i & i = 1, \dots, N \\
& q^d, q_i, w_{il}, \theta_i \geq 0 & i = 1, \dots, N, l = 1, \dots, L \\
& \theta_i \geq \sum_{l=1}^L e_{il} w_{il} - \beta q_i & i = 1, \dots, N \\
& q^d - \sum_{i=1}^I q_i \leq 0
\end{aligned} \tag{3.10}$$

3.1.1 Modeling other Environmental Policies

To evaluate the effectiveness of the tax policy based on the emission factor, we compare it to other market-based environmental policies, namely, carbon tax based on the total emissions, and cap and trade based on the total emissions and based on the emission factors. In addition, we compare the proposed policy to non-market-based environmental regulations such as setting specific caps on the emission factors and on the total emission. In what follows, we show how [SW] can be modified to model such policies.

- **Carbon tax based on total emissions:** when facing a carbon tax on the total emissions, constraints (3.8) are removed from [SW] and the objective function is replaced by

$$\max \gamma q^d - \frac{1}{2} \delta (q^d)^2 - \sum_{i=1}^I \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - \alpha_2 \sum_{i=1}^I \sum_{l=1}^L (e_{il} w_{il}) \quad (3.11)$$

- **Cap on the emission factor:** if the firms face a cap on their emission factors, we can model that by removing constraints (3.8), adding constraints

$$\sum_{l=1}^L e_{il} w_{il} \leq \beta q_i \quad i = 1, \dots, N \quad (3.12),$$

where β is the target production emission factor for the industry, and replacing the objective function by

$$\max \gamma q^d - \frac{1}{2} \delta (q^d)^2 - \sum_{i=1}^I \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) \quad (3.13)$$

- **Cap on the total emissions:** when firm i operates under a cap on its total emissions, we can model that by removing constraints (3.8), replacing the objective function by (3.13), and adding the following constraints

$$\sum_{l=1}^L e_{il}w_{il} \leq \mu_i \quad i = 1, \dots, N \quad (3.14)$$

where μ_i is a cap on the total emissions of firm i which is usually set as a percentage of its historical emission level.

- **Cap-and-trade policy based on the total emissions:** in order to model this policy, constraints (3.8) are removed, and the following constraints

$$\sum_{l=1}^L e_{il}w_{il} \leq \mu_i + E_i \quad i = 1, \dots, N \quad (3.15)$$

are added, where E_i is the quantity of carbon credits purchased or sold by firm i . Note that E_i could be positive or negative depending on whether carbon credits are bought or sold. Given that carbon credits are exchanged at the same price, the objective function is replaced by (3.13). Moreover, since firms are selling and buying credits from each other, the constraint $\sum_{i=1}^I E_i = 0$ is added to balance the amount of carbon credits traded.

- **Cap-and-trade policy based on the emission factors:** To model this policy, constraints (3.8) are removed, the objective function is replaced by (3.13) since carbon credits are exchanged at the same price, and

$$\begin{aligned} \sum_{l=1}^L e_{il}w_{il} &\leq \beta q_i + E_i \quad i = 1, \dots, N \\ \sum_{i=1}^I E_i &= 0 \end{aligned} \quad (3.16)$$

are added.

Under the two cap-and-trade policies, the objective function of firm i is given by $pq_i - \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - \alpha_2 \theta_i - \bar{p} E_i$, where $\bar{p}$ is the permit price which we set it equal to the tax rate and use it to calculate each firm profit or cost. If firm i is a seller, $\bar{p} E_i$ calculates its profit from selling carbon permits and if it is a buyer,

$\bar{p}E_i$ calculates its cost. Given that carbon credits are exchanged at the same price $\bar{p} \sum_{i=1}^I E_i$, the costs and the profits from carbon trading cancel each other, therefore; (3.10) is replaced by (3.13).

3.2 Case Study

In order to test the proposed models, we construct a small and a large case studies in the context of the cement industry. Cement manufacturing is one of the world's most energy intensive industries, with an estimated global CO₂ contribution of 5% (Worrell et al., 2001). In Canada, the contribution of cement industry to the GHG emissions of the emissions-intensive and trade-exposed industries in 2011 is about 13% (see Figure 3.2) (Environment Canada, 2013). Generally, cement manufacturing involves four major steps: raw material extraction, raw material preparation, clinker production, and the finished product making (see Figure 3.3). The production of cement begins by extracting limestone, sand, and clay from quarries and crushing the extracted materials to a specialized size. The obtained raw materials are mixed with additional minerals, to achieve a specific chemical composition, finely ground, and fed into a rotating kiln in which the intense heat allows the mixture to be heated to about 1500°C. The process causes a chemical reaction, calcination, where CO₂ is released and raw materials are transformed into an intermediate product, clinker, that is ground to make cement (Ruth et al., 2000, Worrell et al., 2001). Kilns are usually fuelled by carbon-intensive fossil fuels such as coal, petroleum coke, fuel oil, and natural gas. The CO₂ emissions emitted during the clinker production and combustion of fossil fuels make the clinker manufacturing the most carbon-intensive production step. Electricity is mostly consumed during the preparations of the raw materials and the final product (Worrell et al., 2001).

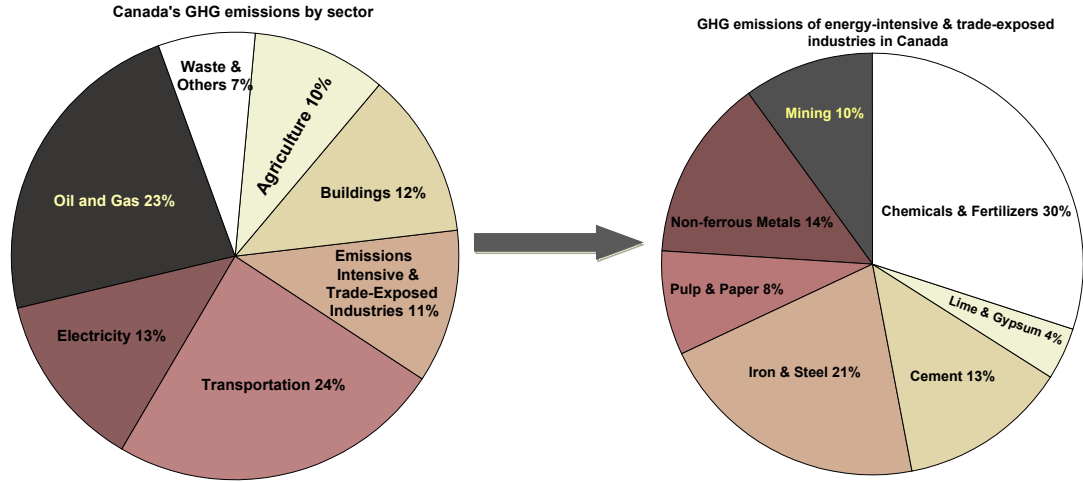


Figure 3.2: The contribution of economic sectors and cement industry to Canada's GHG emissions

In Canada, the cement industry consists of 17 plants with 15 operated by eight companies, producing 98% of Canadian cement. In 2006, the total production of the industry is reported to be more than 14.3 million tonnes mostly concentrated in Ontario and Quebec (Natural Resources Canada, 2009). In 14 plants, kilns are fuelled by coal, petroleum coke, or a combination of both which are carbon-intensive fossil fuels as reported in 2008. Analyzing the electric energy efficiency of 15 plants shows that the efficiency index, which is the amount of electric energy used in cement plants, varies from 36-138, the worst plant has an index of 36 (Natural Resources Canada, 2009). According to the International Energy Agency report (2007), the CO₂ emission factor associated with the production of one tonne of cement in Canada for the years 2003 – 2004 is 0.85 tonne.

To calculate the energy required for production at firm i , constraints (3.5) are replaced by

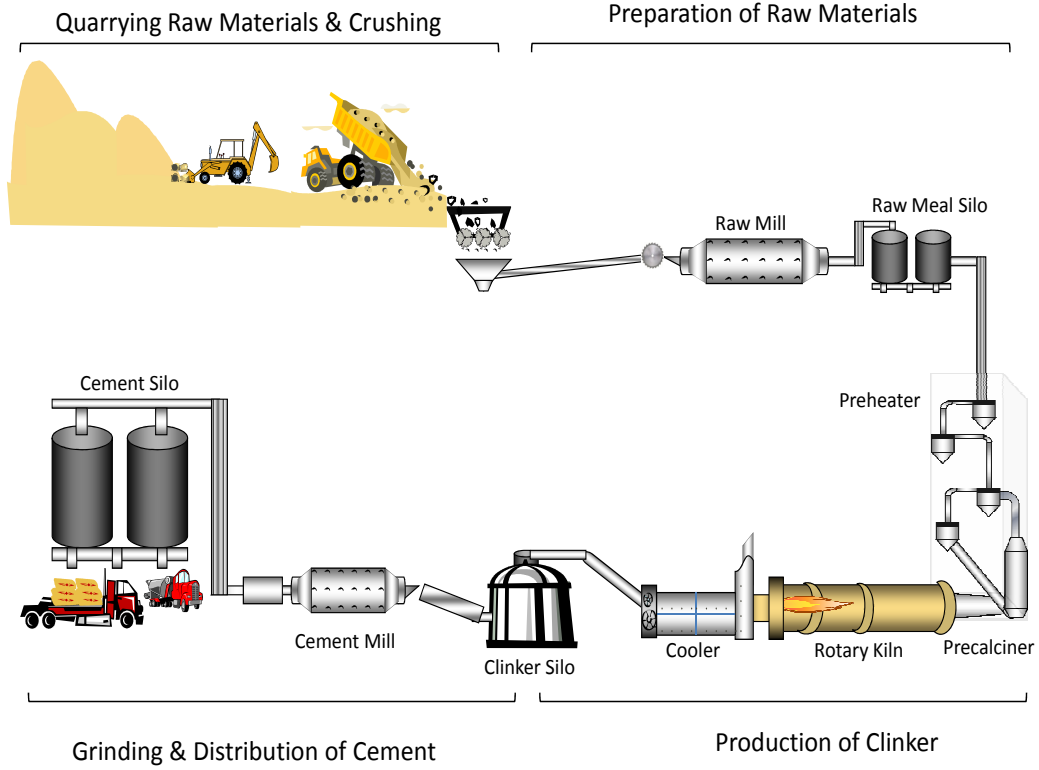


Figure 3.3: Cement production process

$$\sum_{l=1}^L \hat{b}_{il} w_{il} = a_i b_i q_i \quad (3.17),$$

The right-hand side in (3.17) calculates the total amount of energy required by firm i to produce cement from clinker, where a_i (t-clinker/t-cement) is the clinker to cement ratio at firm i , b_i (GJ/t-clinker) is the energy required by firm i to produce clinker, and q_i is the quantity produced of cement (tonne). The left-hand side calculates the total amount of energy provided by the various fuels, where $\hat{b}_{il}$ is the energy content in fuel l when used by firm i (GJ/tonne, m^3 , ...). In general, energy consumption in the cement kiln differs depending on the kiln type and the

process type (e.g., wet, dry, ...) (Worrell et al., 2001).

In addition to the CO₂ emissions, $\sum_{l=1}^L e_{il}w_{il}$, emitted from combustion of fossil fuels to produce cement, estimating cement production emission factor involves three CO₂ emission factors: (1) an emission factor due to calcining limestone to produce clinker, s_i (t-CO₂/t-clinker), (2) an emission factor due to grinding raw materials, ξ_i (t-CO₂/t-raw-material), (3) and an emission factor due to grinding cement, $\hat{\xi}_i$ (t-CO₂/t-cement) (Ruth et al., 2000). The CO₂ emissions emitted during the clinker production is related to calcining the limestone and combustion of fossil fuels. Electricity is mostly consumed during the preparations of the raw materials and the final product (Ruth et al., 2000). A CO₂ emission factor of production in the cement industry can be calculated as follows.

$$x_i = \frac{\sum_{l=1}^L e_{il}w_{il} + s_i a_i q_i + \xi_i \hat{a}_i a_i q_i + \hat{\xi}_i q_i}{q_i} \quad (3.18),$$

where $\hat{a}_i$ (tonnes of raw meal/t-clinker) is the raw material to clinker ratio at firm i . The first term in (3.18) is the total CO₂ emissions from the combustion of fossil fuels to fire the cement kilns, whereas the second term is the CO₂ emissions released from calcining the limestone. The third and forth terms are the CO₂ emissions due to electricity consumed to grind raw materials and final product. Defining $\hat{s}_i$ as $a_i s_i + \xi_i \hat{a}_i + \hat{\xi}_i$, the production emission factor can be written as

$$x_i = \frac{\sum_{l=1}^L e_{il}w_{il}}{q_i} + \hat{s}_i$$

Therefore, the taxed CO₂ emissions of firm i is

$$\theta_i = \max\left(\sum_{l=1}^L e_{il}w_{il} + (\hat{s}_i - \beta)q_i, 0\right).$$

3.3 Results and Discussion

In the small case study, we consider three firms: high, average, and low emitters. We assume that firms can use coal, petroleum coke, and natural gas to fuel kilns. Tables 3.1 and 3.2 show the parameters used in the case study. b_i are selected to be in the range of the average energy consumption per tonne of clinker produced in Canada for the year 2003-2004 as reported in the International Energy Agency report (2007), whereas the clinker-to-cement ratio is the one reported in the same report for the year 2003-2004. $\hat{s}_i$ are selected to give an emission factor that is in the range of the one reported in the International Energy Agency report (2007) for the Canadian cement industry. For the inverse demand function $p(q^d) = \gamma - \delta q^d$, γ and δ are set to 376 and 0.0376 respectively. Assuming that the regulating authority aims for a 12.5% reduction in the industry-specific emission factor which is equivalent to 0.73 t-CO₂/t-cement, we are interested in finding the best tax rate α_2 that achieves this target. To find the best α_2 , we fix the value of α_2 , solve the resulting NLP for several different values of α_2 , and pick the smallest one that achieves the target reduction β for the entire industry. The resulting emission factor of the industry is calculated as $\sum_{i=1}^I \sum_{l=1}^L (e_{il}w_{il} + \hat{s}_i q_i) / \sum_{i=1}^I q_i$, and the best α_2 is the one that induces the industry to have an emission factor $(\sum_{i=1}^I \sum_{l=1}^L (e_{il}w_{il} + \hat{s}_i q_i) / \sum_{i=1}^I q_i) \leq \beta$. The resulting NLP formulation is implemented in GAMS and solved using MINOS. In order to compare the proposed policy to other environmental policies using our case studies, we subtract $\alpha_2 \sum_{i=1}^I \hat{s}_i q_i$ from (3.11), and add $\hat{s}_i q_i$ to the left-hand side of (3.12), (3.14), (3.15), and (3.16).

The aim of this chapter is to evaluate the efficiency of the tax policy based on the emission factor by comparing it against other existing environmental policies. We

Fuels	Variable	Energy	Emissions
	costs		factor
w_{il}	h_l (\$/t, 100m ³ , ..)	$\hat{b}_l$ (GJ/t, 100m ³ , ..)	e_l (t CO ₂ /t, 100m ³ , ..)
Coal	100	32.1	2.457
Petroleum coke	50	23.3	2.53
Natural gas	11	3.72	0.29

Table 3.1: Parameters used in the case study for fuels

Firms	Production costs Capacity			Energy	Emissions	Ratio	Cap on the total
	c_i (\$/t)	t_i	d_i	b_i (GJ/t)	$\hat{s}_i$ (t CO ₂ /t)	a_i	emissions μ_i
A	22	0.001	3000	6	0.5	0.95	2832
B	26	0.001	3000	4.5	0.4	0.95	2143
C	29	0.001	3000	3	0.2	0.95	1275

Table 3.2: Parameters used in the case study for firms

can classify these policies into policies targeting total emissions (absolute): carbon tax, absolute cap-and-trade, and absolute mandatory cap, and policies targeting emission factors: intensity-based cap and trade and mandatory cap on the emission factor. We start by solving [SW] without any environmental regulation and present the results in Table 3.3. The results of this part show that all firms use petroleum coke to fuel kilns. The high emitter, firm A, has the highest emissions and production quantities and generates the highest profit. We then solve [SW] for different tax rates and pick the one that achieves the target reduction in the industry-specific emission factor. Figures 3.4 and 3.5 present the emission factor, the total emission and the social welfare, respectively, of the industry for different tax rates. From Figure 3.4, we can see that a tax rate of \$27 yields an emission factor of 0.721 or a 13.3% reduction in the emission factor which is 0.8% lower

		Firms			Industry
		A	B	C	
Emission factor		1.119	0.864	0.509	0.832
Total emissions (tC)		3356	2540	1512	7409
Production (tonne)		3000	2939	2986	8908
Fuel used%	coal	0	0	0	0
	pet coke	100%	100%	100%	100%
	N. gas	0	0	0	0
Emission Traded (tC)		—	—	—	—
Product price		—	—	—	41.05
Emission cost		0	0	0	0
Profit/Producers' surplus		11463	8641	8812	28917
Consumers' surplus		—	—	—	1491881
Social welfare		—	—	—	1520798

Table 3.3: Results of the small case study under no environmental regulations

than the target level. This emission factor corresponds to an emission level of 6250 tonne or 15.6% reduction in the overall emission. For the comparisons, we use the resulting reduction level in the emission factor, 13.3%, as a target for policies targeting emission factors and the resulting reduction level in the total emissions, 15.6%, as a target for policies targeting overall emissions. Tables 3.4 and 3.5 present the results of solving [SW] under different environmental policies using the target reductions. Table 3.4 shows the percentage changes in the emissions, productions, fuels, and profits of each firm, whereas Table 3.5 displays the percentage changes in the social welfare, consumers' and producers' surpluses, product price, the total production, the total emissions, and the emission factor of the industry. Figures 3.6-3.10 present the results of solving [SW] under environmental policies for either different tax rates or different reduction targets depending on the policy. The next subsections analyze the obtained results in detail.

Policy	Firms	Changes in Emissions%		Changes in	Fuel used%			Emission	Changes in	Emission
		Factor	Total	Production%	coal	pet coke	N. gas	cost	Profit%	Traded
Tax on the emission factor, $\alpha_2 = 26$,	A	0	-10.73	-10.73	0	100	0	27082	-37.43	-
	B	0	2.05	2.08	0	100	0	10467	179.04	-
	C	0	1.06	0.47	0	100	0	0	294.38	-
Tax on the emission factor, $\alpha_2 = 27$,	A	-15.64	-24.85	-11.00	0	0	100	15456	-37.78	-
	B	-15.16	-13.43	2.08	0	0	100	264	186.58	-
	C	0	1.06	0.47	0	100	0	0	304.03	-
Tax on the total emissions, $\alpha_2 = 26$	A	0	-26.70	-26.73	0	100	0	63970	-57.82	-
	B	0	2.05	2.08	0	100	0	67407	145.76	-
	C	0	1.06	0.47	0	100	0	39738	456.96	-
Tax on the total emissions, $\alpha_2 = 27$	A	-15.64	-38.86	-27.60	0	0	100	55404	-58.82	-
	B	-15.16	-13.43	2.08	0	0	100	59394	152.01	-
	C	-17.09	-16.27	0.47	0	0	100	34196	474.40	-
Cap on the emission factor	A	-	-	-	-	-	-	-	-	-
	B	-	-	-	-	-	-	-	-	-
	C	0	1.06	0.47	0	100	0	-	7562.87	-
Cap on the total emissions	A	0	-15.6	-15.67	0	100	0	-	492.86	-
	B	-10.65	-15.6	-5.51	0	29.27	70.73	-	646.01	-
	C	-16.50	-15.6	0.47	0	3.27	96.73	-	691.91	-
Cap and trade based on the emission factor	A	-15.64	-24.94	-11.10	0	0	100	16065	-40.63	595
	B	-4.98	-3.03	2.08	0	67.14	32.86	8100	180.75	300
	C	-17.09	-16.27	0.47	0	0	100	0	504.13	-895
Cap and trade based on the total emissions	A	-2.23	-28.75	-27.17	0	85.77	14.23	0	597.92	-441
	B	0	2.09	2.08	0	100	0	12123	803.16	449
	C	-17.09	-16.27	0.47	0	0	2298	0	849.26	-8

Table 3.4: Comparing different environmental policies for the small case study (firms)

Policy	Changes in	Changes in	Changes in	Changes in	Changes in	Changes in	Changes in	Emission
	Social	Consumers'	Producers'	Product	Total	Total	Industry	cost
	welfare%	surplus%	surplus%	Price%	production%	emissions%	Em. factor%	\$
Tax on the emission factor (\$26)	-2.56	-5.10	128.37	21.07	-2.58	-3.94	-1.44	37549
Tax on the emission factor (\$27)	-2.62	-5.26	133.42	21.75	-2.67	-15.64	-13.34	15721
Tax on the total emissions (\$26)	-11.96	-15.29	159.88	64.97	-7.97	-11.18	-3.49	171115
Tax on the total emissions (\$27)	-12.36	-15.83	166.67	67.33	-8.26	-25.52	-18.87	148995
Cap on the emission factor	-44.47	-88.66	2235.14	541.17	-66.32	-79.38	-38.82	-
Cap on the total emissions	-1.38	-13.02	599.26	54.96	-6.74	-15.64	-9.62	-
Cap and trade (emission factor)	-1.59	-5.33	191.53	22.05	-2.71	-15.64	-13.34	24165
Cap and trade (total emissions)	-1.28	-15.57	735.82	66.21	-8.12	-15.64	-8.17	12123

Table 3.5: Comparing different environmental policies for the small case study (industry)

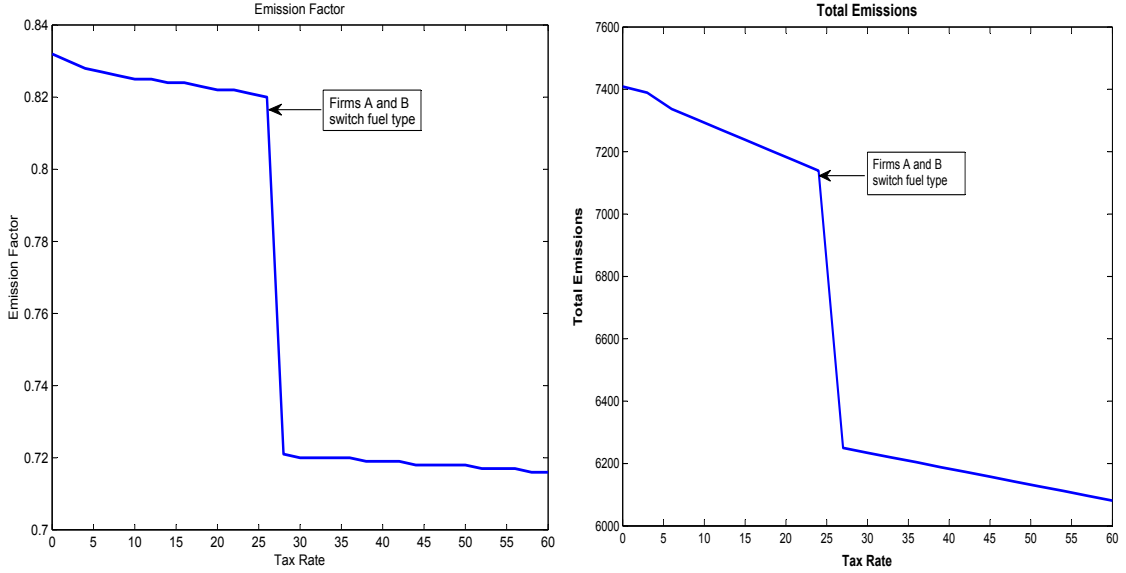


Figure 3.4: The emission factor and the overall emission for different tax rates

3.3.1 Total Emissions and Emission Factors

This subsection examines the impacts of different environmental policies on the total emissions of the industry, which is the collective CO_2 emissions of all firms, as well as the percentage contribution of each firm to the total emissions. In addition, in this subsection we discuss the impacts on the emission factors of the industry and the firms.

Observation 1: *A significant increase in the tax rate imposed on the emission factor does not always result in a significant reduction in the emission factor.*

Figure 3.4 reveals that increasing the tax rates significantly can sometimes yield small reductions in the emission factor. For example, while a tax rate of \$27 achieves an emission factor of 0.721 corresponding to a reduction of 13.3%, a tax rate of \$60 is required to obtain an emission factor of 0.71 which corresponds to a reduction of 14.6%. On the other hand, Figures 3.4 and 3.5 show that a small increase in the tax

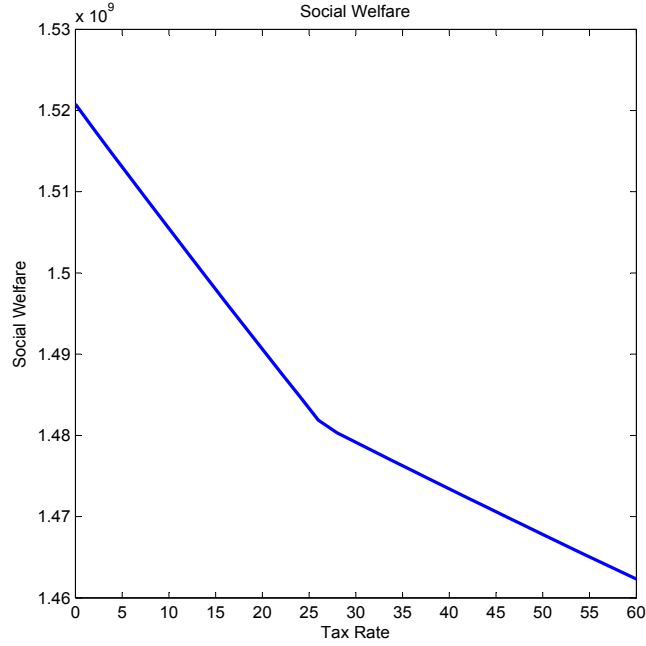


Figure 3.5: The social welfare level for different tax rates

rate can sometimes yield a slight decrease in the social welfare level; however, the reduction in the emission factor and the emission level are significant. For instance, Table 3.5 demonstrates that while increasing the tax rate from \$26 to \$27 reduces the emission factor and the total emission by a further 12%, the impact on the social welfare is about 0.06%.

Observation 2: *Using the same tax rates, the reductions in total emissions and the emission factor achieved under a carbon tax imposed on total emissions are higher than the ones achieved under a carbon tax imposed on the emission factor.*

For instance, after solving [SW] with different values for α_2 , we found that the best tax rate that achieves the target reduction in the industry-specific emission factor is \$27. Table 3.4 shows that using a tax rate of \$27 induces high and average emitters to switch to natural gas, which achieves the target level for the production emission factor and yields a 15.6% reduction in the total CO₂ emissions. On the

other hand, when we solve [SW] under the policy that imposes a tax on the total emissions to find the tax rate that achieves this emission level, we find that a tax rate of \$26 reduces the emission level by 11%, whereas a tax rate of \$27 reduces the emission level by 25% which is higher than the reduction achieved by imposing a tax on the emission factor. Figure 3.6 illustrates that for different tax rates the reductions obtained in the total emissions and the emission factor are higher when the carbon tax are imposed on the overall emissions. However, decision makers need to be aware that imposing a carbon tax on the total emissions has more negative impacts on the quantity produced, the product price, the consumers' surplus, and the social welfare as shown in the next subsections.

Observation 3: *Using a tax rate that achieves a target reduction reduces the emission costs.*

Under a tax on the emission factor, Table 3.4 shows that although using a tax rate of \$26 reduces the emissions of the high emitter by 10.73%, it does not provide an incentive to switch to less carbon-intensive fossil fuels. The table demonstrates that the high emitter reduces its emission by reducing its production quantity. Comparing the emission costs of the average and high emitters with tax rates \$26 and \$27, the table shows that their emission costs are higher with the lower tax rates due to their high emissions. Similarly, with a tax on the total emissions, a tax rate of \$26 does not induce firms to reduce their emission to the target reduction which leads to higher emission costs compared to imposing a tax rate of \$27 on the total emissions. Assuming that the price for the carbon credits is \$27, similar to the tax rate, Tables 3.3 and 3.5 present the emission costs under the cap-and-trade policies which reveal that the emission cost under the intensity-based cap and trade is higher because the quantity of carbon credits traded is higher.

Observation 4: *Imposing a cap on the emission factor would put some firms*

out of business resulting in the highest reduction in total emissions and emission factors. In contrast, policies imposing a cap on total emissions result in the lowest reduction in the emission factor.

Figure 3.6 shows that as the cap on the emission factor becomes stricter, the reduction achieved in the total emissions becomes higher because of driving some firms out of the market. For instance, Table 3.4 illustrates that requiring each firm to reduce its emissions factor to the target level, 0.721, puts the high and the average emitters, firms A and B, out of business. As a result, there is a significant reduction in the emission factor and the total emissions. In contrast, imposing a cap on the emission factor and allowing firms to trade carbon credits provide regulated firms with some flexibility to comply and achieve adequate reduction in the total emissions without putting some firms out of business. Table 3.4 demonstrate that the low emitter, firm C, reduces its emission factor and sells the extra carbon credits to the high and the average emitters, firms A and B, which kept them in the market. In addition to buying carbon credits, the average emitter uses natural gas along with petroleum coke, and the high emitter switches to natural gas to reduce their emission factors.

Table 3.5 illustrates that although there are four policies that achieve the same reduction in the total emissions, 15.6%, the reductions in the emission factors obtained under the policies imposing a cap on the total emissions with and without trading are inferior to the reduction obtained under the intensity-based carbon tax and under the intensity-based cap and trade. The reason is probably due to the higher reduction in the total production under the policies that impose a cap on the total emissions. Table 3.4 shows that both policies imposing a cap on the total emissions induce firms to use natural gas along with petroleum coke. The table also demonstrates that, under a cap-and-trade based on the total emissions, the

high and the low emitters reduce their emission levels below the caps and sell the extra carbon credits to the average emitter.

Observation 5: *Tax policies and a policy imposing a cap on the emission factor reduce the percentage contribution of the high emitters to overall emissions and increase the percentage contributions of the low and average emitters to overall emissions.*

Figure 3.7 displays the percentage contribution of each firm to the total emissions of the industry under different environmental policies. The reductions in the emission levels of the high emitter under carbon taxes and with a cap-and-trade based on the total emissions are due to the change in fossil fuel types and the reduction in the production quantities, whereas the reduction under the policy imposing a cap on the emission factor is due to putting the high emitter out of business. In contrast, the increase in the emission level of the low emitter is attributed to production increases. The figure also illustrates that the highest contribution of the high emitter to the total emissions is found to be with no environmental regulations and under a cap on the total emissions which requires all firms to reduce their emissions by the same percentage; consequently, their contribution to the total emissions stay the same.

3.3.2 Production and Market Price

This subsection examines the changes in the quantity produced by each firm, the total production of the industry which is the collective production of all firms, and the product price under different environmental policies.

Observation 6: *An intensity-based carbon tax and an intensity-based cap and trade have the least impact on total production and product price. On the other*

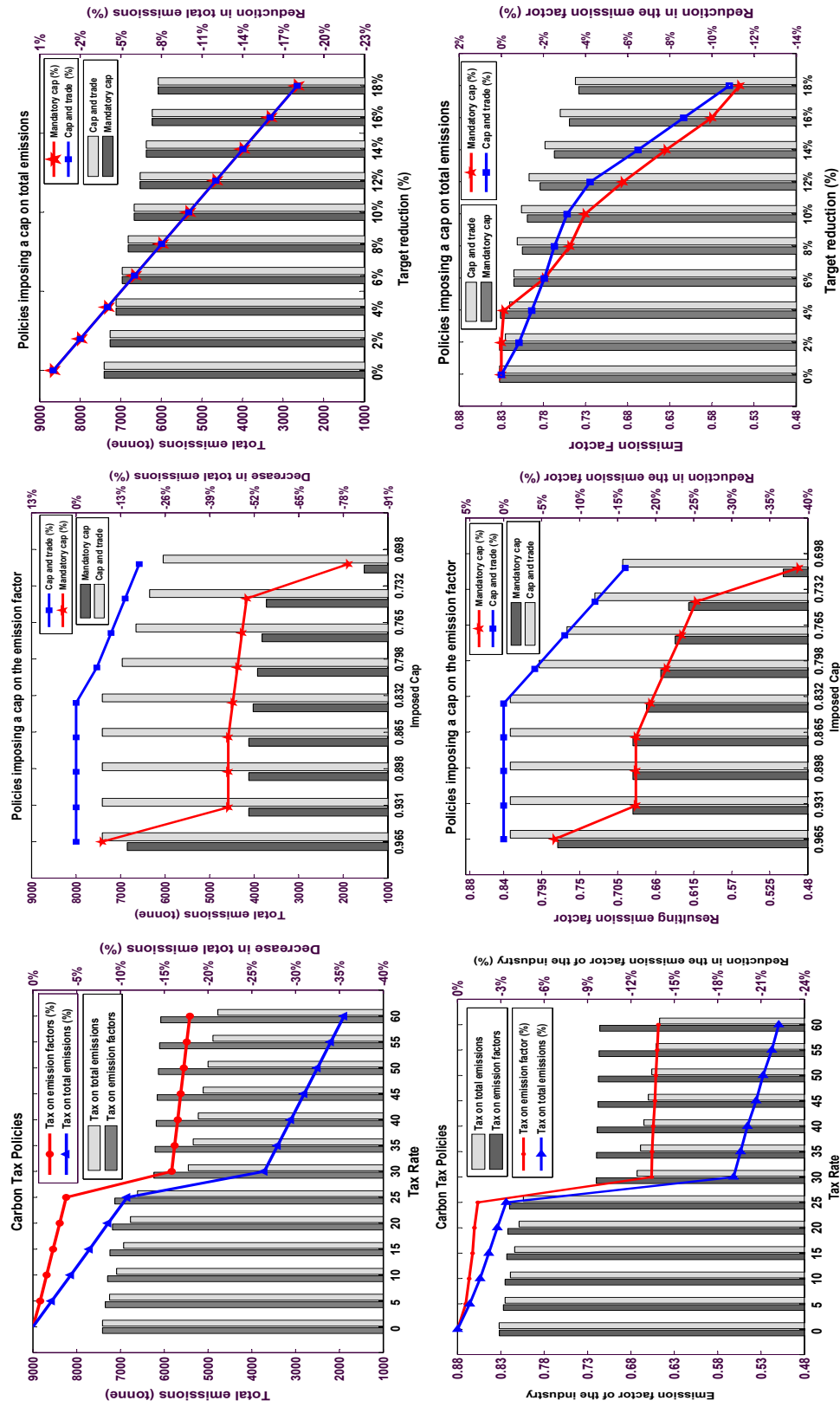


Figure 3.6: Total emissions and emission factors under different environmental policies

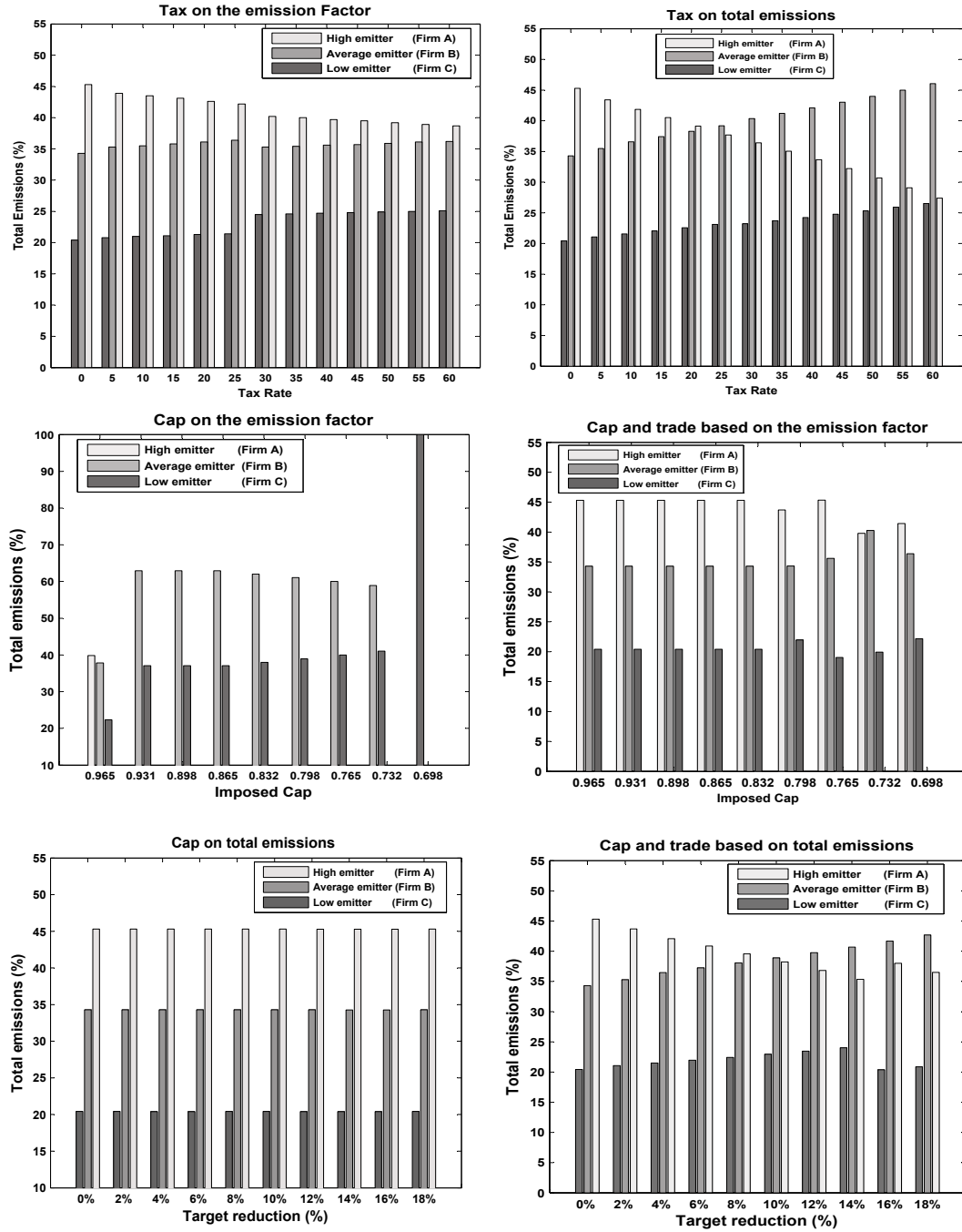


Figure 3.7: Total emissions of regulated firms under different environmental policies

hand, imposing a cap on the emission factor has the most negative impact on the total quantity produced and the product price.

Table 3.5 and Figure 3.8 show that all environmental policies result in a reduction in the total productions which leads to an increase in the market price. However, the table and the figures reveal that a tax on the emission factor and a cap-and-trade based on the emission factor lead to the least reduction in the total production and the least increase in the market price because they allow firms some flexibility to reduce their emission intensity. Firms can reduce their emissions either by switching to less carbon-intensive fuels, reducing production, or paying for extra carbon credits. This flexibility allows firms to comply with the least impact on the production and the product price. For instance, Table 3.5 shows that under a cap-and-trade based on the emission factor, requiring the industry to reduce its emission factor by 13.3% decreases the total production by 2.71% and increases the product price by 22%. These results are slightly inferior to those obtained under the tax based on the emission factor which decreases the total production by 2.67% and increases the market price by 21.75%. Under these two policies, the reduction in the total production can be attributed to the decrease in the quantity produced by the high emitters and the capacity constraints on the low and average emitters. On the other hand, Table 3.5 shows that under a cap on the emission factor, requiring the industry to reduce its emission factor by 13.3% decreases the quantity supplied into the market by 66.32% and increases the product price by 541%. The reason for this significant reduction in the total production is pushing some firms out of the market due to their inabilities to meet the target.

Observation 7: *Imposing a mandatory cap on total emissions without trading has a lower impact on the total production and the market price compared to imposing a cap on total emissions with trading although the differences between the*

impacts of the two policies are not significant.

Table 3.5 demonstrates that placing a cap on the total emissions of each firm reduces the the total production by 6.7% and increases the product price by 54.9%, whereas imposing a cap on the total emissions combined with trading decreases the total quantity produced by 8.1% and increases the product price by 66.2%. This can be attributed to the fact that some firms can benefit from selling carbon credits more than selling the product so they reduce their emissions beyond the cap by reducing productions.

Observation 8: *Although all the environmental policies lead to a reduction in the market share of the high emitter and an increase in the market shares of the low and average emitters, the largest reduction is obtained under a carbon tax on the total emissions, whereas the largest increase is obtained by imposing a cap on the emission factor.*

Figure 3.9 shows the changes in the market share of each firm under different environmental regulations which indicate a decrease in the market share of the high emitter and an increase in the market share of the low and the average emitters. The low emitter obtains the largest market share under a cap on the emission factor and the smallest market share with no environmental policies, whereas the high emitter benefits from no environmental regulations and obtains the largest market share. Under environmental policies, the high emitter has the smallest market share under a carbon tax on the total emissions due to the high emission cost and out of business under a cap on the emission factor which leads to an increase in the market shares of the low and average emitters. For instance, imposing a tax of \$27 on total emissions reduces the market share of the high emitter from 33.6% to 26.5% and increases the market share of the low emitter from 33.3% to 36.7%. In contrast, requiring a reduction of 13.3% in the industry emission factor puts the

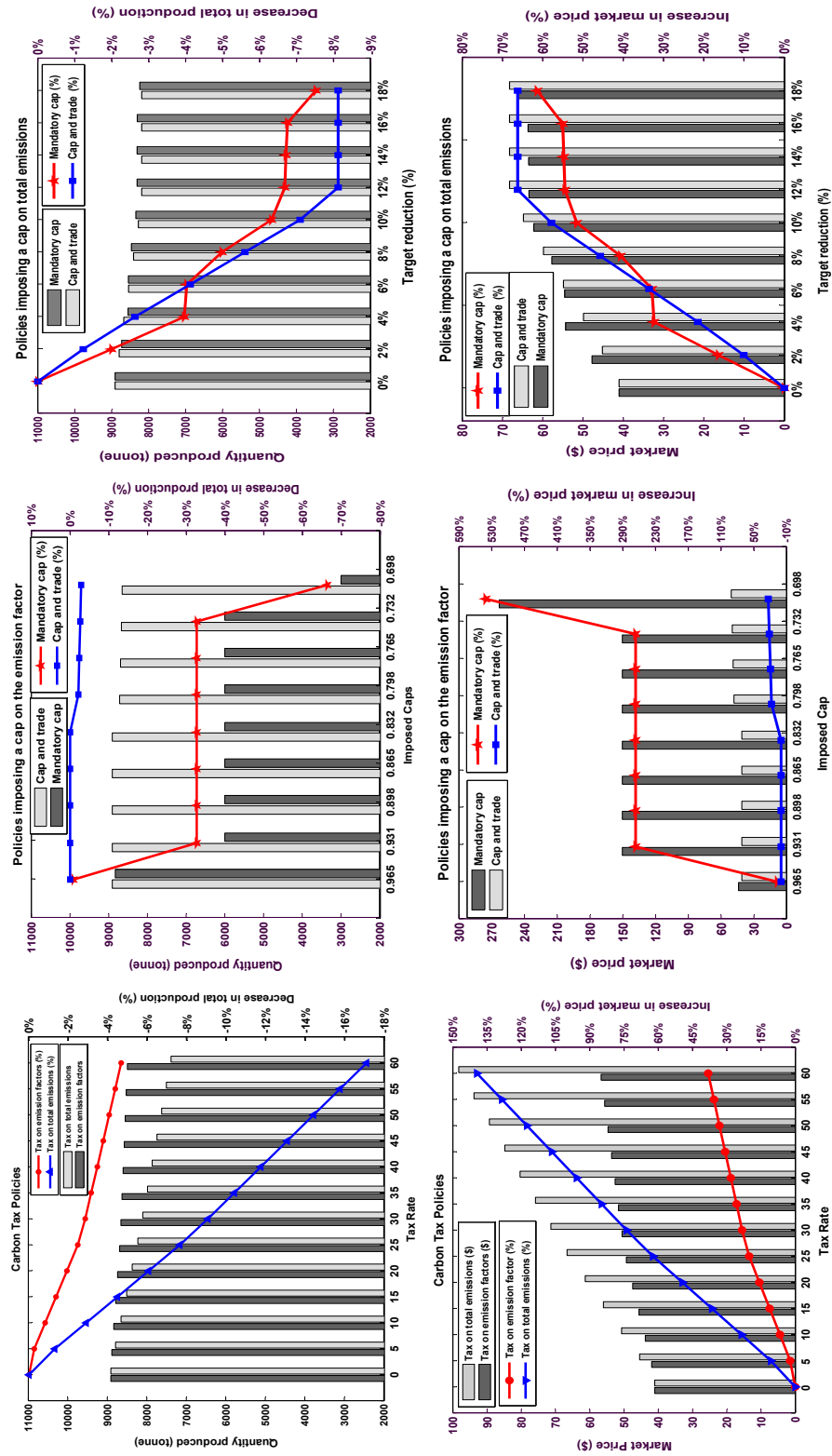


Figure 3.8: Total production and product price under different environmental policies

high emitter out of business and increases the market share of the low emitter from 33.3% to 50%.

3.3.3 Social Welfare and Consumers' and Producers Surpluses

Observation 9: *The least impact on social welfare is found to be with policies that impose a cap on total emissions with and without trading, an intensity-based cap and trade, and an intensity-based carbon tax.*

Figures 3.6 and 3.10 illustrate that adequate reduction in CO₂ emissions can be achieved with a little impact on social welfare under policies that impose a cap on total emissions with and without trading, a cap on the emission factor with trading, and a tax on the emission factor. Yet, Figure 3.10 indicates that policies imposing a cap on the total emissions would provide slightly higher social welfare compared to the intensity-based carbon tax and the intensity-based cap and trade. For example, if the industry is required to reduce its total emissions by 15.6%, Table 3.5 shows that imposing a cap on total emissions with trading yields the lowest reduction in the social welfare which is about 1.28%, followed by a cap on total emissions without trading providing a reduction of 1.38%. The intensity-based policies: cap and trade and carbon tax decrease the social welfare by 1.59% and 2.62%, respectively. Given that the policies imposed on total emissions have more negative impacts on consumers' surplus compared to the two intensity-based policies, their low impacts on the social welfare are probably due to the high increase in the producers' surplus. The highest reduction in the social welfare, 44.47%, which is due to the high reduction in consumers' surplus, is obtained with a mandatory cap on the emission factor.

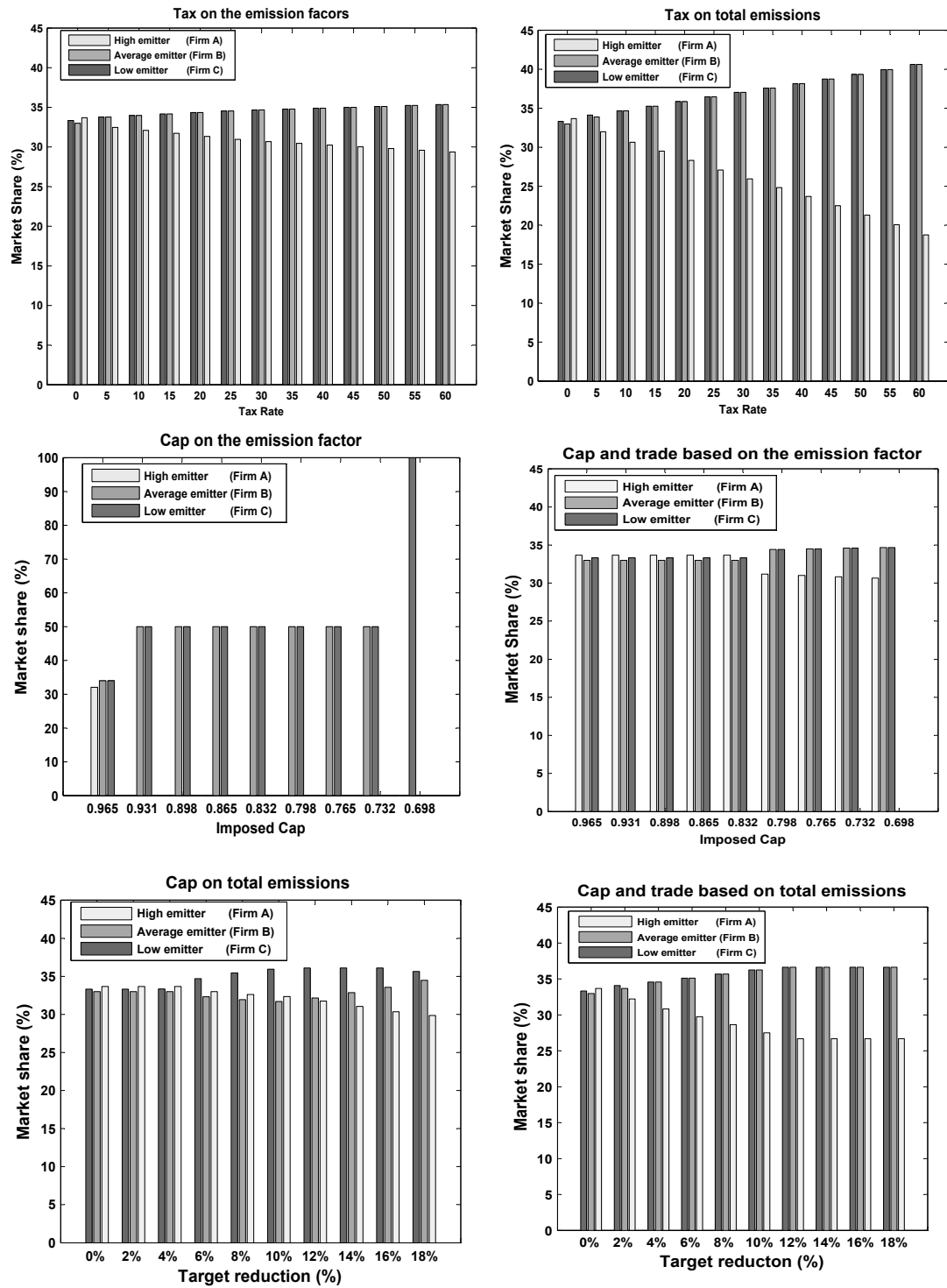


Figure 3.9: Market share of regulated firms under different environmental policies

Observation 10: *The intensity-based carbon tax and the intensity-based cap and trade lead to the least impact on the consumers' surplus.*

Figures 3.8 and 3.10 show that a tax on the emission factor and a cap-and-trade policy based on the emission factor yield the highest production quantities and the lowest market price among the environmental policies which lead to the least reduction in the consumers' surplus. Figure 3.10 also demonstrates that imposing a cap on the emission factor has the most negative impact on consumers' surplus. This reduction in consumers' surplus results from putting some firms out of business and decreasing total production. Table 3.5 shows that for the imposed target reductions, the tax on the emission factor and the cap-and-trade policy based on the emission factor decrease the consumers' surplus by 5.26% and 5.33%, respectively, whereas the cap on the emission factor without trading reduces the consumers' surplus by 88.66%.

Observation 11: *Although all the environmental policies increase producers' surplus, the highest increase is found to be with a mandatory cap on the emission factor.*

Table 3.5 and Figures 3.8 and 3.10 show that all environmental policies increase the market price and generate higher profits for the industry. However, the cap on the emission factor provides the highest producers' surplus because it puts some firms out of business, decreases the total production, and increases the product price. Under a tax on the emission factor, the profit of the industry increases by 133% due to the increase in the product price. Table 3.4 shows that with a tax on the emission factor, the average and low emitters, firms B and C, benefit from this policy and make more profit compared to the case with no environmental regulations. In contrast, the high emitters, firm A, makes less profit due to the reduction in the production quantity and the cost of CO₂ emissions. To calculate the profit of each

firm under the two policies that allow for carbon trading, we assume that the price for the carbon credits is \$27, similar to the tax rate. Although the price for the carbon credits is assumed to be the same, the profits of the industry and all the firms are higher under the cap-and-trade based on total emissions compared to using the cap-and-trade policy based on the emission factor, which is probably due to the higher product price. Table 3.5 illustrates that the high emitter generates the highest profit with no environmental regulations and the lowest profit under the tax on the total emissions due to the high emission cost and the reduction in the quantity produced by the high emitter. On the other hand, the low emitter benefits from environmental regulations and generates higher profits because of the increase in the market price and its market share.

3.3.4 Large case study

Table 3.6 compares the percentage changes in the social welfare, the consumers' and the producers' surplus, the product price, the total production, the total emissions, and the industry emission factor, under different environmental policies using a larger case study involving 12 firms: four high emitters, five average emitters, and three low emitters. The industry has a lower emission factor compared to the small case study, so we assume that the decision maker wants to reduce the emission factor by 10% which can be achieved by imposing a carbon tax of \$27/tC. The results match those for the small case study which suggest that a reduction in the emission factor would lead to a reduction in the total emissions. For instance, reducing the emission factor by 10% reduces the overall emissions by 11.64%. The intensity-based carbon tax and the intensity-based cap and trade have the least impacts on the total productions, market price, and consumers' surplus. On the other hand, the results indicate that imposing a cap on the emission factor puts

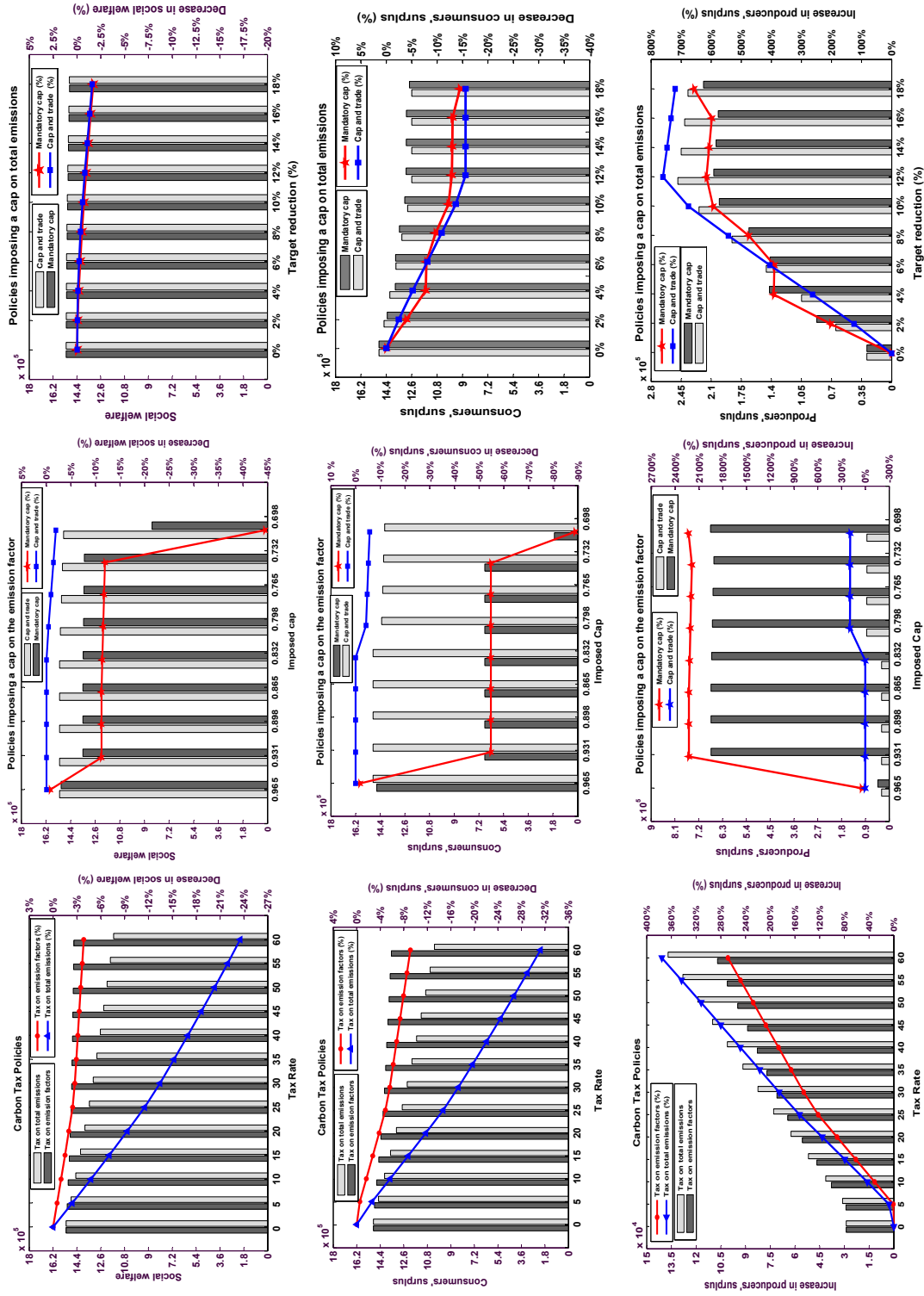


Figure 3.10: Social welfare and consumers' and producers' surpluses under different environmental policies

some firms out of business and significantly reduces the quantity produced and consumers' surplus. If trading takes place, the cap-and-trade policy based on the total emissions has the least impact on social welfare, but the policy significantly impacts consumers' surplus.

3.4 Conclusion

In this chapter, we propose a model of a tax policy based on the emission factor where policy makers set a limit on the production emission factor of a regulated industry and require firms to pay tax if they exceed that target. Using a social welfare maximization model, we test the policy on two case studies constructed in the context of the cement industry and compare the results to other environmental policies. Unlike the major criticism of the intensity-based regulations, which is that the total emissions would increase even if the target level for the emission factor is met, our analysis indicates that a reduction in the emission factor would lead to a significant reduction in the total emissions. Yet, our study show that using a low tax rate would results in no reduction or a minimal reduction in the emission factor and the total emissions. Average and low emitters benefit from the intensity-based carbon tax by supplying higher quantities and making higher profits.

Comparing the carbon tax based on the emission factor to other environmental policies, we found that the policy has more advantages: (1) it yields the highest consumers' surplus and production quantities and the lowest market price; (2) it provides social welfare that is significantly higher than the ones obtained under the mandatory cap on the emission factor and under the carbon tax based on the total emissions; (3) it provides adequate reduction in CO₂ emissions with a little impact

Policy	Changes in	Changes in	Changes in	Changes in	Changes in	Changes in	Changes in	Changes in	Emission
	Social	Consumers'	Producers'	Product	Total	Total	Total	Industry	cost
	welfare%	surplus%	surplus%	Price%	production%	emissions%	Em. factor%		\$
Tax on the emission factor (\$27)	-1.73	-3.35	75.94	13.87	-1.69	-11.64	-10.0		41920
Tax on the total emissions (\$25)	-11.68	-13.54	77.21	57.65	-7.01	-11.79	-5.05		642964
Cap on the emission factor	-9.92	-50.77	1947.82	245.25	-29.83	-42.61	-18.19		-
Cap on the total emissions	-0.98	-11.94	524.15	50.65	-6.16	-11.64	-5.75		-
Cap and trade (emission factor)	-1.02	-3.40	113.16	14.10	-1.71	-11.64	-10.0		59393
Cap and trade (total emissions)	-0.68	-13.32	605.39	56.72	-6.90	-11.64	-5.05		82048

Table 3.6: Comparing different environmental policies for the large case study

on social welfare; (4) it provides a stable price for carbon credits. Although the social welfare under the intensity-based carbon tax is found to be slightly inferior to the ones obtained from the cap-and-trade policies, trading among firms may not take place due to the volatility of permit prices. Therefore, the industry will operate under mandatory caps on the total emissions or on the emission factor which would put some firms out of business, decreases the total production, and increases the product price.

To find the best tax rate, the proposed model is solved for different tax rates, and the smallest one that achieves the target reduction in the industry-specific emission factor is picked. Due to the fact that finding the optimal tax rate has a great impact on the effectiveness of the policy, in the next Chapter, we propose a bilevel model to find the best tax rate.

Chapter 4

A Bilevel Programming Approach for Designing an Intensity-Based Tax Policy

¹In Chapter 3, we model an intensity-based carbon tax and examine its impacts on a regulated sector using a social-welfare maximizing model. To find the best tax rate, we solve the model for different tax rates and pick the one that achieves the target reduction; however, this approach does not find the optimal tax rate. Due to the fact that finding the optimal tax rate has a great impact on the effectiveness of the policy, in this chapter we propose a bilevel formulation to determine the optimal tax rate that achieves the desired trade-off between the target emission factor and the social welfare. The problem of designing a carbon tax based on the emission factor can be viewed as a hierarchical process where the leader, the government, determines the tax rate and the follower, the industry, decides on production quantities and fuel types. In the design of the policy, the government considers the decisions of the

¹The material in this chapter has been published in H. Almutairi and S. Elhedhli, "Carbon tax based on the emission factor: a bilevel programming approach", Journal of Global Optimization, 2013, DOI: 10.1007/s10898-013-0068-8

producers regarding fuel types and production quantities as well as the decisions of the market regarding demand. This chapter is organized as follows. Section 4.1 provides an overview of some important properties of a bilevel programming problem and its applications. Section 4.2 presents a bilevel formulation for designing a carbon tax policy based on the emission factor. Section 4.3 discusses the results of two case studies. Section 4.4 provides concluding remarks.

4.1 Background

4.1.1 General Formulation and Terminology

A Bilevel programming problem (BLPP) describes the hierarchical structure of a system with two independent decision makers, most probably with conflicting objectives, acting non-cooperatively (Gümüs and Floudas, 2001). Thus, BLPP consists of an optimization problem in the upper level, usually referred to as the leader's problem, constrained by a second optimization problem in the lower-level known as the follower's problem. The general formulation of BLPP takes the form (Gümüs and Floudas, 2001; Dempe, 2002).

$$\begin{aligned}
\text{BLPP (1)} \quad & \min_y F(y, x) \\
& \text{s.t. } G(y, x) \leq 0 \\
& \quad H(y, x) = 0 \\
& \min_x f(x, y) \\
& \quad \text{s.t. } g(x, y) \leq 0 \\
& \quad \quad h(x, y) = 0 \\
& x \in X \subset R^{n1}, y \in Y \subset R^{n2}
\end{aligned}$$

where $f, F : R^{n1} \times R^{n2} \rightarrow R$, are the objective functions of the follower and the leader respectively, $g = [g_1, \dots, g_J] : R^{n1} \times R^{n2} \rightarrow R^J$, $G = [G_1, \dots, G_{J'}] : R^{n1} \times R^{n2} \rightarrow R^{J'}$ are the inequality constraints of the lower- and the upper-level problems respectively, and $h = [h_1, \dots, h_I] : R^{n1} \times R^{n2} \rightarrow R^I$, $H = [H_1, \dots, H_{I'}] : R^{n1} \times R^{n2} \rightarrow R^{I'}$ are the equality constraints of the lower- and the upper-level problems respectively.

The BLPP's decision variables are partitioned into two sets of variables y and x (Dempe, 2002). Anticipating the follower's reaction, the leader makes the decision first and selects y that optimizes its objective functions $F(y, x)$. Given the leader decision, the follower solves an optimization problem parameterized in y to find x that optimizes its objective functions $f(x, y)$ (Gümüs and Floudas, 2001). The following definitions are related to BLPP (Colson et al., 2007, Gümüs and Floudas, 2001).

- The relaxed feasible set of BLPP is defined by the constraints of the lower- and the upper-level problems,

$$\Omega = \{(y, x) : y \in Y, x \in X, G(y, x) \leq 0, H(y, x) = 0, g(x, y) \leq 0, h(x, y) = 0\}$$

- The feasible set of the lower-level problem for a given $\bar{y} \in Y$ is defined as

$$\Omega(\bar{y}) = \{x \in X, g(x, \bar{y}) \leq 0, h(x, \bar{y}) = 0\}$$

- Rational reaction set of the lower-level problem for a given $\bar{y} \in Y$ is defined as

$$\Re(\bar{y}) = \{x \in X : x \in \arg \min \{f(\hat{x}, \bar{y}) : \hat{x} \in \Omega(\bar{y})\}\}$$

- inducible region which is the feasible set of BLPP is given by

$$IR = \{(y, x) : (y, x) \in \Omega, x \in \Re(y)\}$$

For a given upper-level decision y , the lower level may have multiple optimal solutions. In this case the reaction set $\mathfrak{R}(y)$ of the lower-level problem is not a singleton. Since the leader does not have a control over the follower reactions, it is hard to estimate its objective function value. Hence, in the literature several approaches are considered to address this situation. The two most common approaches are: the optimistic and pessimistic. In the first approach, the leader assumes that the follower will cooperate with him and select the solution that best suits the leader. Therefore, if the reaction set $\mathfrak{R}(y)$ of the lower-level problem is not a singleton, the leader can choose the course of action in $\Omega(y)$ that benefits him most. Conversely, in the second approach, the leader assumes no cooperation and seeks to minimize the damage resulting from the follower's choice (Colson et al., 2007, Dempe, 2002).

Karush-Kuhn-Tucker Conditions

The conventional solution methodologies to BLPP rely on Karush-Kuhn-Tucker (KKT) optimality conditions. If the lower-level problem is convex and regular, BLPP can be transformed to a single-level problem by replacing the lower level problem by KKT optimality conditions (Colson et al., 2007, Gümüs and Floudas, 2001). BLPP (1) can be written as the following single level.

$$\begin{aligned}
& \min_{y,x,\lambda,\mu} F(y,x) \\
& \text{s.t.} \quad G(y,x) \leq 0 \\
& \quad H(y,x) = 0 \\
& \quad g_i(x,y) \leq 0 \quad \forall i \in I \\
& \quad h_j(x,y) = 0 \quad \forall j \in J \\
& \quad \nabla_x L(y,x,\lambda,\mu) = 0 \\
& \quad \lambda_i g_i(x,y) = 0 \quad \forall i \in I \\
& \quad \lambda_i \geq 0 \quad \forall i \in I
\end{aligned}$$

Where $L(y,x,\lambda,\mu) = f(x,y) + \sum_{i=1}^I \lambda_i g_i(x,y) + \sum_{j=1}^J \mu_j h_j(x,y)$. Generally, the above mathematical program is hard to solve due to the nonconvexities that arise in the equations that define the stationary and complementarity conditions.

4.1.2 Bilevel Programming Applications

BLPP has diverse and many applications in real-world problems involving sequential decision-making processes. Some examples are related, but not limited, to the area of transportation planning, economic, pricing, and GHG mitigation. Below are some of the works that highlight those applications.

- Transportation: applications of BLPP in the field of transportation appear in modeling the transportation network design problem and the hazardous material network design problem. In the former problem, the interest of decision makers at the upper level is balancing the cost of investing in increasing some link capacities against congestion costs, whereas the objective of the network users is minimizing travel time (Ben-Ayed et al., 1992; Leblanc and Boyce,

1986; Marcotte, 1986). In the latter problem, policy makers design a network to be used by hazmat carriers to minimize total risk taking into account the carrier's optimal routes choices that minimizes its cost (Erkut and Gzara, 2007; Kara and Verter, 2004; Marcotte et al. 2009).

- Economics: one of BLPP applications in economics arise in modeling a market with a leader firm and multiple follower firms as a Stackelberg game (Stackelberg, 1952). The leader company moves first by choosing its production quantity taking into account the followers optimal reaction. In contrast, the followers observe the leader's decision and choose their production quantities. Another classical example in economics is the principal-agent problem where there is a principle who hires an agent to act on his/her behalf (Dempe, 1995). The principle designs contract parameters that maximize his/her profit and provide an incentive to the agent who observe the contract parameters and chooses the efforts that maximizes his/her expected utility functions. Hobbs and Nelson (1992) modeled the electric utility planning problem as BLPP. At the upper level, the electric utility controls electric rate and subsidizes energy conservation programs to minimize costs or maximize benefits while customers at the lower level maximize their benefits from energy consumption minus consumption costs.
- Pricing: Lavigne et al. (2000) studied the electricity market and employed a Stackelberg model to price electricity. Labbé et al. (1998) modeled toll-setting problem as BLPP where the leader seeks to maximize its revenue collected from setting tolls on some links of a transportation network and the network's users minimize their total costs involving tolls and travel cost. Brotcorne et al. (2008) exploited BLPP to determine prices in airline and telecommunication

industries and to include decisions related to network designs.

- GHG mitigation: the bilevel models for GHG emission reduction are devoted to carbon taxes imposed on the total amount of emissions and subsidies. Kainuma et al. (1999) utilize a bilevel programming model to evaluate the effects of imposing a combination of a linear carbon tax and subsidies on selecting energy-saving technologies and consequently reducing Japanese GHG emissions. The government problem is to minimize the total CO₂ emissions by using carbon tax and subsidies, whereas the consumers' problem is to choose the optimal combination of energy that minimizes their costs. By trying different tax rates, the results indicate that using a low tax rate without subsidy is insufficient to reduce CO₂ emissions. Zhou et al. (2011) present a bilevel optimization approach to design effective and efficient incentive policies that encourage investment in renewable energy. In the lower level problem, a central decision maker wants to expand the generation capacity of an energy system to serve projected demand of electricity with minimum total cost. The aim of the upper level problem is to encourage the lower-level planner to invest more in renewable energy by imposing a carbon tax and subsidies. The results show that combining tax and subsidies is more efficient than using each policy separately. Bard et al., (2000) presents a bilevel programming formulation that can be used to help decision makers to design a policy that encourages petro-chemical industry to produce biofuel from farm crops. In the model, the objective of the government, the leader, is to minimize the annual tax credits it allows the petro-chemical industry for producing biofuels. In contrast, the objective of the agricultural sector, the follower, is to maximize profits by selecting the best mix of crops to grow as well as the percentage of land allocated to non-food crops.

4.2 Problem Formulation

We formulate the problem of designing a carbon tax policy based on the emission factor as a bilevel programming problem. We consider a similar situation to the one presented in Section 3.1 where a regulatory authority is interested in reducing the production emission factor of a polluting industry by designing an intensity-based carbon tax policy that reaches the target reduction with the least impact on the industry. The polluting industry consists of multiple firms each having a capacity limit and a quadratic production cost. Regulated firms produce a single homogeneous product and generate CO₂ emissions in proportion to their output levels. CO₂ emissions are emitted from burning fossil fuels to produce energy that is required for production. Regulated companies are required to monitor and report their production emission factor which is an average value that reflects the level of CO₂ emissions per unit of production. Assuming that the regulatory authority sets a target emission factor for the industry and taxes firms if they exceed that target, the regulatory agency is interested in finding the tax rate that induces firms to reduce their production emission factor. On the contrary, given the carbon tax rate and assuming a competitive market which its equilibrium model can be formulated as a social welfare maximization problem (Gabriel et al., 2012, Hazell and Norton, 1986), the regulated industry chooses its output level that maximizes the social welfare. The hierarchical process of designing a carbon tax scheme leads to a bilevel formulation. At the upper level, the government determines the tax rate, whereas at the lower level, the industry, decides on the production level and the fuel types. Firms can reduce their emission intensities by switching to less carbon-intensive fuels. The decision of the tax rate made at the upper-level problem affect the social welfare level, the production quantities, and the choice of fuel type. In contrast,

the decisions made at the lower-level problem regarding fuel types and production levels influence the production emission factor.

For the formulation, we use the same notation presented in Section 3.1 and some additional notation:

Indices	i	: Index for firms, $i \in 1, \dots, N$.
	l	: Fuel type $l \in 1, \dots, L$.
Parameters	c_i	: Variable cost per unit produced at firm i .
	t_i	: Constant associated with the quadratic cost at firm i .
	h_{il}	: Fuel l cost at firm i .
	d_i	: Production capacity at firm i .
	b_i	: Thermal energy consumption at firm i (GJ/tonne).
	$\hat{b}_{il}$	: Energy content in fuel l at firm i (GJ/tonne, m ³ ...).
	e_{il}	: CO ₂ emission factor of fuel type l at firm i .
	β	: A target production emission factor above which firms pay tax.
	γ	: Intercept of inverse demand curve.
	δ	: Slope of inverse demand curve.
Variables	q_i	: Quantity produced at firm i .
	q^d	: Quantity demanded in the market.
	w_{il}	: Amount of fuel l used at firm i .
	x_i	: Production emission factor for firm i .
	E	: Production emission factor for the entire industry.
	σ_0	: Deviation from the target emission factor.
	s_0	: Deviation from the total emissions.
	p	: Market price.
	α_2	: Tax rate.

4.2.1 Lower-Level Problem

In Section 3.1, we propose the following social welfare maximization model for a polluting industry that operates under a carbon tax based on the emission factor.

$$[\text{SW}]: \max \gamma q^d - \frac{1}{2} \delta (q^d)^2 - \sum_{i=1}^I \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) - \sum_{i=1}^I \alpha_2 \theta_i \quad (4.1)$$

$$\text{s.t. } q_i \leq d_i \quad i = 1, \dots, N \quad (4.2)$$

$$\sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i \quad i = 1, \dots, N \quad (4.3)$$

$$\theta_i \geq \sum_{l=1}^L e_{il} w_{il} - \beta q_i \quad i = 1, \dots, N \quad (4.4)$$

$$q^d - \sum_{i=1}^I q_i = 0 \quad (4.5)$$

$$q^d, q_i, w_{il}, \theta_i \geq 0 \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.6)$$

The objective function (4.1) maximizes the sum of consumers' and producers' surpluses (in which payments and revenue cancel each other). The first and the second terms in the objective function correspond to the consumers' surplus. The third and the fourth terms in (4.1) denote the production cost which we assume to be a quadratic; whereas the fifth term represents the fuel cost. The last term in (4.1) correspond to the emission cost. Constraints (4.2) are the production capacity limit for each firm. Constraints (4.3) calculate the amount of fossil fuels required by firm i to produce a quantity q_i . Constraints (4.4) calculate the taxed CO₂ emissions for each firm. Constraint (4.5) is the market clearing condition. Constraints (4.6) are the nonnegativity constraints.

4.2.2 Upper-Level Problem

The regulatory authority problem consists of determining the tax rate that induces the industry to achieve the target production emission factor.

$$\max E \quad (4.7)$$

$$\text{s.t.} \quad \sum_{i=1}^I \sum_{l=1}^L e_{il} w_{il} = E \sum_{i=1}^I q_i \quad (4.8)$$

$$0 \leq E \leq \beta, \quad (4.9)$$

$$0 \leq \alpha_2 \leq \alpha_2^{ub} \quad (4.10)$$

The objective function (4.7) maximizes the resulting emission factor of the industry to reach the specified target. Constraint (4.8) which is nonlinear, calculates the resulting emission factor of the industry, whereas constraints (4.9) and (4.10) are the lower and the upper bounds on the emission factor of the industry and the tax rate, respectively.

Maximizing the emission factor is equivalent to minimizing the deviation from the target emission factor:

$$\sigma_0 = \beta - E = \beta - \frac{\sum_{i=1}^I \sum_{l=1}^L e_{il} w_{il}}{\sum_{i=1}^I q_i}.$$

With this, the upper level problem is equivalent to:

$$\begin{aligned} \min \quad & \sigma_0 \\ \text{s.t.} \quad & \frac{\sum_{i=1}^I \sum_{l=1}^L e_{il} w_{il}}{\sum_{i=1}^I q_i} + \sigma_0 = \beta \\ & 0 \leq \alpha_2 \leq \alpha_2^{ub} \\ & \sigma_0 \geq 0 \end{aligned}$$

As this problem is nonlinear, we multiply the constraint by $\sum_{i=1}^I q_i$ and instead solve the linear program:

$$\begin{aligned}
& \min \quad s_0 \\
& \text{s.t.} \quad \sum_{i=1}^I \sum_{l=1}^L e_{il} w_{il} + s_0 = \beta \sum_{i=1}^I q_i \quad (4.11) \\
& \quad \quad 0 \leq \alpha_2 \leq \alpha_2^{ub} \\
& \quad \quad s_0 \geq 0 \quad (4.12)
\end{aligned}$$

where s_0 is the deviation from the total emissions.

4.2.3 Bilevel Formulation

By combining the upper- and lower-level problems, the bilevel formulation of designing a carbon tax faced by the government agency is:

$$\begin{aligned}
& \min \quad s_0 \\
& \text{s.t.} \quad \sum_{i=1}^I \sum_{l=1}^L e_{il} w_{il} + s_0 = \beta \sum_{i=1}^I q_i \\
& \quad \quad 0 \leq \alpha_2 \leq \alpha_2^{ub} \\
& \quad \quad \max \quad \gamma q^d - \frac{1}{2} \delta (q^d)^2 - \sum_{i=1}^I \sum_{l=1}^L (c_i q_i + t_i q_i^2 + h_{il} w_{il}) \\
& \quad \quad \quad - \sum_{i=1}^I \alpha_2 \theta_i \\
& \quad \quad \text{s.t.} \quad q_i \leq d_i \quad i = 1, \dots, N \\
& \quad \quad \quad \sum_{l=1}^L \hat{b}_{il} w_{il} = b_i q_i \quad i = 1, \dots, N \\
& \quad \quad \quad -\theta_i + \sum_{l=1}^L e_{il} w_{il} - \beta q_i \leq 0 \quad i = 1, \dots, N \\
& \quad \quad \quad q^d - \sum_{i=1}^I q_i = 0 \\
& \quad \quad \quad q_i, q^d, w_{il}, \theta_i \geq 0 \quad i = 1, \dots, N, l = 1, \dots, L \\
& \quad \quad s_0 \geq 0
\end{aligned}$$

The decision of the tax rate made at the upper-level problem affects the social welfare level at the lower-level problem, whereas the decisions made at the lower-level problem regarding the production quantities and the type and the quantities of the fossil fuels influence the CO₂ emission factor.

When the lower level problem is convex in the upper-level decision variables and satisfies a constraint qualification, the bilevel problem can be transformed to a single-level problem by replacing the lower-level problem by its Karush-Kuhn-Tucker (KKT) optimality conditions (Colson et al., 2007, Gümüs and Floudas, 2001). Defining $r_i, \lambda_i, \zeta_i, p$ to be the dual variables associated with constraints (4.2), (4.3), (4.4), and (4.5) respectively, the KKT optimality conditions of the lower-level problem are given by

Primal feasibility:

	Dual variable	
$q_i \leq d_i$	$r_i \geq 0$	$i = 1, \dots, N$
$\sum_{l=1}^L \hat{b}_{il} w_{il} - b_i q_i = 0$	λ_i	$i = 1, \dots, N$
$-\theta_i + \sum_{l=1}^L e_{il} w_{il} - \beta q_i \leq 0$	$\zeta_i \geq 0$	$i = 1, \dots, N$
$q^d - \sum_{i=1}^I q_i = 0$	p	
$q_i, w_{il}, \theta_i \geq 0$		$i = 1, \dots, N, l = 1, \dots, L$

Dual feasibility

$$p - \gamma + \delta q^d \geq 0 \quad (4.13)$$

$$c_i + 2t_i q_i + r_i - b_i \lambda_i - \beta \zeta_i - p \geq 0 \quad i = 1, \dots, N \quad (4.14)$$

$$\hat{b}_{il} \lambda_i + e_{il} \zeta_i + h_{il} \geq 0 \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.15)$$

$$\alpha_2 - \zeta_i \geq 0 \quad i = 1, \dots, N \quad (4.16)$$

$$r_i, \zeta_i \geq 0 \quad i = 1, \dots, N \quad (4.17)$$

Associating slack variables $s_i^1, s_i^2, s^3, s_i^4, s_{il}^5, s_i^6$ with constraints (4.2), (4.4), and (4.13)–(4.17) respectively, the primal and dual feasibility constraints can be rewritten as

$$q_i - d_i + s_i^1 = 0 \quad i = 1, \dots, N \quad (4.18)$$

$$-\theta_i + \sum_{l=1}^L e_{il} w_{il} - \beta q_i + s_i^2 = 0 \quad i = 1, \dots, N \quad (4.19)$$

$$p - \gamma + \delta q^d - s^3 = 0 \quad (4.20)$$

$$c_i + 2t_i q_i + r_i - b_i \lambda_i - \beta \zeta_i - p - s_i^4 = 0 \quad i = 1, \dots, N \quad (4.21)$$

$$\hat{b}_{il} \lambda_i + e_{il} \zeta_i + h_{il} - s_{il}^5 = 0 \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.22)$$

$$\alpha_2 - \zeta_i - s_i^6 = 0 \quad i = 1, \dots, N \quad (4.23)$$

Complementary slackness conditions

$$s_i^1 r_i = 0 \quad i = 1, \dots, N \quad (4.24)$$

$$s_i^2 \zeta_i = 0 \quad i = 1, \dots, N \quad (4.25)$$

$$s^3 q^d = 0 \quad (4.26)$$

$$s_i^4 q_i = 0 \quad i = 1, \dots, N \quad (4.27)$$

$$s_{il}^5 w_{il} = 0 \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.28)$$

$$s_i^6 \theta_i = 0 \quad i = 1, \dots, N \quad (4.29)$$

The bilevel formulation can be transformed to a single-level problem that includes the optimality conditions of the industry problem into the government problem.

$$\min s_0$$

$$\text{s.t. } (4.3), (4.5), (4.6), (4.10) - (4.12), \text{ and } (4.17) - (4.29)$$

The complementary slackness conditions (4.24) – (4.29) can be linearized by associating binary variables $z_i^1, z_i^2, z^3, z_i^4, z_{il}^5, z_i^6$ and a large constant M with each equality constraint (Bard, 1998). The resulting mixed integer program (MIP) is

[MIP]: $\min s_0$

s.t. (4.3), (4.5), (4.6), (4.10) – (4.12),

(4.17) – (4.23), and

$$s_i^1 \leq Mz_i^1 \quad i = 1, \dots, N \quad (4.30)$$

$$r_i \leq M(1 - z_i^1) \quad i = 1, \dots, N \quad (4.31)$$

$$s_i^2 \leq Mz_i^2 \quad i = 1, \dots, N \quad (4.32)$$

$$\zeta_i \leq M(1 - z_i^2) \quad i = 1, \dots, N \quad (4.33)$$

$$s^3 \leq Mz^3 \quad (4.34)$$

$$q^d \leq M(1 - z^3) \quad (4.35)$$

$$s_i^4 \leq Mz_i^4 \quad i = 1, \dots, N \quad (4.36)$$

$$q_i \leq M(1 - z_i^4) \quad i = 1, \dots, N \quad (4.37)$$

$$s_{il}^5 \leq Mz_{il}^5 \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.38)$$

$$w_{il} \leq M(1 - z_{il}^5) \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.39)$$

$$s_i^6 \leq Mz_i^6 \quad i = 1, \dots, N \quad (4.40)$$

$$\theta_i \leq M(1 - z_i^6) \quad i = 1, \dots, N \quad (4.41)$$

$$z \in \{0, 1\} \quad i = 1, \dots, N, l = 1, \dots, L \quad (4.42)$$

4.3 Results and Discussion

To test the proposed model we use the same case study that we have constructed in Section 3.3. Assuming that the regulating authority aims for a 12.5% reduction in the production emission factor, we are interested in finding the best tax rate, α_2 , that achieves the target reduction in the industry-specific emission factor. The resulting MIP formulation is implemented in MATLAB 7.4 and solved using CPLEX.

Tables 4.1 and 4.2 display the results of the small case study. The first set of the results in Tables 4.1 and 4.2 show the solutions of solving [SW] with no carbon tax or a target emission factor for the industry. The results show that all firms use petroleum coke to fuel kilns. The high emitter, firm A, produces its full capacity and generates the highest profit because of its low production cost. However, the contribution of firm A to the overall emissions is about 45%, whereas its emission factor is 34% higher than the emission factor of the industry. The second set of the results in Tables 4.1 and 4.2 present the solutions of the transformed bilevel model, [MIP]. We found that the best tax rate that achieves the target reduction in the industry-specific emission factor is \$26.49/tC which also reduces the total emissions by 14.5%. This tax rate reduces the quantity produced by the high emitters by 10% and induces the average and the low emitters to produce their full capacities. Under this tax rates, the product price increases by 21% leading to 131% increase in the producers' surplus. However, the profit of the high emitter has dropped by 37%, whereas the profits of the average and low emitters have increased by 182% and 300%, respectively, leading to a higher profit for the industry. The solution of [MIP] demonstrates that firm A uses petroleum coke along with natural gas, firm B switches to natural gas, and firm C continues using petroleum coke. However, solving [SW] using the obtained tax rate provides different fuel type for firm A, which is switching from petroleum coke to natural gas, as presented in the third set of the results in Table 4.2. Although Tables 4.1 and 4.2 demonstrate that the social welfare, the quantity produced, the product price, the consumers' and the producers' surpluses obtained from solving [SW] are the same as the ones obtained from solving [MIP], the emission factor, the total emissions, and the taxed emissions of firm A are different. This indicates that the lower level problem has multiple solutions for some given tax rates. Specifically, firm A has the option to use petroleum

coke along with natural gas and pay more carbon tax or to use natural gas and pay less carbon tax. Both solutions lead to the same cost and the same profit for firm A and the same social welfare for the industry. Although it is preferable to have a lower emission factor and lower overall emissions, the value of the objective function of the government would be higher if firm A chooses the second solution. This happened because of our choice of the objective function of the government; the first solution minimizes the deviations from the total emissions and the target emission factor, whereas the deviations if firm A chooses the second solution are 79 and 0.009, respectively.

4.3.1 An alternative objective function for the upper-level problem

When the solutions of the lower-level problem is not uniquely determined for each, or some, upper-level solutions, the bilevel programming problem is considered to be unstable. The most common approaches in the literature to overcome the problem of having multiple solutions are the optimistic and pessimistic (Dempe, 2002). In this thesis, we assume that the leader takes the optimistic position which assumes that the follower will choose the best solution for the leader. However, this solution has a higher emission level which is not preferable. Therefore, we need an alternative objective function that provides a better value for the objective function of the leader when the industry selects the solution with the lower emission level. Hence, we modify (4.7) to the following weighted objective function for the upper-level problem $\max \tau \sum_{i=1}^I q_i - \nu E$, where $\tau, \nu \in [0, 1]$ are parameters that indicate the relative importance of the quantity produced and the emission factor for the decision makers. We solve the following bilevel program by transforming it to a single level

	Target Em.	Tax rate	Quantity	Emission	Total	Product	Social	Consumers' surplus	Producers' surplus
	factor (β)	α_2	demand. (q^d)	factor	emissions	price	welfare	surplus	surplus
No carbon tax	—	—	8908	0.832	7409	41.05	1520798	1491881	28917
Optimal solution of [MIP]	0.73	26.49	8673	0.73	6331	49.87	1481187	1414300	66886
Optimal solution of [SW] given α_2	0.73	26.49	8673	0.721	6252	49.87	1481187	1414300	66886

Table 4.1: Results of the small case study (industry)

	Firms	Production	Fuel type			Emission	Total	Taxed	Profit	Total
	i	q_i	Coal	Petroleum	coke	Natural gas	emissions	emissions		cost
No carbon tax	A	3000.0	0	733		0	1.12	3356	0	11463 111695
	B	2939.5	0	539		0	0.864	2540	0	8641 112038
	C	2968.5	0	363		0	0.509	1512	0	8812 113056
Optimal solution of [MIP]	A	2673	0	110		3405	0.974	2603	651.8	7147 126200
	B	3000	0	0		3447	0.733	2199	9.79	24452 125182
	C	3000	0	366		0	0.509	1528	0	35287 114347
Optimal solution of [SW] given α_2	A	2673	0	0		4096	0.944	2524	573	7147 126200
	B	3000	0	0		3447	0.733	2199	9.79	24452 125182
	C	3000	0	366		0	0.509	1528	0	35287 114347

Table 4.2: Results of the small case study (firms)

mixed integer nonlinear program using KKT conditions as shown previously.

$$\begin{aligned} \max \quad & \tau \sum_{i=1}^I q_i - \nu E \\ \text{s.t.} \quad & (4.8) - (4.10), \text{ and } (4.1) - (4.6) \end{aligned}$$

$$\begin{aligned} [\text{MINLP}]: \max \quad & \tau \sum_{i=1}^I q_i - \nu E \\ \text{s.t.} \quad & (4.3), (4.5), (4.6), (4.8) - (4.10), (4.17) - (4.23), \text{ and } (4.30) - (4.42) \end{aligned}$$

A Small Case Study

Letting $\tau = \nu = 0.5$, we implement [MINLP] in GAMS and solve it using BARON for different target emission factor. Tables 4.3-4.6 compare the results of [MINLP] for different target emission factor to the results of solving [SW] given the obtained tax rate. Table 4.3 presents the tax rates required to achieve different reduction targets, as well as the percentage changes in the quantity demanded (q^d), the emission factor (EF), the overall emission (TE), the product price (P), the social welfare (SW), and the consumers' and the producers surpluses (CS) and (PS). Tables 4.4-4.6 show the percentage changes in the production quantities, fuel types, emission factors, total emissions, profits, and costs of each firm for different reduction targets. The tables demonstrate that using the new objective function provides stable solutions. Tables 4.3-4.6 and Figure 4.1 illustrate that lowering the target emission factor and increasing the tax rates decreases the social welfare and drives some or all firms out of business, e.g., reducing the emission factor by 50% would drive all firms out of business. The tables and the figure also demonstrate that the tax rates

increase with lowering the target emission factor then start to drop when the high and the average emitters are out of business.

Table 4.3 and Figure 4.1 show that in some cases, achieving a reduction in the emission factors requires a significant increase in the tax rate. For instance, decreasing the target emission factor by 27.5% requires increasing the tax rate from \$26.49 to \$1095.27 which drives the high emitter, firm A, out of business and decreases the production of the average emitter, firm B, by 27.36%. Moreover, this tax rate decreases the total production, the overall emission, the social welfare, and the consumer surplus by 42.36%, 58.42%, 38.54%, and 66.77%, respectively, and increases the price and the producer surplus by 345.6% and 1418%, respectively. Note that although the tax rate is \$1095.27, the actual emission costs due to producing a tonne of cement is given by $\alpha_2(x_i - \beta)$. Therefore, the emission costs of firms A and B are $\$1095.27(0.94 - 0.6) = \$372.39$ and $\$1095.27(0.727 - 0.6) = \$139.1$, respectively. Given that a competitive firm maximizes its profit by selecting the output level at which $p = c_i + 2t_i q_i + r_i - a_i b_i \lambda_i + (s_i - \beta)\zeta_i$, firm A exits the market and firm B produces 2135 tonne of cement at the current market price for cement of \$182.92. Decision makers need to weight the impact of selecting a target emission factor and imposing a tax rate to achieve that target. In some cases, different emission factors can be obtained by the same tax rates; however, the impact on the social welfare, the total emissions, and other factors are different. For example, if the decision makers need to choose between reducing the emission factor by 7.5% or 12.5%, we can see that both targets can be achieved by the same tax rate, \$26.49. However, the former decreases the social welfare and the total emissions by 2.21% and 13.78%, respectively, while the latter decreases them by 2.6% and 15.62%, respectively. Given the small differences in the effects on the social welfare, the latter achieves a higher reduction in the total emissions and therefore provides a better

target.

Table 4.3 and Figure 4.1 show that a decrease in the target emission factor significantly decreases the overall emissions. The reduction is a result of either switching to less carbon-intensive fuels or reducing production quantities. Tables 4.4-4.6 demonstrate that a tax rate of \$26.49 and a target reduction of 12.5% induce high and average emitters to switch to natural gas to reduce their emissions factor. On the other hand, decreasing the emission factor by more than 15% and increasing the tax rates push the high and average emitters to switch from natural gas to coal and reduce their productions in order to comply with the target and to reduce their costs. The tables and the figure also show that the producers' surplus increases with the increase in the tax rate due to the increase in the market price while the consumers' surplus decreases. The producers' surplus and the market price reach their maximum when the high and average emitters are out of business allowing the low emitter to generate the highest profit. The increase in the tax rates and the reduction in the emission factor significantly reduce the production quantities and the profit of the high emitter.

Large Case Studies

Table 4.7 shows the impact of different target emission factors using large examples consisting of 12, 20, and 30 firms. The table presents the target and the achieved reduction in the emission factor, the corresponding tax rates, the percentage decrease or increase in total emissions, productions, market price, social welfare, consumers' and producers' surpluses, and the number of firms compared to the no tax case. The table also shows the CPU time in seconds which increases with the increase in the number of firms and the target reduction. The results of the large examples are consistent with the results of the small example. The table illustrates that the tax

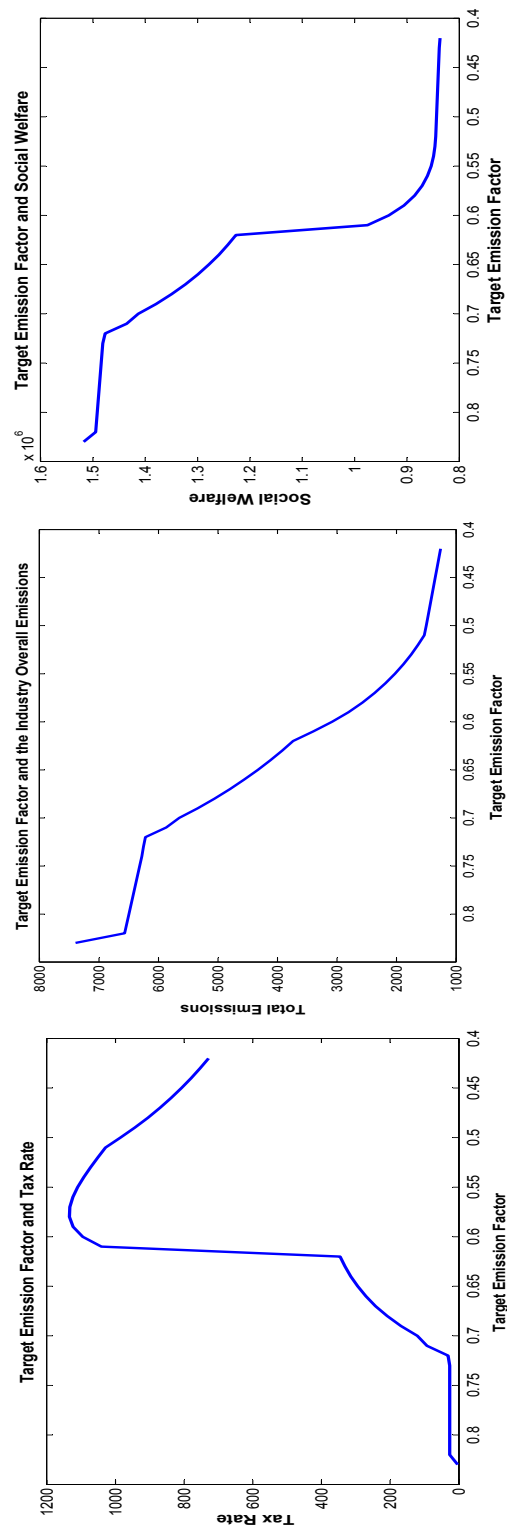


Figure 4.1: The impact of different target emission factors (small example)

Targ. red. in EF%	Tax rate	[MINLP]								[SW]							
$\beta\%$	α_2 \$/tC	Percentage Changes in								Percentage Changes in							
		$q^{d\%}$	EF%	TE%	P%	SW%	CS%	PS%		$q^{d\%}$	EF%	TE%	P%	SW%	CS%	PS%	
0.2	3.25	-0.02	-0.2	-0.23	0.19	-0.21	-0.05	-8.39		-0.02	-0.2	-0.23	0.19	-0.21	-0.05	-8.39	
2.5	26.49	-2.04	-10.0	-11.82	16.59	-1.81	-4.03	112.55		-2.04	-10.0	-11.82	16.59	-1.81	-4.03	112.55	
5	26.49	-2.19	-10.9	-12.81	17.81	-2.01	-4.32	117.23		-2.19	-10.9	-12.81	17.81	-2.01	-4.32	117.23	
7.5	26.49	-2.33	-11.8	-13.78	19.05	-2.21	-4.61	121.92		-2.33	-11.8	-13.78	19.05	-2.21	-4.61	121.92	
10	26.49	-2.49	-12.6	-14.77	20.27	-2.41	-4.91	126.61		-2.49	-12.6	-14.77	20.27	-2.41	-4.91	126.61	
12.5	26.49	-2.64	-13.3	-15.62	21.49	-2.60	-5.20	131.30		-2.64	-13.3	-15.62	21.49	-2.60	-5.20	131.30	
15	92.53	-7.17	-15	-20.76	58.51	-5.61	-13.83	418.30		-7.17	-15	-20.76	58.51	-5.61	-13.83	418.30	
17.5	168.55	-13.06	-17.5	-27.87	106.48	-9.30	-24.40	769.69		-13.06	-17.5	-27.87	106.48	-9.30	-24.40	769.69	
20	242.41	-19.59	-20	-35.23	159.76	-13.00	-35.33	1138.89		-19.59	-20	-35.23	159.76	-13.00	-35.33	1138.89	
22.5	314.81	-27.73	-23	-44.39	226.19	-17.19	-47.76	1559.82		-27.73	-23	-44.39	226.19	-17.19	-47.76	1559.82	
25	345.88	-32.30	-25.5	-49.53	263.48	-19.34	-54.16	1776.91		-32.30	-25.5	-49.53	263.48	-19.34	-54.16	1776.91	
27.5	1095.27	-42.36	-27.9	-58.42	345.60	-38.54	-66.77	1418.08		-42.36	-27.9	-58.42	345.60	-38.54	-66.77	1418.08	
30	1134.12	-50.19	-30	-65.27	409.50	-41.78	-75.19	1681.58		-50.19	-30	-65.27	409.50	-41.78	-75.19	1681.58	
32.5	1124.16	-56.15	-32.7	-70.48	458.12	-43.40	-80.77	1884.31		-56.15	-32.7	-70.48	458.12	-43.40	-80.77	1884.31	
35	1092.35	-60.83	-35	-74.57	496.35	-44.16	-84.66	2045.09		-60.83	-35	-74.57	496.35	-44.16	-84.66	2045.09	
37.5	1051.28	-64.62	-37.5	-77.88	527.19	-44.44	-87.48	2175.71		-64.62	-37.5	-77.88	527.19	-44.44	-87.48	2175.71	
40	985.68	-66.32	-40	-79.75	541.17	-44.52	-88.66	2232.54		-66.32	-40	-79.75	541.17	-44.52	-88.66	2232.54	
42.5	905.61	-66.32	-42.5	-80.56	541.17	-44.63	-88.66	2227.04		-66.32	-42.5	-80.56	541.17	-44.63	-88.66	2227.04	
45	837.83	-66.32	-45	-81.37	541.17	-44.73	-88.66	2221.55		-66.32	-45	-81.37	541.17	-44.73	-88.66	2221.55	
47.5	779.49	-66.32	-47.5	-82.18	541.17	-44.84	-88.66	2216.05		-66.32	-47.5	-82.18	541.17	-44.84	-88.66	2216.05	
50	--	--	--	--	--	--	--	--		--	--	--	--	--	--	--	

Table 4.3: A comparison of the results of [MINLP] and [SW] for different target emission factor (industry)

Targ.	Tax	[MINLP]										[SW]									
red. in	rate	Changes in										Changes in									
EF	α_2	Prod.%	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%	Prod%.	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%
%	\$/tC	q_i	C.	P.C.	N.G	factor%	em.%	em.(tC)	%	cost%	q_i	C.	P.C.	N.G	factor%	em.%	em. (tC)	%	cost%		
0.2	3.25	-0.60	0	100	0	-0.09	-0.60	861	-22.42	1.86	-0.60	0	100	0	-0.09	-0.60	861	-22.42	1.86		
2.5	26.49	-9.13	0	0	100	-15.64	-23.27	366	-35.13	10.20	-9.13	0	0	100	-15.64	-23.27	366	-35.13	10.20		
5	26.49	-9.57	0	0	100	-15.64	-23.66	418	-35.77	10.92	-9.57	0	0	100	-15.64	-23.66	418	-35.77	10.92		
7.5	26.49	-10.00	0	0	100	-15.64	-24.05	470	-36.40	11.62	-10.00	0	0	100	-15.64	-24.05	470	-36.40	11.62		
10	26.49	-10.47	0	0	100	-15.64	-24.40	522	-37.02	12.31	-10.47	0	0	100	-15.64	-24.40	522	-37.02	12.31		
12.5	26.49	-10.90	0	0	100	-15.64	-24.79	573	-37.65	12.99	-10.90	0	0	100	-15.64	-24.79	573	-37.65	12.99		
15	92.53	-24.37	0	0	100	-15.64	-36.17	531	-55.08	27.60	-24.37	0	0	100	-15.64	-36.17	531	-55.08	27.60		
17.5	168.55	-41.83	100	0	0	-16.35	-51.31	429	-73.42	29.75	-41.83	100	0	0	-16.35	-51.31	429	-73.42	29.75		
20	242.41	-61.23	100	0	0	-16.35	-67.55	309	-88.19	9.91	-61.23	100	0	0	-16.35	-67.55	309	-88.19	9.91		
22.5	314.81	-85.40	100	0	0	-16.35	-87.78	129	-98.33	-47.59	-85.40	100	0	0	-16.35	-87.78	129	-98.33	-47.59		
25	345.88	-98.97	100	0	0	-16.35	-99.12	9.95	-99.99	-95.80	-98.97	100	0	0	-16.35	-99.12	9.95	-99.99	-95.80		
27.5	1095.27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
30	1134.12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
32.5	1124.16	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
35	1092.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
37.5	1051.28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
40	985.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
42.5	905.61	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
45	837.83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
47.5	779.49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		

Table 4.4: A comparison of the results of [MINLP] and [SW] for different target emission factor (firm A)

Targ.	Tax	[MINLP]										[SW]									
red. in	rate	Changes in										Changes in									
EF	α_2	Prod.%	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%	Prod.%	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%
%	\$/tC	q_i	C.	P.C.	N.G	factor%	em.%	em. (tC)	%	em.%		q_i	C.	P.C.	N.G	factor%	em.%	em.(tC)	%		
0.2	3.25	-0.56	0	100	0	0.00	-0.55	99	-1.06	-0.29	-0.29	-0.56	0	100	0	0.00	-0.55	99	-1.06	-0.29	-0.29
2.5	26.49	2.06	0	58.6	41.4	-6.25	-4.33	0	186.69	6.06	6.06	2.06	0	58.56	41.44	-6.25	-4.33	0	186.69	6.06	6.06
5	26.49	2.06	0	43.3	56.7	-8.56	-6.69	0	185.75	7.48	7.48	2.06	0	43.3	56.7	-8.56	-6.69	0	185.75	7.48	7.48
7.5	26.49	2.06	0	28.0	72.0	-10.88	-9.06	0	184.83	8.90	8.90	2.06	0	28.0	72.0	-10.88	-9.06	0	184.83	8.90	8.90
10	26.49	2.06	0	12.7	87.3	-13.19	-11.42	0	183.90	10.31	10.31	2.06	0	12.7	87.3	-13.19	-11.42	0	183.90	10.31	10.31
12.5	26.49	2.06	0	0	100	-15.16	-13.43	9.79	182.98	11.73	11.73	2.06	0	0	100	-15.16	-13.43	9.79	182.98	11.73	11.73
15	92.53	2.06	0	0	100	-15.16	-13.43	69.7	638.87	17.26	17.26	2.06	0	0	100	-15.16	-13.43	69.7	638.87	17.26	17.26
17.5	168.55	2.06	100	0	0	-15.86	-14.13	111	1155.73	30.11	30.11	2.06	100	0	0	-15.86	-14.13	111	1155.73	30.11	30.11
20	242.41	2.06	100	0	0	-15.86	-14.13	171	1651.42	50.45	50.45	2.06	100	0	0	-15.86	-14.13	171	1651.42	50.45	50.45
22.5	314.81	2.06	100	0	0	-15.86	-14.13	261	2126.61	86.83	86.83	2.06	100	0	0	-15.86	-14.13	261	2126.61	86.83	86.83
25	345.88	2.06	100	0	0	-15.86	-14.13	321	2323.84	112.61	112.61	2.06	100	0	0	-15.86	-14.13	321	2323.84	112.61	112.61
27.5	1095.27	-27.36	100	0	0	-15.86	-38.90	271	-47.25	244.51	244.51	-27.36	100	0	0	-15.86	-38.90	271	-47.25	244.51	244.51
30	1134.12	-51.11	100	0	0	-15.86	-58.86	211	-76.09	166.49	166.49	-51.11	100	0	0	-15.86	-58.86	211	-76.09	166.49	166.49
32.5	1124.16	-69.17	100	0	0	-15.86	-74.06	151	-90.49	84.67	84.67	-69.17	100	0	0	-15.86	-74.06	151	-90.49	84.67	84.67
35	1092.35	-83.36	100	0	0	-15.86	-86.02	91.6	-97.23	6.70	6.70	-83.36	100	0	0	-15.86	-86.02	91.6	-97.23	6.70	6.70
37.5	1051.28	-94.83	100	0	0	-15.86	-95.67	31.6	-99.73	-64.97	-64.97	-94.83	100	0	0	-15.86	-95.67	31.6	-99.73	-64.97	-64.97
40	985.68	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
42.5	905.61	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
45	837.83	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
47.5	779.49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4.5: A comparison of the results of [MINLP] and [SW] for different target emission factor (firm B)

Targ. red. in	Tax rate	[MINLP]										[SW]									
		Changes in										Changes in									
		Prod.%	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%	Prod.%	Fuel type%			Em.	Total	Tax.	Profit	Total	cost%
EF	α_2	q_i	C.	P.C.	N.G	factor%	em.%	em.(tC)	%	cost%		q_i	C.	P.C.	N.G	factor%	em.%	em.(tC)	%	cost%	
%	\$/tC																				
0.2	3.25	1.06	0	100	0	0	1.06	0	2.7	1.14	1.06	1.06	0	100	0	0	1.06	0	2.7	1.14	1.06
2.5	26.49	1.06	0	100	0	0	1.06	0	232.0	1.14	1.06	1.06	0	100	0	0	1.06	0	232.0	1.14	1.06
5	26.49	1.06	0	100	0	0	1.06	0	249.1	1.14	1.06	1.06	0	100	0	0	1.06	0	249.1	1.14	1.06
7.5	26.49	1.06	0	100	0	0	1.06	0	266.2	1.14	1.06	1.06	0	100	0	0	1.06	0	266.2	1.14	1.06
10	26.49	1.06	0	100	0	0	1.06	0	283.3	1.14	1.06	1.06	0	100	0	0	1.06	0	283.3	1.14	1.06
12.5	26.49	1.06	0	100	0	0	1.06	0	300.4	1.14	1.06	1.06	0	100	0	0	1.06	0	300.4	1.14	1.06
15	92.53	1.06	0	100	0	0	1.06	0	817.8	1.14	1.06	1.06	0	100	0	0	1.06	0	817.8	1.14	1.06
17.5	168.55	1.06	0	100	0	0	1.06	0	1488.0	1.14	1.06	1.06	0	100	0	0	1.06	0	1488.0	1.14	1.06
20	242.41	1.06	0	100	0	0	1.06	0	2232.7	1.14	1.06	1.06	0	100	0	0	1.06	0	2232.7	1.14	1.06
22.5	314.81	1.06	0	100	0	0	1.06	0	3161.2	1.14	1.06	1.06	0	100	0	0	1.06	0	3161.2	1.14	1.06
25	345.88	1.06	0	100	0	0	1.06	0	3682.4	1.14	1.06	1.06	0	100	0	0	1.06	0	3682.4	1.14	1.06
27.5	1095.27	1.06	0	100	0	0	1.06	0	4829.9	1.14	1.06	1.06	0	100	0	0	1.06	0	4829.9	1.14	1.06
30	1134.12	1.06	0	100	0	0	1.06	0	5722.9	1.14	1.06	1.06	0	100	0	0	1.06	0	5722.9	1.14	1.06
32.5	1124.16	1.06	0	100	0	0	1.06	0	6402.3	1.14	1.06	1.06	0	100	0	0	1.06	0	6402.3	1.14	1.06
35	1092.35	1.06	0	100	0	0	1.06	0	6936.5	1.14	1.06	1.06	0	100	0	0	1.06	0	6936.5	1.14	1.06
37.5	1051.28	1.06	0	100	0	0	1.06	0	7367.6	1.14	1.06	1.06	0	100	0	0	1.06	0	7367.6	1.14	1.06
40	985.68	1.06	0	89.16	10.84	-1.77	-0.79	0	7554.3	1.81	1.06	1.06	0	89.16	10.84	-1.77	-0.79	0	7554.3	1.81	1.06
42.5	905.61	1.06	0	66.26	33.74	-5.70	-4.76	0	7536.3	3.21	1.06	1.06	0	66.26	33.74	-5.70	-4.76	0	7536.3	3.21	1.06
45	837.83	1.06	0	43.34	56.66	-9.63	-8.73	0	7518.3	4.62	1.06	1.06	0	43.34	56.66	-9.63	-8.73	0	7518.3	4.62	1.06
47.5	779.49	1.06	0	20.22	79.78	-13.56	-12.70	0	7500.2	6.02	1.06	1.06	0	20.22	79.78	-13.56	-12.70	0	7500.2	6.02	1.06
50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 4.6: A comparison of the results of [MINLP] and [SW] for different target emission factor (firm C)

rates significantly increase with lowering the target emission factors which lead to significant reductions in total emissions, productions, social welfare, and consumers' surplus. The percentage of firms affected by the tax rates and the target reductions also increases as the tax rates rises and the emission factor decreases putting all firms out of business as the target reduction reaches 50%. On the other hand, when the quantities supplied to the market decrease and the market price increases, the remaining firms, low emitters, generate huge profits. Low emitters benefit from this policy because they do not pay tax and the high tax rates combined with the low emission factors keep the high emitters out of the market. The reduction in the emission factor leads to almost the same reduction in the total emissions for low targets but as the target reduction increases, the reduction in the total emissions is almost doubled which is due to the reduction in the productions and switching fuel types. The table demonstrates that moderate emission targets can be achieved with moderate tax rates. For instance, target reductions below 20% is achievable with moderate tax rates and have less impacts on the industry compared to 30% reduction in the emission factors.

Table 4.8 displays the effects of increasing or decreasing some of the parameters of the 12-firm example on the tax rates as compared to the taxes obtained in Table 4.7. The table shows that for low target reduction, 10%, $\pm 10\%$ changes in the production cost or other parameters related to the emission factor of the firms would not affect the tax rates. For a 20% or more target reductions, the variations in the parameters related to the emission factors, however, have more impact on the differences in the tax rates than changes in the production costs. The tax rates should be higher for 20% or more target reductions if the production cost turns out to be less than estimated by 10% and should be lower if the production cost is higher than expected by 10%. On the other hand, $\pm 10\%$ variations in the

Number of firms	Target reduction in the em. factor (β)%	Achieved reduction%	Tax rate (α)	Change in the total em. %	Change in the production%	Change in the price%	Change in the SW%	Change in the CS%	Change in the PS%	% of firms out of business	CPU sec.
12	10	10	26.49	-11.64	-1.69	+13.86	-1.72	-3.34	+75.93	0	3.22
	20	20	264.20	-35.28	-18.88	+155.22	-9.26	-34.20	+1186.04	16	3.46
	30	30	3456.25	-76.34	-66.38	+545.67	-54.27	-88.70	+1595.79	66	3.51
	40	40	1622.90	-84.26	-73.69	+605.70	-55.20	-93.08	+1760.03	75	4.48
	50	100	8851.04	-	-100	-	-	-	-	100	3.39
20	10	10	26.49	-11.17	-1.39	+11.05	-1.81	-2.76	+36.44	0	61.46
	20	20	458.44	-40.92	-26.03	+206.86	-14.03	-45.28	+1237.70	25	109.34
	30	30	2626.84	-74.66	-64.04	+508.88	-47.24	-87.07	+1547.65	65	427.83
	40	40	21183.90	-90.51	-84.15	+668.75	-71.48	-97.49	+970.23	85	463.92
	50	100	6802.24	-	-100	-	-	-	-	100	165.45
30	10	10	26.49	-11.45	-1.46	+11.67	-1.73	-2.90	+45.66	0	5430.97
	20	20	549.50	-41.77	-27.03	+215.97	-13.80	-46.75	+1317.68	30	5310.6
	30	30	3097.21	-75.38	-65.03	+519.66	-47.41	-87.77	+1583.67	67	5550.83
	40	40	22496.22	-93.68	-89.44	+714.75	-80.46	-98.89	+664.17	90	6326.06
	50	100	6802.24	-	-100	-	-	-	-	100	180.2

Table 4.7: The impact of different target emission factors (Large Examples)

parameters related to the emission factors lead to volatility in the tax rates.

Change in the parameters	Impact on the tax rates				
	Target reduction in the em. factor (β)%				
	10%	20%	30%	40%	50%
Cost c_i (-10%)	0	+3.51	+1.23	+1.08	+0.87
Cost c_i ($+10\%$)	0	-3.17	-1.23	-1.08	-0.87
Electricity & calcination EF $\hat{s}_i$ (-10%)	0	+1.18	+14.50	+13.28	+13.11
Electricity & calcination EF $\hat{s}_i$ ($+10\%$)	0	-8.59	-7.24	-4.95	+2.69
Energy consumption b_i (-10%)	0	+7.20	-1.51	-2.03	-7.46
Energy consumption b_i ($+10\%$)	0	-9.80	-0.11	+0.61	+2.94

Table 4.8: The Impact of Changing Some of the Parameters on the Tax Rates (12 Firms)

4.4 Conclusion

This chapter presents a bilevel formulation to design a carbon tax policy based on the emission factor. At the upper level, the government sets a target level for the emission factor of the industry and tax firms if they exceed that target. Assuming a competitive market, at the lower level, the industry decides on the production quantity and the fuel types that maximize the social welfare given the tax rate and the market price. Therefore, the problem of the regulatory authorities is to find the best tax rate that achieves a specific target. We propose two objective functions for the government: one is to minimize the deviation from the target reduction and the other is to maximize the weighted difference between production and emission factor. We transform the bilevel model into a single-level MINLP by replacing the lower-level problem by its KKT optimality conditions and linearizing

complementary slackness. We test the transformed model on several examples constructed in the context of the cement industry.

The results indicate that the proposed model finds the optimal tax rate that induces firms to reduce their emission factors and consequently reduces the overall emissions. Higher reduction in the emission factors significantly increases the tax rates, decreases the social welfare and production quantities, and may put some firms out of business. On the other hand, adequate reduction in the emission factors, below 20%, is achievable with moderate tax rates that have a little impact on the industry and lead to a large reduction in the overall emissions. Although, the optimal tax rate reduces the quantity supplied by the high emitters and increases the quantity supplied by the low and average emitters, the overall quantities decrease leading to a higher market price and higher profits for the low and average emitters.

In this chapter, the effectiveness of the intensity-based carbon tax in reducing the emission of a polluting industrial sector is tested in the context of the cement industry. The policy is found to reduce the CO₂ emissions with a little impact on the social welfare. To examine the effectiveness of the policy on reducing the CO₂ emissions of a different polluting industry, the next chapter tests the policy in the context of supply chain design to find the tax rate that induces firms to reduce their transport-related CO₂ emissions.

Chapter 5

Green Supply Chain Redesign through an Intensity-Based Tax Policy

In this chapter, we examine the effectiveness of the intensity-based carbon tax on reducing CO₂ emissions from a major supply chain activity, namely transportation. Specifically, we model a situation where policy makers set a target emission factor for transportation and tax companies if they exceed that level. We assume that firms can reduce their emission factors by changing the design of their supply chain networks, reducing shipment frequency, and using electric trucks. We model the problem as a bilevel program where at the upper level the government decides on the tax rate and at the lower level firms decide on the design of their supply chain and truck types. However, due to the difficulty of the bilevel problem as it has nonlinearities in the upper-level problem as well as binary and integer variables in the lower-level problem, we find the tax rate by solving the lower-level problem for different tax rates and picking the lowest one that achieves the target reduction. This chapter is organized as follows. Section 5.1 reviews some related literature. Section 5.2 details the problem formulation. Section 5.3 gives a case study used to

carry out the analysis. Section 5.4 presents the results and Section 5.5 concludes the chapter.

5.1 Background

Traditionally, companies employ two performance measures to evaluate the effectiveness and efficiency of their supply chains (SC): cost and service level. However, environmental regulations and increasing customer awareness of environmental issues such as global warming, pressure companies to include sustainability in their performance measures (Labuschagne and Brent, 2005, Matthews et al., 2008). As a result, new concepts such as sustainable and green supply chain management (GrSCM) have recently emerged (Srivastara, 2007). Seuring and Muler (2008) define sustainable supply chain management as:

the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements.

Many organizations are realizing the necessity of moving toward sustainability and are starting to take actions towards monitoring and reducing their carbon footprints. For instance, Wal-Mart engaged in an environmental plan to reduce energy use, waste, and greenhouse gas emissions by 20% by 2012. Dell changed its transportation mode from air to ground in its green campaign. IBM established its environmental management system and shows strong commitments through its

pollution prevention program (Kumar, 2007). Despite the voluntary steps that have been taken by some companies to reduce the levels of their CO₂ emissions, the achieved reduction is insufficient to combat climate change. Plambeck (2012) discusses some examples that illustrates how firms can profitably reduce their emissions and concludes that without environmental policies these efforts cannot address the threat of climate change. Chen et al. (2011) show that significant reductions in emissions can be achieved by imposing a low tax rate. On the other hand, Hoen et al. (2011a) find that while imposing a low tax rate induces some firms to shift to more energy-efficient transport modes, other firms require a high tax rate to reduce their emissions. Plambeck and Taylor (2013) argue that under a cap-and-trade system, volatility in the price of carbon credits reduces the incentive to improve energy efficiency and in order to promote investment in clean technologies a high tax rate must be imposed.

Designing effective environmental policies that reduce the negative impacts of industries on the environment and help organizations achieve sustainability cannot be undertaken in isolation from the strategic and operational decisions of the regulated entities. However, in light of the reviewed literature, the work that explicitly addresses the issue of climate change within the context of green supply chain management focuses on quantifying the carbon footprint of supply chains, analysing the practices that can be used to reduce emissions, and evaluating the performance of supply chains under environmental policies or voluntarily targets with no attention paid to the policy design. Lee (2011) examines the integration of carbon footprint in automobile supply chain management using Hyundai Motor Company as an example. The analysis reveals that identifying and measuring direct and indirect carbon emissions across the supply chain can help companies in setting a target for improving the carbon footprint per unit produced. Sundarakani et al. (2010)

propose an analytical model to quantify the carbon footprint across supply chains. Particularly, the proposed model calculates the GHG emissions from raw material, manufacturing, warehousing, and inbound and outbound logistics. Kannan et al. (2009) propose a closed loop supply chain model that integrates the forward and reverse logistics in a built-to-order supply chain. The model is tested on two case studies and solved using genetic algorithm. Caniato et al. (2012) compare two groups of companies: established international brands and small companies to investigate the factors driving fashion companies to adopt sustainable practices, the practices that can be used to improve environmental sustainability, and the resulting performance measures. The analysis shows that large companies focus on products and process improvement whereas small companies focus on reshaping their supply chains. Benjaafar et al. (2010) use a lot-sizing model to examine the impact of operational decisions on carbon emissions and show that a significant reduction can be achieved by making adjustments in the order quantities. Chen et al. (2011) exploit the economic order quantity model to show that carbon emissions can be reduced by some operational adjustments if the operational decisions that reduce emissions are different from the operational decisions that reduce cost. Nagurney and Yu (2012) propose an oligopoly model for fashion supply chain competition to capture brand differentiation and environmental consciousness. Each firm is assumed to have a weighted objective function that maximizes its profit and minimizes its emissions. Variational inequality theory is exploited to formulate the problem and solve several examples. The results demonstrate the effects of changing the cost and the emission functions as well as the weights associated with the emissions on the demand, the product price, and the profit. Cruz and Matsypura (2009) develop a framework to model a supply chain network that is environmentally conscious. The model considers the multicriteria decision-making behaviour

of manufacturers, retailers, and consumers, which includes: the maximization of profit and the minimization of emissions and risk.

Hua et al. (2011) propose an environmental inventory model that integrates carbon footprints into the classic economic order quantity (EOQ) under a cap-and-trade policy. The impact of the carbon price and carbon cap on order decisions and total costs are examined. Choi (2013) examine how a carbon tax affects the optimal choice of sourcing decisions under tow types of contracts in the context of fashion supply chain. A carbon tax that only imposed on outsourced products can induce retailers to source locally. Hoen et al. (2011) use a profit-maximization model to study the effect of switching transport modes on meeting a voluntary target reduction and find that a reduction in the emissions can be achieved by switching from road transport to rail transport. Ramudhin et al. (2008) employ a multi-objective mixed-integer linear programming model to integrate the price of carbon credits into the design of supply chain. To reduce the emissions of production and transportation activities, firms may switch to a slower transport mode, change suppliers, or by carbon credits. Gemechu et al. (2012) examine a carbon tax imposed on products based on their carbon footprint which is calculated using the methods of life cycle analysis (LCA) and environmentally extended input-output analysis (EIO). A case study of the pulp and paper sector in Spain is used to carry out the analyses. The work of Gemechu et al. (2012) is similar to our work in that it targets the emission intensity of products; however, our work differs in several aspects. First, our work focuses on integrating the decisions of regulated intensities into the design of the intensity-based carbon tax to find the best tax rate that achieves a target reduction, whereas environmental tax in Gemechu et al. (2012) is set to be equal to the price of carbon permits in the European Union's Emissions Trading Scheme. Second, our work studies a carbon tax scheme that requires

companies to pay tax only if their emission intensities exceed a target level; on the contrary, environmental tax in Gemechu et al. (2012) is imposed on all the emissions of the product. Third, we study a carbon tax scheme that targets the CO₂ emission factor of an energy intensive activity. On the other hand, Gemechu et al. (2012) calculate all the direct and indirect GHG emissions of a product. Gemechu et al. (2012) demonstrate that this calculation is time consuming and labor intensive and because it involves covering every aspect of the supply chain, it is highly subject to error. The results of the case study show that the production related energy has the highest impact on the life cycle of the product. Moreover, CO₂ emissions, mostly energy related, account for 90% of the calculated GHG emissions.

5.2 Problem Formulation

We consider a situation where decision makers impose a carbon tax to reduce the transportation emission factor (denoted by E) due to multiple supply chains. Specifically, policy makers set a target emission factor (β) per product transported and tax companies if they exceed that limit. Assuming that the regulatory authority options are limited to influencing firms' decisions, policy makers are interested in finding the tax rate, α_2 , that achieves the target reduction. The industry is assumed to consist of N companies with independent supply chains that ship a homogeneous product. Each company $i = 1, \dots, N$ owns a supply chain network that consists of existing suppliers, where shipping points are denoted by $m \in \{1, \dots, M_i\}$, potential geographical sites $j \in \{1, \dots, J_i\}$ for locating distribution centers (DCs), and customer zones $k \in \{1, \dots, K_i\}$ at fixed locations (Figure 5.1). Each DC has a capacity limit of s_{ij} and incurs an annual fixed cost of f_{ij} . Firm i can use domestic suppliers and/or offshore suppliers which have lower production costs. The shipping

points of local suppliers are assumed to be their plants, whereas the shipping points of offshore suppliers are assumed to be the container terminal at the port of entry. Products purchased from offshore suppliers are transported to the destination port through vessels then shipped to DCs using trucks. Shipping points and customer zones are connected to DCs by different types of trucks denoted by $l \in \{1, \dots, L_i\}$. Trucks which are powered by diesel, gasoline, and electricity are assumed to be available at DC j to operate on long- and short-distance routes. However, electric trucks can only operate on short distance routes (less than 60 km due to battery life). Trucks are assumed to be owned or rented by each supply chain and a percentage of the truck cost is assumed to be allocated to each shipment as fixed costs denoted by t_{imjl} and $\hat{t}_{ijkl}$ (the former is the fixed cost of the shipment from the shipping point $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$ and the later is the fixed cost of a shipment from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$). The number of shipments v_{imjl} between shipping point $m \in M_i$ and DC $j \in J_i$ using truck $l \in L_i$ is calculated as $\hat{s}_{il}v_{imjl} = q_{imjl}$, where $\hat{s}_{il}$ and q_{imjl} represent the truck capacity and the quantity shipped from shipping point $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$, respectively. Similarly, the number of shipments $\hat{v}_{ijkl}$ between DC $j \in J_i$ and customer zone $k \in K_i$ using truck $l \in L_i$ is calculated as $\hat{s}_{il}\hat{v}_{ijkl} = \hat{q}_{ijkl}$, where $\hat{q}_{ijkl}$ represent the quantity shipped from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$. Customer demand, d_{ik} , over a given long-term period is assumed to be known.

The transport-related CO₂ emissions of the product shipped from shipping point $m \in M_i$ consists of two parts. The first one is the CO₂ emissions generated by the transportation mode that is used to deliver the product to the shipping point $m \in M_i$ which is calculated as $\hat{e}_{im} \sum_{j \in J_i} \sum_{l \in L_i} q_{imjl}$, where $\hat{e}_{im}$ is the emission factor of the transportation mode (note that this emission factor is zero for domestic

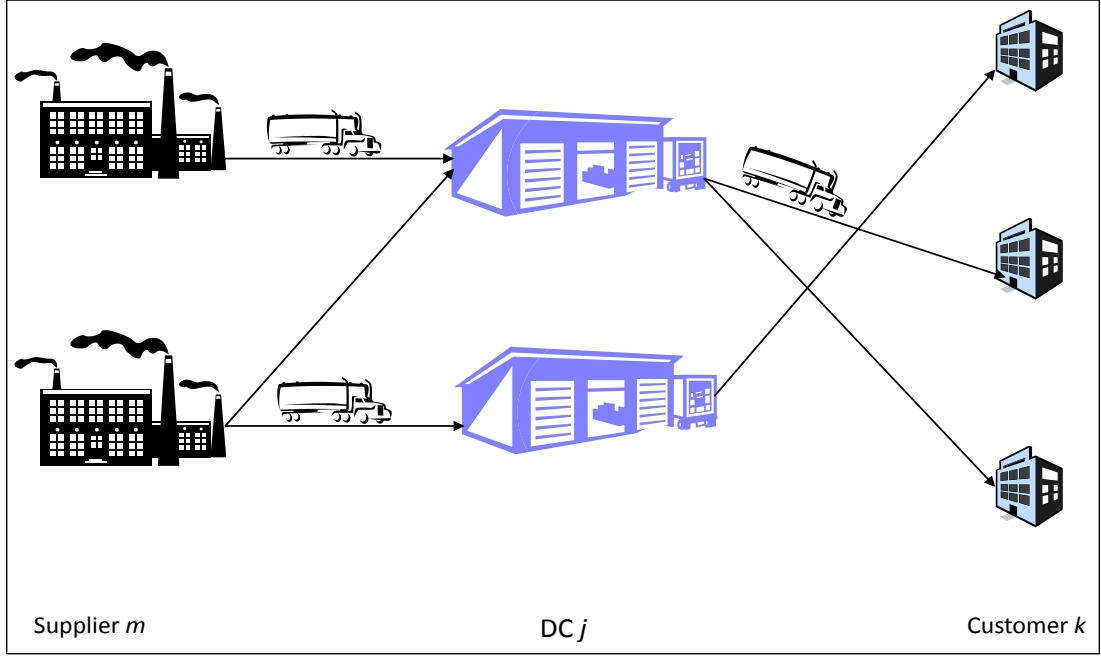


Figure 5.1: A three-echelon green supply chain network of firm i

suppliers since the product is shipped directly from plants to DCs, whereas for offshore suppliers this emission factor is the one of the vessels used). The second one is the CO₂ emissions generated by trucks that are used to deliver the product to DCs. Given that companies are responsible for their own transportation, they bear the fuel cost and the emissions of the return trips. The total fuel or electricity, w_{imjl} , required by truck $l \in L_i$ to deliver shipments between shipping point $m \in M_i$ and DC $j \in J_i$ is represented by $w_{imjl} = (b_{il} + \hat{b}_{il})a_{imj}v_{imjl}$ where b_{il} and $\hat{b}_{il}$ are the fuel or electricity consumption (Liter, MWh/km) for a loaded and an empty truck, respectively, and a_{imj} is the distance from shipping point $m \in M_i$ to DC $j \in J_i$. The transport-related CO₂ emissions of the product shipped from DCs is the emissions generated by trucks used. The total fuel or electricity, $\hat{w}_{ijkl}$, required by truck $l \in L_i$ to deliver shipments between DC $j \in J_i$ and customer zone $k \in K_i$ is

represented by $\hat{w}_{ijkl} = (b_{il} + \hat{b}_{il})\hat{a}_{ijk}\hat{v}_{ijkl}$ where $\hat{a}_{ijk}$ is the distance from DC $j \in J_i$ to customer zone $k \in K_i$. Regulated companies are required to monitor and report their emission factor, x_i , which is an average value that reflects the level of CO₂ emissions per unit shipped.

Knowing the emission factors of the transportation mode and the emission factors e_{il} (kg/Liter, MWh) for the electricity or the fuels used for truck $l \in L_i$ will assist companies in calculating their total emissions

$$TE_i = \sum_{m \in M_i} \sum_{j \in J_i} \sum_{l \in L_i} e_{il} w_{imjl} + \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} e_{il} \hat{w}_{ijkl} + \hat{e}_{im} \sum_{m \in M_i} \sum_{j \in J_i} \sum_{l \in L_i} q_{imjl}$$

and consequently their emission factors as

$$x_i = \frac{TE_i}{\sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}}$$

Assuming that regulatory authorities freely allocate each company certain number of carbon credits, $\beta \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}$, firms are required to pay tax only if their emission factors exceed the target level β . Therefore, the CO₂ emission cost of firm i is given by

$$g(x_i) = \begin{cases} 0 & \text{for } 0 \leq x_i \leq \beta \\ \alpha_2 \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}(x_i - \beta) & \text{for } x_i > \beta. \end{cases} \quad (5.1)$$

Defining c_{imjl} to be the production and shipping cost per unit shipped from shipping point $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$, $\hat{c}_{ijkl}$ to be the average handling cost per unit shipped from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$, h_{il} to be the fuel or electricity cost (\$/Liter, MWh, ..), and y_{ij} to be a

binary variable that equals 1 if DC $j \in J_i$ is opened and 0 otherwise, the objective function of each supply chain is to minimize the total fixed and the variable costs. Transport-related CO₂ emissions can be reduced by strategic changes in network design, using electric trucks, and reducing shipment frequency. The hierarchical process of the problem leads to a bilevel formulation where at the upper level, the government determines the tax rate, and at the lower level, companies seek to find the optimal network configuration and the optimal type of trucks that have the minimum total costs.

The bilevel formulation of designing a carbon tax faced by the decision makers is:

$$\min E \quad (5.2)$$

$$\text{s.t.} \quad \sum_{i=1}^N TE_i = E \sum_{i=1}^N \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl} \quad (5.3)$$

$$0 \leq E \leq \beta, \quad (5.4)$$

$$0 \leq \alpha_2 \leq \alpha_2^{ub} \quad (5.5)$$

$$\begin{aligned} \min \quad & \sum_{i=1}^N \sum_{m \in M_i} \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} (f_{ij}y_{ij} + t_{imjl}v_{imjl} \\ & + \hat{t}_{ijkl}\hat{v}_{ijkl} + c_{imjl}q_{imjl} + \hat{c}_{ijkl}\hat{q}_{ijkl} + h_{il}w_{imjl} \\ & + h_{il}\hat{w}_{ijkl}) + \sum_{i=1}^N g(x_i) \end{aligned} \quad (5.6)$$

$$\text{s.t.} \quad \sum_{j \in J_i} \sum_{l \in L_i} \hat{q}_{ijkl} \geq d_{ik} \quad \forall i, k \in K_i \quad (5.7)$$

$$\sum_{m \in M_i} \sum_{l \in L_i} q_{imjl} = \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl} \quad \forall i, j \in J_i, \quad (5.8)$$

$$w_{imjl} = (b_{il} + \hat{b}_{il})a_{imj}v_{imjl} \quad \forall i, m \in M_i, j \in J_i, l \in L_i \quad (5.9)$$

$$\hat{w}_{ijkl} = (b_{il} + \hat{b}_{il})\hat{a}_{ijk}\hat{v}_{ijkl} \quad \forall i, j \in J_i, k \in K_i, l \in L_i \quad (5.10)$$

$$\begin{aligned} TE_i = & \sum_{m \in M_i} \sum_{j \in J_i} \sum_{l \in L_i} (\hat{e}_{im}q_{imjl} + e_{il}w_{imjl}) \\ & + \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} e_{il}\hat{w}_{ijkl} \end{aligned} \quad i = 1, \dots, N \quad (5.11)$$

$$x_i \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl} = TE_i \quad i = 1, \dots, N \quad (5.12)$$

$$\hat{s}_{il}v_{imjl} = q_{imjl} \quad \forall i, m \in M_i, j \in J_i, l \in L_i \quad (5.13)$$

$$\hat{s}_{il}\hat{v}_{ijkl} = \hat{q}_{ijkl} \quad \forall i, j \in J_i, k \in K_i, l \in L_i \quad (5.14)$$

$$\sum_{m \in M_i} \sum_{l \in L_i} q_{imjl} \leq s_{ij}y_{ij} \quad \forall i, j \in J_i \quad (5.15)$$

$$\sum_{m \in M_i} \sum_{l \in L_i} \hat{s}_{il}v_{imjl} \leq s_{ij}y_{ij} \quad \forall i, j \in J_i \quad (5.16)$$

$$\sum_{k \in K_i} \sum_{l \in L_i} \hat{s}_{il}\hat{v}_{ijkl} \leq s_{ij}y_{ij} \quad \forall i, j \in J_i \quad (5.17)$$

$$q_{imjl}, \hat{q}_{ijkl}, w_{imjl}, \hat{w}_{ijkl}, x_i, TE_i \geq 0 \quad \forall i, j \in J_i, k \in K_i, l \in L_i \quad (5.18)$$

$$y_{ij} \in \{0, 1\}, v_{imjl}, \hat{v}_{ijkl} \geq 0 \text{ and integer} \quad \forall i, j \in J_i, k \in K_i, l \in L_i \quad (5.19)$$

(5.2)–(5.5) correspond to the upper-level problem. The objective function of the regulatory authority (5.2) minimizes the emission factor of transporting products. Constraint (5.3) which is nonlinear calculates the emission factor of transportation for the entire industry. Constraints (5.4) and (5.5) are the lower and the upper bounds on the emission factor for the industry and the tax rate, respectively. (5.6)–(5.19) represent the lower-level problem. The objective function of the lower-level problem (5.6) minimizes the total fixed and the variable costs of all supply chains. The first, the second, and the third terms in the objective function represent the fixed costs of opening DCs and using trucks. The fourth term is the production and transportation costs of products shipped from suppliers to DCs, whereas the fifth term is the shipping and handling costs of products shipped from DCs to customers. The sixth and the seventh terms in the objective functions are the fuel or energy costs. The last term in the objective function is the CO₂ emission cost. Constraints (5.7) ensure that the demand is satisfied. Constraints (5.8) are product flow conservation constraints at DCs. Constraints (5.9) and (5.10) calculate the fuel or the electricity used by each truck for each shipment. Constraints (5.11) and (5.12) calculate the total emissions and the emission factor of transportation for each supply chain, respectively. Constraints (5.13) and (5.14) calculate the number of shipment between shipping points and DCs and between DCs and customer zones using a specific truck. Constraints (5.15), (5.16), and (5.17) force capacity restrictions on the opened DCs and ensure that only opened DCs are used.

From (5.1) and (5.12), the taxed CO₂ emission level can be represented by the maximum of

$$(TE_i - \beta \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}, 0).$$

Defining $\theta_i = \max(T E_i - \beta \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}, 0)$, the CO₂ emission cost of firm i can be represented as $\alpha_2 \theta_i$. Hence, the objective function of the industry (5.6) can be rewritten as:

$$\min \sum_{i=1}^N \sum_{m \in M_i} \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} (f_{ij} y_{ij} + t_{imjl} v_{imjl} + \hat{t}_{ijkl} \hat{v}_{ijkl} + c_{imjl} q_{imjl} + \hat{c}_{ijkl} \hat{q}_{ijkl} + h_{il} w_{imjl} + h_{il} \hat{w}_{ijkl}) + \sum_{i=1}^N \alpha_2 \theta_i,$$

and constraints (5.12) can be replaced by the following constraints

$$\theta_i \geq T E_i - \beta \sum_{j \in J_i} \sum_{k \in K_i} \sum_{l \in L_i} \hat{q}_{ijkl}, \quad i = 1, \dots, N.$$

5.3 Case Study

We construct a case study consisting of two firms, Firm1 and Firm2; each owns a supply chain that has two known suppliers, three candidate locations for DCs, and two retailers at fixed locations. The high-cost domestic suppliers, which are supplier 2 of each firm, are located in Canada, whereas the offshore suppliers are located in China. Container barge with emission factor of 19.6 g CO₂/tonne-km are assumed to be used to ship the product to Canada (CEEIC-ECTA, 2011). The distance calculator on the website of sea rates is used to calculate the distance between supply ports and destination ports. The product is measured by its shipping package which we assume its weight is 30 lb and its dimensions are $1.04 \times 0.73 \times 0.647$ m. The weight of the product as well as the distance and the emission factor of the vessels used are employed to calculate the emission factor e_{im} of each firm which are found to be 5.79 kg/ product and 5.87 kg/ product for Firm 1 and Firm 2, respectively. The distance between DCs and retailers are given in Table 5.1. Table 5.2 presents DCs capacities and fixed costs as well as demand at retailers. We assume that each supply chain owns four types of trucks: class-5 gasoline, class-7 diesel, class-8

diesel, and class-5 electric trucks. Class-8 diesel trucks are available only for routes longer than 80 km and between container terminal and DCs while electric trucks can be used only for routes less than 60 km. The weight of the product and the dimensions are used to calculate truck capacities in terms of the product. Table 5.3 shows the capacity, the dimensions, and the costs of trucks, the costs of fuels and electricity, the fuel and electricity consumption of loaded and empty trucks, and the CO₂ emission factors of fuels and electricity (Cooper et al., 2009, Environment Canada (Electricity Intensity Tables, Fuel Combustion), IESO, Logistics Solution Builders, 2006, MIT, Tunnell & Brewster, 2005, U.S. Department of Energy, 2012, VTT, 2006). We also assume that the fixed cost of each shipment is 1.19% of the truck cost.

DCs	Shipping points				Retailers			
	Firm 1		Firm 2		Firm 1		Firm 2	
	1	2	1	2	1	2	1	2
1	55	200	41	59	280	500	245	419
2	220	400	439	456	42	790	57	585
3	560	320	260	390	800	35	900	55

Table 5.1: Distance between shipping points and DCs and between retailers and DCs

Firms	DC capacity $\times (10^3)$			DC cost $\times (10^3)$			Retailer demand	
	1	2	3	1	2	3	1	2
1	20	20	20	250	250	250	8000	10000
2	20	20	20	250	250	250	8000	10000

Table 5.2: Capacity and costs of DCs and demand at retailers

Truck Types	Payload capacity Max (lbs.)	Truck dimensions (m)			Truck cost	Product capacity	Fuel/electr. cost (\$/L, MWh)	Fuel/electr. consum. (L, MWh/km)		CO ₂ EF (kg/L, MWh)
		Length	Width	Height				empty	loaded	
Class 5 Gasoline medium-duty	8700	8.75	2.6	4.15	60000	192	1.3	0.13	0.28	2.29
Class 7 Diesel heavy-duty	30000	16.5	2.6	4.15	153000	363	1.25	0.20	0.39	2.66
Class 8 Diesel heavy-duty	45000	23.16	2.6	4.15	172000	509	1.25	0.29	0.52	2.66
Class 5 Electric medium-duty	6000	6.25	2.6	4.15	150000	137	19.33	0.0005	0.001	100

Table 5.3: Capacity, cost, and fuel/electricity consumption of trucks

5.4 Results and Discussion

We construct several examples based on the case study. In the first example, we use the data presented in Tables 5.1-5.3. Assuming that the regulatory authority aims for 15% reduction in the transportation emission factor, we are interested in finding the best tax rate α_2 that achieves the target reduction. Because of the difficulty of the bilevel problem as it has nonlinearities in the upper-level problem as well as binary and integer variables in the lower-level problem, we use an alternative approach to find the tax rate that achieves the target reduction in the emission factor. We fix the value of α_2 in the lower-level problem, solve the resulting mixed integer program (MIP) for several values of α_2 , and pick the lowest α_2 that achieves the target emission factor. The resulting MIP is implemented in GAMS 23.3 and solved using COINCPLEX. Table 5.4 presents the results of solving the lower-level problem with no carbon tax. The results show that each firm opens one distribution center to serve its customers and uses offshore suppliers. The results also show that Firm 1 doesn't use electric trucks whereas Firm 2 uses electric trucks in 2.3% of its shipments.

	Emission	Total	Total	Opened	Used	Use of electric
	factor	emission	cost	DCs	suppliers	Trucks%
Firm1	7.850	142134	3530695	DC ₁₁	Sup ₁	0
Firm2	7.617	140630	3622614	DC ₂₁	Sup ₁	2.3
Industry	7.733	282764	7153309	DC ₁₁ ,DC ₂₁	Sup ₁	1.25

Table 5.4: Results with no carbon tax

Table 5.5 shows the percentage reduction in the emission factor and total emissions, the percentage change in total costs, opened DCs, used suppliers, and the

percentage use of electric trucks for different tax rates. From the table, we can see that tax rates ranging between \$10/kg CO₂ and \$70/kg CO₂ do not induce firms to reduce their emission factors to the target level. A tax rate of \$77/kg CO₂ induces Firm 1 and Firm 2 to reduce their emissions factors by 16.71% and 13.93%, respectively, which results in 15.34% reduction in the emission factor of the industry. The table also demonstrates that achieving the target reduction reduces the total emissions by 15.98% and increases the total cost by 36.82%. The table reveals that firms comply by increasing the use of electric trucks, opening additional DCs, and using domestic and offshore suppliers. These results also presented in Figure 5.2, which shows the network design of each firm with no carbon tax and with the effective tax rate \$77. With no carbon tax both firms open one DC and use offshore suppliers. With a tax rate of \$77 firms open two DCs and use the domestic and offshore suppliers. Table 5.5 illustrates that with tax rates ranging between \$10/kg CO₂ and \$40/kg CO₂ Firm 2 reduces its emission factor by increasing the use of electric trucks. With a tax rate of \$50, in addition to increasing the use of electric trucks Firm 2 reduces its emission factor by opening another DC. The table shows that tax rates ranging between \$10 and \$50 do not induce Firm 1 to use electric trucks whereas a tax rate of \$60 does. Tax rates beyond \$77 do not have impact on the firms' decisions, emissions, and costs since firms' emission factors are below the target.

We compare the carbon tax policy based on the emission factor to the tax policy targeting total emissions. In order to modify the lower-level problem to operate under a tax on total emissions, we set $\beta = 0$. We solve the previous example for different tax rates and present the percentage reduction in the emission factor and total emissions, the percentage change in total costs, opened DCs, used suppliers, and the percentage use of electric trucks in Table 5.6. Table 5.6 shows that with

Tax rate\$	Reduction in the EF%				Reduction in the total emissions%				Change in total cost%				Opened DCs		Used suppliers		Use of E. Trucks%	
	Industry	Firm1	Firm2		Industry	Firm1	Firm2		Industry	Firm1	Firm2		Firm1	Firm2	Firm1	Firm2	Firm1	Firm2
10	1.55	1.59	1.51	0.75	0.40	0.40	1.10	5.96	7.00	4.94	DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	3.70		
20	1.63	1.59	1.69	1.80	0.40	0.40	3.21	10.49	13.00	7.53	DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	5.20		
30	1.97	1.59	2.38	2.03	0.40	0.40	3.67	16.32	19.00	13.72	DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	50.8		
40	2.37	1.59	3.22	2.54	0.40	0.40	4.70	21.92	24.99	18.75	DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	60.30		
50	4.66	1.59	7.89	5.00	0.40	0.40	9.64	25.68	30.99	20.51	DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁	Sup ₁	0	73.50		
60	5.03	2.15	8.10	5.90	1.60	1.60	10.25	30.02	37.93	22.31	DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁	Sup ₁ ,Sup ₂	48.6	56.15		
70	8.47	4.20	12.88	7.77	2.46	2.46	13.13	36.03	44.32	27.95	DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	65.7	65.60		
77	15.34	16.71	13.93	15.98	16.89	16.89	15.07	36.82	46.36	27.52	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	21.1	74.80		
80	15.34	16.71	13.93	15.98	16.89	16.89	15.07	36.82	46.36	27.52	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	21.1	74.80		
90	15.34	16.71	13.93	15.98	16.89	16.89	15.07	36.82	46.36	27.52	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	21.1	74.80		

Table 5.5: Results for different tax rates (Tax policy based on the emission factor)

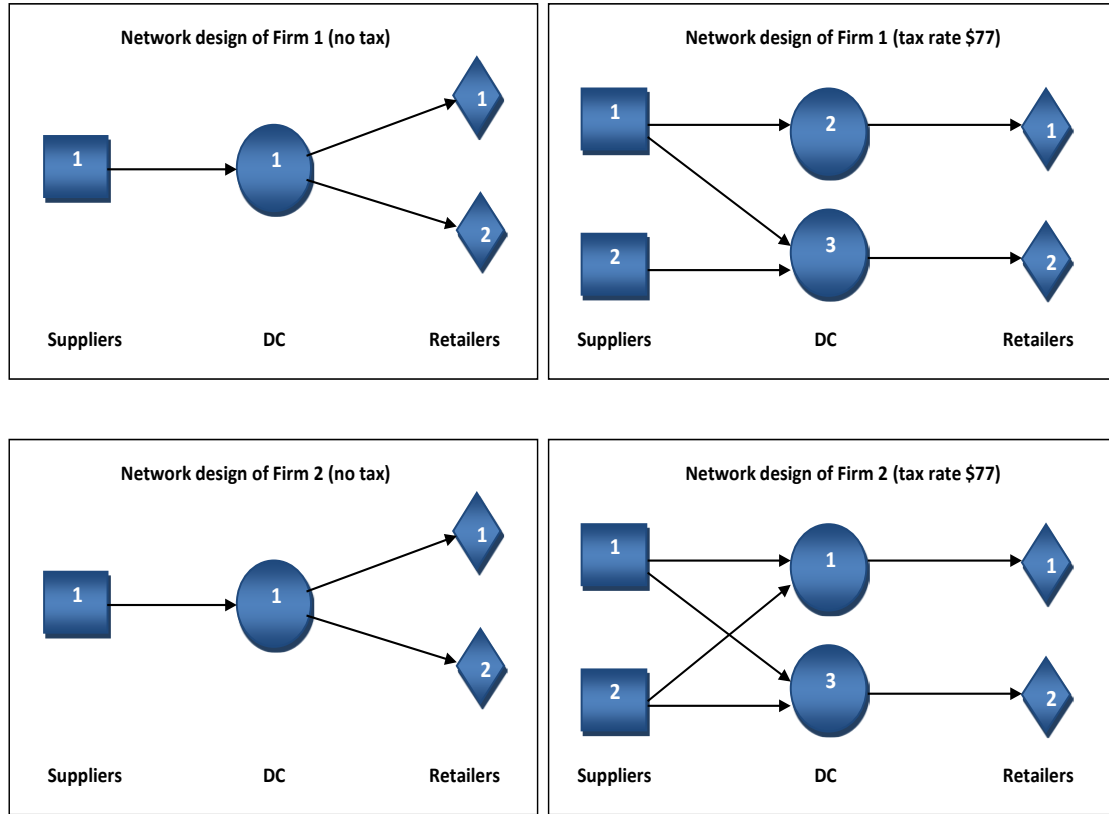


Figure 5.2: Network design with and without carbon tax

tax rates ranging between \$10 and \$60 the reduction in the emission factors and the total emissions are not significant although there is a significant increase in the total costs. Firm 2 increases the use of electric trucks, opens additional DC and uses both suppliers with tax rates higher than \$50. Firm 1 uses electric trucks under tax rates higher than \$50 and changes its network design under tax rates higher than \$60. A tax rate of \$70 is found to reduce the emission factor and the total emissions by further 8.38% and 8.01%, respectively, compared to the results of the effective tax rate of \$77 under carbon tax based on the emission factor; however, it increases the total cost by 237.49%. The table demonstrates that as the tax rates increase, firms switch to domestic suppliers, the reduction in the total emissions and the emission

factor increases, and the total cost significantly increases. Figure 5.3 presents the reduction in the emission factors and total emissions and the increase in the total cost for different tax rates under both policies that impose a tax on the emission factor and total emissions. The figures indicate that for tax rates ranging between \$10 and \$60 the differences in the emission factors and total emissions are not significant; however, the tax policy based on the emission factor has a significantly lower cost.

To see the impact of the costs and the capacity of electric trucks on firms' decisions, we construct Examples 2 – 11 which have the same data presented in Tables 5.1-5.3 except that we decrease the fixed cost of the electric trucks in Examples 2 – 6 by 10% each time and increase the capacity of electric trucks in Examples 7 – 11 by 10% each time. Table 5.7 compares the results of Examples 2 – 11 to the ones obtained under the tax policy based on the emission factor using a tax rate of \$77. Table 5.7 indicates that as the fixed cost of the electric trucks decrease, the tax rates required to achieve the target reduction increase. Decreasing the fixed costs of electric trucks assists firms in achieving lower CO₂ emissions and emission factors at lower costs. Firm 2 maintains the same network design obtained under a tax rate of \$77 but increases the use of electric trucks. Firm 1 changes the design of its supply chain and opens DC 1 instead of DC 2 to benefit from using electric trucks between supplier 1 and DC 1. Increasing the capacity of the electric trucks by 10% has no impact on the tax rate although the achieved CO₂ emissions and emission factors are lower. On the other hand, increasing the capacity of the electric trucks by 20% – 50% increases the tax rates; however, the tax rates are lower than the ones required in Examples 2 – 6. Although firms are able to lower their CO₂ emissions and emission factors at lower costs in Examples 7 – 11 compared to the results of using a tax rate of \$77, the obtained results are higher than the ones

Tax rate\$	Reduction in the EF%				Reduction in the total emissions%				Change in total cost%				Opened DCs		Used suppliers		Use of E. Trucks%	
	Industry	Firm1	Firm2		Industry	Firm1	Firm2		Industry	Firm1	Firm2		Firm1	Firm2	Firm1	Firm2	Firm1	Firm2
10	1.31	1.59	1.05		1.72	0.40	3.04		41.78	41.10	42.44		DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	1.6
20	1.59	1.59	1.63		1.78	0.40	3.17		78.28	81.20	75.44		DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	43.61
30	1.59	1.59	1.63		1.78	0.40	3.17		109.34	113.27	105.51		DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	43.61
40	1.55	1.59	1.55		1.94	0.40	3.49		154.55	161.38	147.89		DC ₁₁	DC ₂₁	Sup ₁	Sup ₁	0	45.80
50	4.36	1.59	5.95		4.14	0.40	7.91		193.22	201.48	185.17		DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁	Sup ₁	0	57.03
60	4.98	2.89	5.92		8.86	3.13	14.66		241.10	248.71	233.69		DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁	Sup ₁ ,Sup ₂	42.86	59.72
70	23.72	23.58	24.94		23.99	24.99	19.75		274.31	277.38	271.32		DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	45.91	64.11
77	35.60	25.22	37.93		37.69	36.40	39.00		284.01	287.49	280.62		DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	56.15	75.93
80	47.28	47.03	47.75		53.00	42.23	63.88		293.04	303.82	282.53		DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₂	65.43	77.04
90	51.86	52.22	51.41		67.13	63.31	70.99		296.92	308.37	285.76		DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₂	Sup ₂	69.71	80.55

Table 5.6: Results for different tax rates (Tax policy based on total emissions)

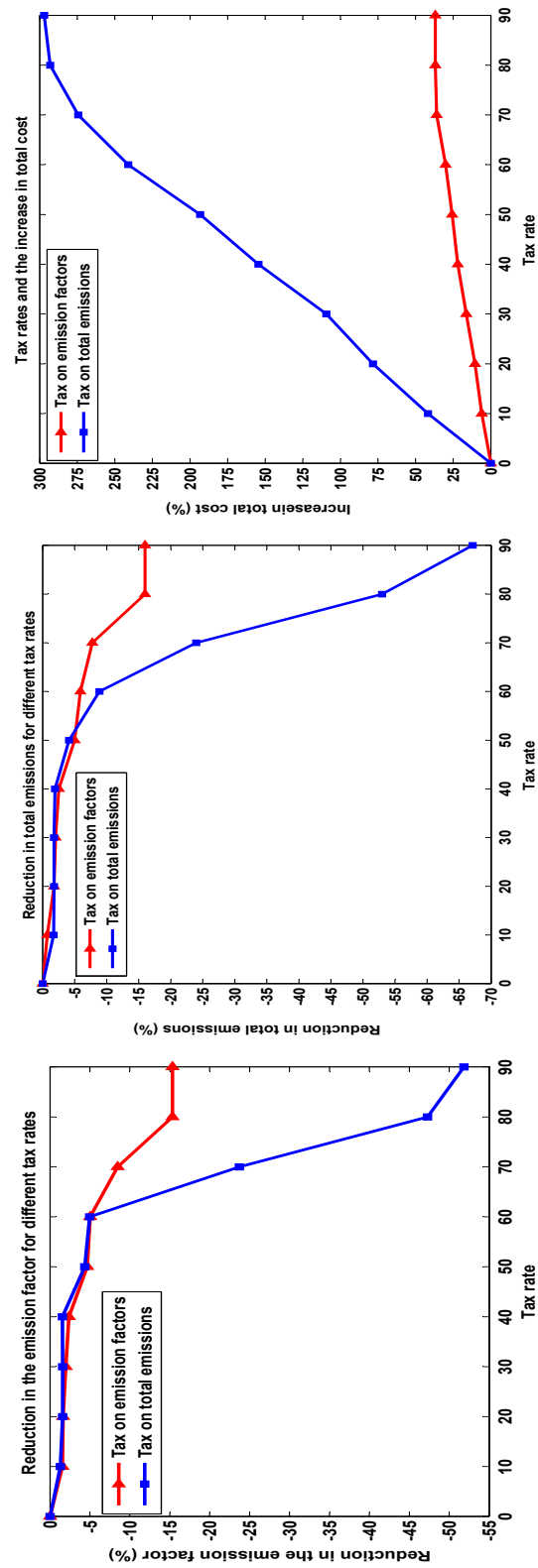


Figure 5.3: The emission factor, the overall emissions, and the total cost for different tax rates

achieved from decreasing the cost of electric trucks. Firm 2 does not change the design of its supply chain but decreases the percentage use of electric trucks due to increasing their capacities. Increasing the capacity of electric trucks beyond 10% induces Firm 1 to increase the use of electric trucks and change the design of its supply chain when the capacity is increased by 50%.

To examine the impact of the fuel costs and the fuel consumption of heavy-duty trucks on firms' decisions, we construct Examples 12 – 21 which have the same data presented in Tables 5.1-5.3 except that we increase the fuel cost in Examples 12 – 16 by 5% each time and decrease the fuel consumption of class-8-diesel truck in Examples 17 – 21 by 5% each time. Table 5.8 compares the results of Examples 12 – 21 to the ones obtained under the tax policy based on the emission factor using a tax rate of \$77. The table shows that increasing fuel costs decrease the tax rate required to achieve the target reduction and increase the total costs. Firms keep the design of their supply chains but increase the percentage use of electric trucks. Although increasing fuel costs decreases the tax rate, the achieved reduction in the CO₂ emissions and the emission factors are higher. Improving the fuel consumption of class-8-diesel truck increases the tax rates; however, this increase is lower than the one obtained from decreasing the fixed costs of electric trucks. Decreasing the fuel consumption of class-8-diesel truck helps firms in achieving lower CO₂ emissions and emission factors at lower costs. The table illustrates that firms reduce the percentage use of electric trucks as the fuel consumption improves until they use no electric trucks. When the fuel consumption is improved beyond 15%, Firm 1 closes one of its DCs and utilizes class-8-diesel truck, whereas Firm 2 closes its second DCs when the fuel consumption is improved by 30%. Comparing the impacts of fuel cost and fuel consumption, Table 5.8 demonstrates that changing both parameters leads to almost the same reduction in the CO₂ emissions and emission factors; however,

Change in	Change in the results															
the parameters	Tax	Emission factor%			Total emissions%			Total cost%			Opened DCs		Used suppliers		Use of E. Trucks%	
E-truck cost	rate%	Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Firm1	Firm2	Firm1	Firm2	Firm1	Firm2
EX.2 (−10%)	6.49	−0.13	−0.12	−0.09	−0.15	−0.19	−0.13	−0.27	−0.37	−0.15	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	37.9	1.3
EX.3 (−20%)	18.18	−0.25	−0.22	−0.10	−0.29	−0.32	−0.27	−0.46	−0.51	−0.28	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	38.2	4.7
EX.4 (−30%)	22.08	−0.49	−0.60	−0.23	−0.66	−0.93	−0.79	−0.98	−1.20	−1.08	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	43.3	6.1
EX.5 (−40%)	25.97	−0.51	−0.61	−0.25	−0.70	−0.94	−0.80	−2.50	−2.90	−1.27	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	44.58	7.0
EX.6 (−50%)	29.87	−0.95	−1.01	−0.58	−1.36	−1.19	−1.65	−3.01	−3.86	−2.63	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	53.75	10.60
E-truck capac.																
EX.7 (+10%)	0.00	−0.17	−0.34	−0.11	−0.21	−0.35	−0.16	−0.13	−0.33	−0.08	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	−2.7	−3.81
EX.8 (+20%)	2.60	−0.08	−0.02	−0.14	−0.24	−0.03	−0.45	−0.75	−0.47	−1.06	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	29.96	−5.69
EX.9 (+30%)	7.79	−0.05	−0.16	−0.07	−0.73	−1.41	−0.14	−0.84	−0.11	−1.69	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	33.62	−9.80
EX.10 (+40%)	11.69	−0.19	−0.35	−0.13	−0.41	−0.78	−0.36	−0.54	−1.03	−0.14	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	37.33	−12.11
EX.11 (+50%)	12.99	−0.16	−0.27	−0.12	−0.59	−0.64	−0.39	−0.67	−1.10	−0.18	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	40.2	−17.04

Table 5.7: Changes in the results of Examples 2-11 compared to the result of the effective tax rate \$77

improving fuel consumptions achieves that reduction at lower costs.

In order to analyze the effects of electricity emission factor and costs, we build Examples 22 – 31 which have the same data presented in Tables 5.1-5.3 except that we decrease the emission factor of electricity in Examples 22 – 26 by 10% each time and decrease the electricity costs in Examples 27 – 31 by 10% each time. The results of Examples 22 – 31 in Table 5.9 show that decreasing the emission factor of electricity increases tax rates. The achieved reduction in the emission factor and total costs are found to be higher compared to the result of the effective tax rate \$77. The results of Examples 22 – 25 indicate that Firms maintain the same supply chain and increases the percentage use of electric trucks. When the electricity emission factor is decreased by 50%, Firm 1 changes the configuration of its network and opens DC 1 instead of DC 2 to benefit from electric trucks. The results of Examples 27 – 31 show that decreasing electricity cost has the same impacts on the firms' decisions and the tax rates; it increases the tax rates, decreases the CO₂ emissions and emission factor at lower costs, and increases the percentage use of electric trucks. Comparing the impacts of changing all the previous parameters, we found that the one that achieves lower overall emissions and emission factors at lower costs is reducing the fuel consumption of class-8-diesel truck.

5.5 Conclusion

In this chapter, we presented a bilevel programming model to integrate the design of supply chains into the design of a carbon tax policy based on the emission factor. At the upper level, the government sets a target emission factor per product transported and taxes firms if they exceed that level. Therefore, the government

Change in	Change in the results															
the parameters	Tax	Emission factor%			Total emissions%			Total cost%			Opened DCs		Used suppliers		Use of E. Trucks%	
Fuel cost	rate%	Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Firm1	Firm2	Firm1	Firm2	Firm1	Firm2
EX.12 (+10%)	-1.30	-0.12	-0.02	-0.21	-0.46	-0.35	-0.55	0.39	0.15	0.67	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	17.94	0.10
EX.13 (+15%)	-2.60	-0.64	-0.37	-0.95	-1.02	-0.40	-1.63	1.36	1.05	1.71	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	25.05	4.38
EX.14 (+20%)	-3.90	-1.03	-1.52	-1.06	-2.83	-3.42	-2.24	3.80	4.13	3.43	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	45.57	5.87
EX.15 (+25%)	-6.49	-1.85	-3.76	-1.08	-2.67	-3.80	-2.11	9.70	8.99	10.50	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	56.71	10.39
EX.16 (+30%)	-6.49	-2.02	-4.64	-2.38	-2.35	-4.72	-2.96	12.25	12.47	12.00	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	64.11	12.14
Fuel consum.																
EX.17 (-10%)	6.49	-0.12	-0.15	-0.19	-0.17	-0.23	-0.28	-0.81	-1.41	-0.97	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	-7.72	-20.07
EX.18 (-15%)	6.49	-0.57	-0.15	-1.01	-0.72	-0.27	-1.89	-1.08	-1.29	-1.01	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	-10.25	-26.93
EX.19 (-20%)	11.69	-1.65	-1.15	-2.15	-1.70	-1.22	-2.30	-4.09	-5.66	-2.34	DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	-21.10	-38.65
EX.20 (-25%)	11.69	-2.14	-1.47	-2.41	-2.40	-1.55	-2.54	-4.66	-5.85	-3.10	DC ₁₁	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	-21.10	-38.65
EX.21 (-30%)	12.39	-2.52	-2.60	-2.43	-2.63	-2.05	-3.19	-6.10	-7.89	-4.10	DC ₁₁	DC ₂₁	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	-21.10	-74.80

Table 5.8: Changes in the results of Examples 12-21 compared to the result of the effective tax rate \$77

Change in the parameters	Change in the results													
	Tax rate%	Emission factor%			Total emissions%			Total cost%		Opened DCs		Used suppliers		Use of E. Trucks%
		Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Indus.	Firm1	Firm2	Firm1	Firm2	Firm1	Firm2
Electricity EF														
EX.22 (−10%)	2.60	0.12	0.10	0.16	−0.02	−0.03	−0.02	−0.04	−0.07	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	5.18
EX.23 (−20%)	3.90	0.05	0.07	0.03	−0.11	−0.04	−0.14	−0.12	−0.25	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	6.62
EX.24 (−30%)	5.19	0.04	0.07	0.02	−0.22	−0.04	−0.37	−0.83	−1.09	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	7.12
EX.25 (−40%)	11.69	−0.03	−0.03	−0.05	−0.36	−0.09	−0.55	−0.97	−1.30	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	7.27
EX.26 (−50%)	16.88	−0.20	−0.14	−0.28	−0.54	−0.74	−0.68	−1.41	−1.48	DC ₁₁ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	20.39
Electricity cost														
EX.27 (−10%)	1.30	0.05	0.07	0.02	−0.05	−0.10	−0.01	−0.15	−0.39	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	0.80
EX.28 (−20%)	2.60	−0.03	−0.05	0.00	−0.68	−0.91	−0.07	−0.36	−0.75	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	3.20
EX.29 (−30%)	7.79	−0.65	−1.15	−0.42	−1.20	−1.37	−0.44	−1.03	−1.29	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	12.64
EX.30 (−40%)	9.09	−0.80	−1.15	−0.69	−1.40	−1.37	−0.67	−1.03	−1.29	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	14.02
EX.31 (−50%)	18.20	−1.20	−1.20	−1.04	−1.72	−2.11	−1.18	−1.24	−1.38	DC ₁₂ ,DC ₁₃	DC ₂₁ ,DC ₂₃	Sup ₁ ,Sup ₂	Sup ₁ ,Sup ₂	22.32

Table 5.9: Changes in the results of Examples 22-31 compared to the result of the effective tax rate \$77

is interested in finding the best tax rate that achieves the target reduction. At the lower level, firms make decisions regarding the design of their supply chain and the type of trucks used. Due to the difficulty of the bilevel problem as it has nonlinearities in the upper-level problem as well as binary and integer variables in the lower-level problem, we find the tax rate α_2 that achieves the target reduction by fixing α_2 in the lower-level problem, solving the resulting MIP for several values of α_2 , and picking the one that achieves the target reduction and has the lowest impact on the industry. In order to test the proposed model, we constructed a case study and tested the impact of some parameters using several examples.

The results indicate that a reduction in the transport-related emission factor reduces the overall emissions by almost the same percentage. We found that firms reduce their emission factors by opening more DCs that are close to customers, use domestic and offshore suppliers, utilize large trucks, and use electric trucks. By comparing the carbon tax based on the emission factor to the carbon tax imposed on the total emissions, we found that for tax rates ranging between 0\$ and \$60, the differences in the achieved emission factors and overall emissions are small. However, the carbon tax imposed on the total emissions significantly increases the total cost. By varying some of the parameters, we found that the reduction in the total emissions and the emission factors achieved from increasing fuel cost and decreasing fuel consumption are higher than the ones obtained from varying other parameters. The results demonstrate that improving the cost and the capacity of electric trucks would induce firms to use them more; however, improving the fuel consumption of heavy-duty diesel trucks would result in more reduction at lower costs.

Chapter 6

Conclusion

In this thesis, we model and study an intensity-based carbon tax that targets the emission factor due to production or transportation activities. Specifically, we study a carbon tax scheme where policy makers set a target emission factor for a specific industry and tax firms if they exceed that limit.

In Chapter 3, we propose a social welfare maximization model for an intensity-based carbon tax that targets the production emission factor of manufacturing industries represented by cement industry. The policy is tested on case studies constructed in the context of the cement industry and is compared to other environmental policies. Unlike the major criticism of the intensity-based regulations, which is that the total emissions would increase even if the target level for the emission factor is met, our analysis indicates that a reduction in the emission factor would lead to a significant reduction in the total emissions. Yet, our study shows that using a low tax rate would result in no reduction or a minimal reduction in the emission factor and the total emissions. Comparing the carbon tax based on the emission factor to other environmental policies, we found that the policy has more advantages: (1) it yields the highest consumers' surplus and production quantities and the lowest market price; (2) it provides social welfare that is significantly higher than the ones obtained under the mandatory cap on the emission factor and under

the carbon tax based on the total emissions; (3) it provides adequate reduction in CO₂ emissions with a little impact on social welfare; and (4) it provides a stable price for carbon credits.

In Chapter 3, the best tax rate is found by enumeration. In Chapter 4, we propose a bilevel formulation to design a carbon tax policy based on the production emission factor of a manufacturing industry. At the upper level, the government sets a target level for the production emission factor of the industry and taxes firms if they exceed that target. Assuming a competitive market, at the lower level, the industry decides on the production quantity and the fuel types that maximize the social welfare given the tax rate and the market price. After testing the transformed model on several examples, constructed in the context of the cement industry, we find that the proposed model finds the optimal tax rate that induces firms to reduce their emission factors and consequently reduces the overall emissions. Higher reduction in the emission factors significantly increases the tax rates, decreases the social welfare and production quantities, and may put some firms out of business. On the other hand, adequate reduction in the emission factors, below 20%, is achievable with moderate tax rates that have a little impact on the industry and lead to a large reduction in the overall emissions.

To examine the effectiveness of the policy on reducing the CO₂ emissions of a different polluting industry, in Chapter 5, we present a bilevel formulation to integrate the design of supply chains into the design of a carbon tax policy based on the emission factor. At the upper level, the government sets a target emission factor per product transported and taxes firms if they exceed that level. Therefore, the government is interested in finding the best tax rate that achieves the target reduction. At the lower level, firms make decisions regarding the design of their supply chain and the type of trucks used. Because of the difficulty of the bilevel

problem as it has nonlinearities in the upper-level problem as well as binary and integer variables in the lower-level problem, we use an alternative approach to find the tax rate that achieves the target reduction. We fix the value of the tax rate in the lower-level problem, solve the resulting mixed integer program for several tax rates, and pick the one that achieves the target reduction and has the lowest impact on the industry. To test the proposed model, we construct a case study and test the impact of some parameters using several examples. The results show that the effective tax rate induces firms to reduce their emission factors and consequently decreases the overall emissions by almost the same percentage. Firms reduce their emission factors by redesigning their supply chain, utilizing large trucks, and using electric trucks. The results also indicate that improving the fuel consumption of heavy-duty diesel trucks could be an alternative to using electric trucks as the reduction achieved by decreasing the fuel consumption is higher than the one obtained from improving the cost and the capacity of electric trucks. Future research will focus on investigating the impact of the policy on different market structures; namely, monopolistic and oligopolistic markets and on constructing an efficient solution methodology for the model proposed in Chapter 5 to find the best tax rate.

APPENDICES

Appendix A

Chapter-3 Notation

Indices	i	: Index for firms, $i \in 1, \dots, N$.
	l	: Fuel type $l \in 1, \dots, L$.
Parameters	c_i	: Variable cost per unit produced at firm i .
	t_i	: Constant associated with the quadratic cost at firm i .
	h_{il}	: Fuel l cost at firm i .
	d_i	: Production capacity at firm i .
	b_i	: Thermal energy consumption at firm i (GJ/tonne).
	$\hat{b}_{il}$	: Energy content in fuel l at firm i (GJ/tonne, m ³ ...).
	e_{il}	: CO ₂ emission factor of fuel type l at firm i .
	β	: A target production emission factor above which firms pay tax.
	γ	: Intercept of inverse demand curve.
	δ	: Slope of inverse demand curve.
Variables	q_i	: Quantity produced at firm i .
	q^d	: Quantity demanded in the market.
	w_{il}	: Amount of fuel l used at firm i .
	x_i	: Production emission factor for firm i .
	θ_i	: Taxed CO ₂ emissions of firm i .
	p	: Product market price.
	$\bar{p}$	: Permit price.
	a_i	: Clinker to cement ratio at firm i (t-clinker/t-cement).
	$\hat{a}_i$	: Raw material to clinker ratio at firm i (t-raw-meal/t-clinker)

s_i : Emission factor due to calcining limestone (t-CO₂/t-clinker).
 ξ_i : Emission factor due to grinding raw materials (t-CO₂/t-raw-meal).
 $\hat{\xi}_i$: Emission factor due to grinding cement (t-CO₂/t-cement).
 α_2 : Tax rate.

Appendix B

Chapter-4 Notation

Indices	i	: Index for firms, $i \in 1, \dots, N$.
	l	: Fuel type $l \in 1, \dots, L$.
Parameters	c_i	: Variable cost per unit produced at firm i .
	t_i	: Constant associated with the quadratic cost at firm i .
	h_{il}	: Fuel l cost at firm i .
	d_i	: Production capacity at firm i .
	b_i	: Thermal energy consumption at firm i (GJ/tonne).
	$\hat{b}_{il}$	: Energy content in fuel l at firm i (GJ/tonne, m ³ ...).
	e_{il}	: CO ₂ emission factor of fuel type l at firm i .
	β	: A target production emission factor above which firms pay tax.
	γ	: Intercept of inverse demand curve.
	δ	: Slope of inverse demand curve.
Lower-level variables	q_i	: Quantity produced at firm i .
	q^d	: Quantity demanded in the market.
	w_{il}	: Amount of fuel l used at firm i .
	x_i	: Production emission factor for firm i .
	θ_i	: Taxed CO ₂ emissions of firm i .
	p	: Product market price.
	r_i	: Dual variables associated with capacity constraints.
	λ_i	: Dual variables associated with energy constraints.
	ζ_i	: Dual variables associated with taxed emissions constraints.

Upper-level variables E : Production emission factor for the entire industry.

σ_0 : Deviation from the target emission factor.

s_0 : Deviation from the total emissions.

α_2 : Tax rate.

Appendix C

Chapter-5 Notation

Indices	i	: Index for firms, $i \in 1, \dots, N$.
	M_i	: Shipping points of firm i , $m \in \{1, \dots, M_i\}$
	K_i	: Customer zones of firm i , $k \in \{1, \dots, K_i\}$.
	J_i	: Potential distribution center locations of firm i , $j \in \{1, \dots, J_i\}$.
	L_i	: Truck types of firm i , $l \in \{1, \dots, L_i\}$
Parameters	c_{imjl}	: Average production and shipping cost per unit shipped from shipping point $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$.
	$\hat{c}_{ijkl}$	: Average handling cost per unit shipped from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$.
	s_{ij}	: Capacity limit of DC j of firm i .
	f_{ij}	: Fixed cost of opening DC j of firm i .
	h_{il}	: Fuel or electricity cost (\$/Liter, MWh, ..) of truck l at firm i .
	d_{ik}	: Demand at customer zone k of firm i .
	b_{il}	: Fuel or electricity consumption (Liter, MWh/km) for a loaded truck l at firm i .
	$\hat{b}_{il}$	: Fuel or electricity consumption (Liter, MWh/km) for an empty truck l at firm i .
	$\hat{s}_{il}$	: Capacity of truck l at firm i .
	t_{imjl}	: Fixed costs of shipments from shipping points $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$ at firm i .

	$\hat{t}_{ijkl}$	: Fixed cost of a shipment from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$ at firm i .
	a_{imj}	: Distance from shipping point $m \in M_i$ to DC $j \in J_i$ of firm i .
	$\hat{a}_{ijk}$	: Distance from DC $j \in J_i$ to customer zone $k \in K_i$ of firm i .
	e_{il}	: CO ₂ emission factor (kg/Liter, MWh) for the electricity or the fuels used for truck $l \in L_i$ at firm i .
	$\hat{e}_{im}$	: Emission factor of the transportation mode used to deliver the product to the shipping point $m \in M_i$ of firm i .
	β	: A target production emission factor above which firms pay tax.
Lower-level variables	q_{imjl}	: Quantity shipped from shipping point $m \in M_i$ to DC $j \in J_i$ using truck $l \in L_i$ at firm i .
	$\hat{q}_{ijkl}$	: Quantity shipped from DC $j \in J_i$ to customer zone $k \in K_i$ using truck $l \in L_i$ at firm i .
	w_{imjl}	: Fuel/electricity used by truck $l \in L_i$ to deliver shipments between shipping point $m \in M_i$ and DC $j \in J_i$ of firm i .
	$\hat{w}_{ijkl}$	: Fuel/electricity used by truck $l \in L_i$ to deliver shipments between DC $j \in J_i$ and customer zone $k \in K_i$ of firm i .
	v_{imjl}	: Number of shipments between shipping point $m \in M_i$ and DC $j \in J_i$ using truck $l \in L_i$ at firm i .
	$\hat{v}_{ijkl}$	: Number of shipments between DC $j \in J_i$ and customer zone $k \in K_i$ using truck $l \in L_i$ at firm i .
	y_{ij}	: Binary variable that equals 1 if DC $j \in J_i$ is opened and 0 otherwise.
	TE_i	: Total emissions for firm i .
	x_i	: Production emission factor for firm i .
Upper-level variables	E	: Production emission factor for the entire industry.
	α_2	: Tax rate.

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