Trade and the Environment:
The Political Economy of CO_2 Emission Leakage with Analysis of the Steel and Oil Sands Industries

by
Gabriel A. Chan

Submitted to the DEPARTMENT OF POLITICAL SCIENCE
and the DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCE

in Partial Fulfillment of the Requirements for the Degrees of

BACHELOR OF SCIENCE IN POLITICAL SCIENCE

and

BACHELOR OF SCIENCE IN EARTH, ATMOSPHERIC AND PLANETARY SCIENCE

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
JUNE 2009

Signature of Author: Signature redacted
Department of Political Science
Department of Earth, Atmospheric and Planetary Science
May 22, 2009

Certified by: Signature redacted
Kenneth A. Oye
Associate Professor,
Department of Political Science
Thesis Supervisor

Certified by: Signature redacted
Ronald G. Prinn
TEPCO Professor of Atmospheric Science,
Department of Earth, Atmospheric and Planetary Science
Thesis Supervisor

Certified by: Signature redacted
Sergey Paltsev
Principal Research Scientist,
MIT Joint Program on the Science and Policy of Global Change
Second Reader

Accepted by: Signature redacted
Charles Stewart III
Professor and Head,
Department of Political Science

Accepted by: Signature redacted
Samuel Bowring
Robert R. Shrock Professor of Geology
Department of Earth, Atmospheric and Planetary Science
Chair, Committee on Undergraduate Program

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Climate Change Science

In 2007, scientists and governmental officials from around the world contributed to the United Nations-authorized Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report. Through peer-reviewed scientific research and governmental review, the IPCC came to the conclusion that "warming of the climate system is unequivocal," and that "most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." The IPCC Fourth Assessment states that humans have "more likely than not" contributed to the phenomena of more frequent "warm spells/heat waves," larger "area[s] affected by droughts," more "intense tropical cyclones...and heavy precipitation events," and "extreme high sea level[s]." Citing "high agreement" and "much evidence," the IPCC states that "with current climate change mitigation policies and related sustainable development practices, global GHG [greenhouse gas] emissions will continue to grow over the next few decades." (Intergovernmental Panel on Climate Change, 2007)

1.1.1 Economic Impacts of Climate Change

While global greenhouse gas emissions continue to rise, it remains highly uncertain how severely rising temperatures will adversely impact human systems in the long-run. In 2006, Sir Nicholas Stern, an economist for the British government, attempted to aggregate the future damages and costs of unmitigated climate change. One of Stern's central findings was that "if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP (Gross Domestic Product) each year, now and forever," with the potential for damages to "rise to 20% of GDP or more." (Stern, 2006) Despite considering a wide array of future damages through integrated assessment tools and receiving high praise from UK Prime Minister Tony Blair, critics were not satisfied. Criticism of the Stern report focused on alleged "very basic economics mistakes" and the use of "pessimistic" discount rates. (Cox & Vadon, 2007) Nevertheless, Stern's report stands out as one of the few attempts to calculate the sum of the costs of greenhouse gas emission externalities. In addition to pure economic costs, one particular point of concern for climate scientists is the potential for a climate tipping point, or point of no return, after which the impacts of climate change will have gained so much momentum that they cannot be stopped. A climate tipping point, needless to say, will be a hindrance for future generations' capacity for self-determination. (Eilperin, 2006)

Aggressive greenhouse gas emission reductions have the potential to significantly and permanently damage the global economy, but the balance between economic growth and greenhouse gas emissions does not have to involve a direct tradeoff between the two quantities. The Kaya identity provides a framework for relating a country's greenhouse gas emissions and its economic strength. The identity gives total greenhouse gas emissions as the product of population, output per capita, energy intensity of the economy, and carbon intensity of the energy supply. And as an identity, the Kaya identity is always exactly true. (Deutch & Lester, 2004)

$$\mathrm{C}=\mathrm{P}\times\left(\frac{\mathrm{Y}}{\mathrm{P}}\right)\times\left(\frac{\mathrm{E}}{\mathrm{Y}}\right)\times\left(\frac{\mathrm{C}}{\mathrm{E}}\right) \tag{1.1}$$

C: GHG Emissions, E: Energy Consumed, Y: GDP, P: Population

Taking the derivative of the Kaya identity results in the following equation, useful for analyzing the dynamic properties of national systems:

$$\frac{\partial \mathrm{C}}{\mathrm{C}}=\frac{\partial \mathrm{P}}{\mathrm{P}}+\frac{\partial(\mathrm{Y/P})}{(\mathrm{Y/P})}+\frac{\partial(\mathrm{E/Y})}{(\mathrm{E/Y})}+\frac{\partial(\mathrm{C/E})}{(\mathrm{C/E})} \tag{1.2}$$

The Kaya identity and its derivative provide a concrete framework for how a country's greenhouse gas emissions can decrease while its gross domestic product per capita simultaneously increases. For example, a developed country, such as the United States, has a population growth rate below one percent. (U.S. Central Intelligence Agency, 2008) Assuming the US population growth rate is zero, if a hypothetical policy measure mandates a freeze on the growth rate of carbon emissions, gross domestic product per capita will increase exactly as the inverse of the sum of the percent change in the carbon intensity of the energy supply and the percent change in the energy intensity of the economy. The same results persist when the zero population growth constraint is slightly relaxed. This implies that GDP per capita can increase even with greenhouse gas emissions constrained at current levels, so long as steps are taken to either improve energy efficiency (per dollar of economic output) or reduce the carbon intensity of energy generation.

While the Kaya identity reveals how developed countries with low population growth rates and relatively low economic growth rates can avoid increasing greenhouse gas emissions through mild improvements in efficiency or decarbonization, the same result does not hold for developing countries. For example, India, a country 17 times poorer than the United States, has an annual population growth rate of 1.6% and an annual economic growth rate of 8.5%. (U.S. Central Intelligence Agency, 2008) In order for India to freeze the growth of its carbon emissions without decreasing its economic growth rate, even if the government mandated a freeze on population growth, the Indian economy would have to decarbonize by a total of 8.5% annually (10.1% annually if population is not frozen). For China, another rapidly growing developing country, in order to freeze its carbon emissions, it would have to decarbonize its economic output by over 12% annually. (U.S. Central Intelligence Agency, 2008) To frame the magnitude of these constraints, from 1990 to 2005, the United States, arguably the most technologically advanced country in the world, decarbonized its economy by less than 2% per year, a rate far faster than the global average. Even more troubling, the global average carbon intensity of the economy has been increasing since 2002, making it even more unlikely that China or India could come close to stabilizing their carbon emissions without sacrificing economic growth. (Raupach, et al., 2007)

1.1.2 Climate Change and the Developing World

Once emitted, greenhouse gases remain in the atmosphere for long periods of time, ranging from decades to several centuries, making historical emitters responsible for current warming trends and current emitters responsible for future global warming. (Blasing & Smith, 2006) In 2004, developed economies emitted 59% of global greenhouse gas emissions, yet formed only 20% of the world population. Further, the same minority of richest countries were responsible for 77% of cumulative emissions since the beginning of the Industrial Revolution in the mid-18th century. (Raupach, et al., 2007) However, the dynamic of international wealth and industrial might is rapidly changing. Despite only accounting for 41% of greenhouse gas emissions in 2004, 73% of the growth in emissions is attributed to the developing and least-developed countries, foreshadowing the large role these countries will play in future environmental degradation. (Raupach, et al., 2007) Led by China and India, today's developing countries will drive the increases in energy-related greenhouse gas emissions for at least the next thirty years.

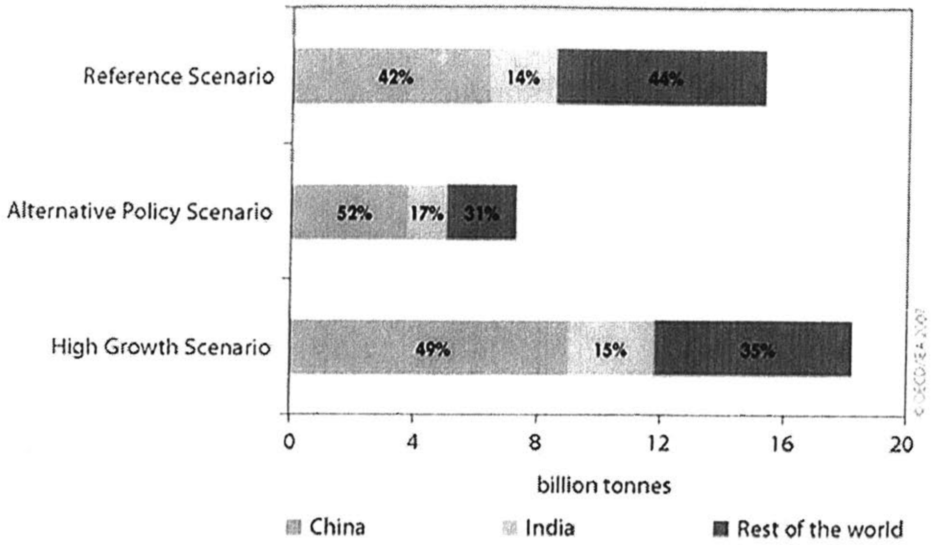


Figure 1.1: Over 50% of the increase in energy-related CO_2 emissions from 2005-2030 is driven by China and India in all three scenarios. The "reference scenario" models the trends in energy and CO_2 emissions under current policies. The "alternative policy scenario" models a world in which policies for energy security, energy efficiency, and the environment are enacted. The "high growth scenario" models a world in which China and India continue their high levels of economic growth.

In view of China and India's unprecedented surge of economic growth, supplying energy to the so-called "two giants" while avoiding irreversible environmental harm is the most crucial challenge of "all governments" concerned with "moving the world onto a more sustainable energy path." [9] Adding to the challenge, coal is a largely abundant resource in China and India [10], it is significantly cheaper than other energy alternatives [11], and it is the most harmful energy source for the environment. In order to meet this global challenge, governments from around the world must work together and combine policy action with induced technological transformation at meaningful scale.

1.2 Economic Growth and the Environment

1.2.1 Economic Growth and Environmental Quality

In the traditional conceptualization of pollution, economic growth is fueled by industrial activity, which reciprocally fuels further economic growth. Pollution is unintentionally generated by industrial activity, emitted from the production line as a by-product of an unrelated process. Once produced, pollutants enter the public domain where inhabitants of a local or foreign region (or in the case of greenhouse gases, all regions) bear the costs of a degraded environment. Economists have labeled these types of additional costs of economic activity born on others, not on the actors themselves, "negative externalities." In the presence of a negative externality, as long as a polluter behaves independently from those who suffer from the pollution, the market will fail to operate efficiently.[1] In the presence of this type of market failure, the government is justified in intervening to induce the polluting firm to reduce its emissions.

Recently, economists have theorized that under certain conditions, pollutants behave more like traditional economic goods than like the negative externalities of other activities. In this more recent conceptualization of pollution, economists theorize that environmental quality, the mathematical equivalent of avoided pollution, behaves like a normal good. Normal goods are products for which an individual's demand increases as his/her income increases. Additionally, some economists have argued that environmental quality specifically behaves as a luxury good, a subclass of normal goods.

---

[1] A market failure that arises from a negative externality, such as pollution, can be resolved without 3rd-party intervention if the people who suffer from the pollution negotiate a transfer of payments to bribe the polluter to stop its emissions. This solution was first proposed by Ronald Coase (1960), and while it is economically efficient in theory, the so-called "Coasian solution" is both difficult to implement due to high organization costs, and often highly inequitable.

Luxury goods are normal goods that an individual begins to demand more of at a rate that outpaces the growth in the individual's income. The debate over the proper classification of environmental quality as either a luxury good or as a non-luxury normal good can be distilled down to the search for a single quantity: the income elasticity of demand for environmental quality (IEDEQ), the rate at which the demand for environmental quality changes as income changes. Determining the IEDEQ is an important empirical question because it provides a framework for assessing how important environmental quality will be to individuals as the world becomes wealthier. Obviously, individuals cannot satisfy their demand for environmental quality unilaterally because environmental quality cannot be directly purchased; it is a public good. Rather, individuals must rely on the government, the monopolistic provider of environmental quality, to satisfy their demand for the good. Therefore, under the assumption that political leaders strive to enact the will of their constituents (as the fundamental principles of democratic governance suggest), governments should strive to aggregate individual demand for environmental quality and then formulate a policy response to meet that demand. If this mechanism accurately describes how the political process operates, the IEDEQ will provide a sound estimate for how governments will manage the environment as wealth grows.

If environmental quality does behave as an economic good demanded by many individuals and supplied only by the government, environmental policy should be set stringently enough to achieve the level of environmental quality that matches the public's aggregated demand. Further, continuing with the assumption that environmental quality is a normal good (with demand driven by individual income), it follows that poorer jurisdictions will have lower levels of environmental quality, but that as a jurisdiction becomes wealthier, it will eventually begin to demand environmental quality. Through the political mechanism described in the previous paragraph, environmental quality will begin to increase as wealth rises. However, in considering the relationship between economic development and environmental quality, only considering the absence of pollution (i.e. environmental quality) ignores one of the key realities of pollutants gleaned from the traditional conceptualization of pollutants (as externalities of unrelated economic activities): emissions of pollutants increase proportionally to the unrelated activities that produce pollution as by-products. The EKC resolves this disharmony by suggesting a 2-stage relationship between economic growth and environmental quality.

1.2.1.1. The Environmental Kuznets Curve

Nearly all polluting activities that degrade the environment rely either on a minimal preexisting degree of industrialization and infrastructure or require potentially prohibitive initial capital investment. Therefore, the world's poorest jurisdictions (with little industrialization, infrastructure, or capital stock) will likely have near-zero levels of pollution. However, as these jurisdictions undergo a transformation that induces increased per-capita wealth, the initial barriers to polluting activities can be overcome, and emissions of many pollutants will likely increase very rapidly. Continuing with this theoretical framework, environmental quality will likely continue to decrease, driven by increasing per-capita wealth enabling pollutant emission as a negative externality of increased economic activity. In this scenario, degradation of the environment will worsen until rising wealth reaches a threshold level, at which point individuals are compelled to demand environmental quality. As wealth continues to increase, environmental quality will begin to improve, and theoretically, environmental quality will return to pre-industrial levels. This description of the theoretical trajectory of a jurisdiction's level of environmental degradation as it undergoes economic development is called the "Environmental Kuznets Curve," (EKC) named after Nobel Prize-winning economist Simon Kuznets. Figure 1.2 is the plot of the theoretical model of the EKC. (Kolstad, 2000)

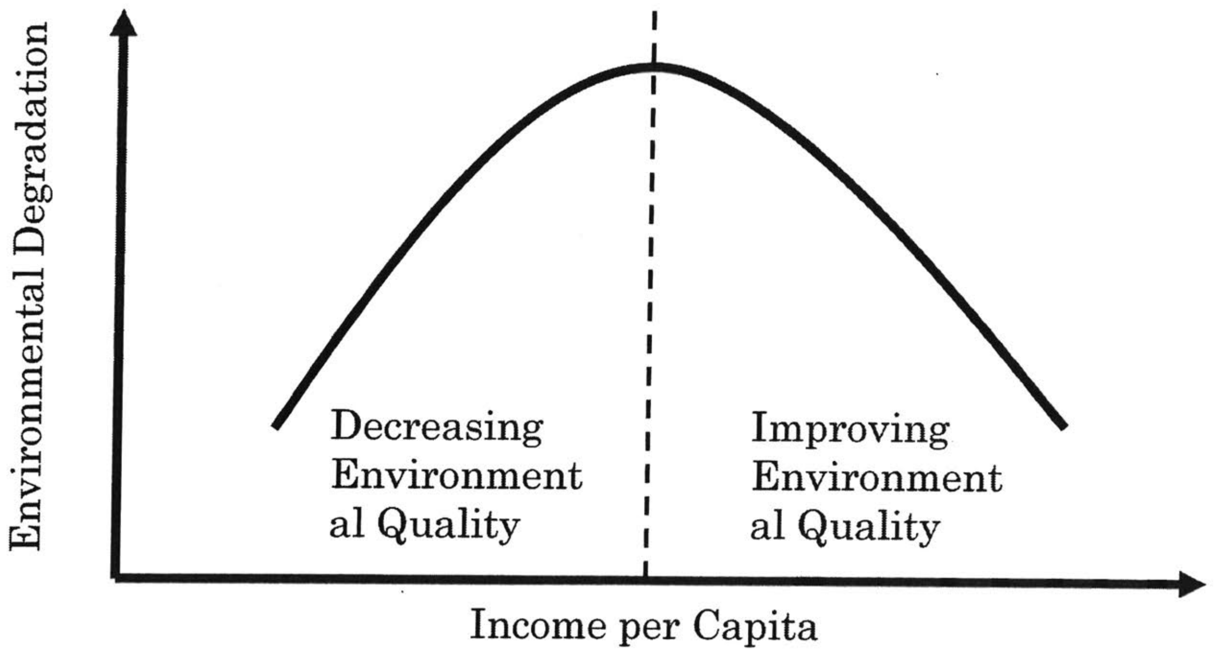


Figure 1.2: A stylized graph of the Environmental Kuznets Curve showing the hypothetical relationship between income per capita and environmental degradation

Although Kuznets developed the "Kuznets Curve" to understand the effect of wealth on economic inequality, the application of Kuznets's framework of analysis for investigating pollution has lived on in the field of environmental economics and remains one of the field's most provocative and important theories, despite a lack of convincing empirical evidence. The EKC theory offers a justification for environmental policy measures that significantly deviate from many current practices. It suggests that if a third-party intervener (such as the World Bank) wanted to improve the environmental quality of a poor, industrializing jurisdiction, instead of directly investing in improving the jurisdiction's environmental quality, the third-party could focus entirely on raising the per-capita wealth of the jurisdiction. Through the EKC relationship, the jurisdiction's environmental quality would improve endogenously with no additional intervention. (Kolstad, 2000)

If true, the conclusion that economic growth actually improves environmental quality would reconcile the perennial policy debate that pits economic concerns against environmental concerns. Many environmentalists maintain that the rapid economic growth of developing countries is a threat to the environment. However, the EKC posits that these growing developing countries will only degrade the environment while they are poor, and after they experience enough economic growth, they will return to their pre-industrial level of emissions. The Kuznets theory is attractive both for its clear logic and for its proposed conclusion that environmental problems can be endogenously solved by increasing wealth; however, the EKC still lacks conclusive comprehensive empirical evidence of the theory's conclusions across different types of pollutants. (See Section II for a review of the literature.) In fact, the EKC theory may apply differently to different types of environmental degradation depending on the characteristics of a pollutant. Specifically, the validity of the Kuznets theory rests on the assumption that wealthier entities will reduce emissions of a pollutant by demanding regulatory policy. However, it is also possible that jurisdictions that exhibit an apparent EKC relationship actually reduce their emissions as wealth increases for other reasons. For example, an economy could exhibit an apparent EKC development pattern through technological improvements in energy production or through shifting the focus of their economy towards more knowledge or service-based industries that don't produce pollution.

Since pollution can take so many different forms, the characteristics of the pollutant itself are significant factors that determine the nature of a policy response for reducing emissions. The characteristics of a pollutant regarding how it is produced and how it negatively affects the environment will likely heavily influence whether the EKC is a reasonable model of reality. Some of the characteristics of a pollutant that predict how it will be treated both economically and politically within a jurisdiction are:

- The effective lifespan of the pollutant as an environmentally harmful substance
- The distribution of the pollutant's damage across both time and space
- The damage caused by a pollutant at a location dependent on where it was emitted
- The type of damage the pollutant induces (e.g. illness, crop loss, climate change, etc.)
- The types of activities that produce the pollutant and the cost of avoiding emissions
- The feasibility of measuring and monitoring emissions at a point source of pollution
- The pollutant's visibility and odor detectable without special equipment

Carbon dioxide (CO_2), unlike many other types of pollution, is invisible, odorless, and almost entirely harmless to human health. Additionally, CO_2 is a stock pollutant, with an atmospheric lifetime on the order of decades to centuries. And even though global CO_2 levels are increasing at an increasing rate, the most significant impacts of current CO_2 emissions will be felt far into the future. Additionally, CO_2 molecules in the atmosphere mix thoroughly around the world in less than 2 weeks, so the location of

CO_2 emitters is irrelevant to the atmospheric concentration. The damage from CO_2 emissions is largely caused by rising temperatures, which will affect everyone on the planet by raising sea levels, reducing crop yields, and increasing the likelihood of severe storms, floods, and droughts. (IPCC, 2007) CO_2 is emitted through several industrial processes, but most importantly, the combustion of fossil fuels for energy production as oil in vehicles and as coal and natural gas in power plants, is driving expected environmental degradation.

1.3 The Emissions Leakage/Competitiveness Issue

When one region enacts environmental regulation to limit pollution, if that region is economically tied to another region (e.g. the two regions are trade partners), pollution levels may increase in the unregulated region; the increase in emissions in the unregulated region are leaked emissions. The emission leakage rate is the positive change in emissions in an unregulated region divided by the negative change in emissions (emission reductions) in a regulated region. Emission leakage occurs when environmental regulation is imperfect: when open economies are under different levels of environmental regulatory stringency. Imperfect environmental regulation can cause emission leakage through two mechanisms: firm relocation and changing factor prices.

1.3.1 Firm Relocation

Market-based environmental regulation to reduce pollution sets a marginal price on emissions. Therefore, to operate in a region with environmental regulation, firms face increased production costs. Therefore, if a firm can relatively easily relocate to another region, if the cost of relocation is less than the cost of complying with environmental regulation, the firm may choose to relocate to avoid regulation. Alternatively, if a multinational corporation with production capacity in many regions may choose to increase its production capacity in an unregulated region if some of its production capacity becomes subject to increased costs due to environmental regulation. Finally, firms that compete with one another that are located in different regions will gain new artificial competitive advantages under incomplete environmental regulation. Economically, these three mechanisms are equivalent for assessing emission leakage.

1.3.2 Changing Factor Prices

Incomplete environmental regulation can also induce emission leakage by changing the factor prices of production for some energy-intensive goods. Many factor inputs for production, such as primary metals, paper, glass, and petroleum products are traded on global markets. Many factor inputs have global prices. Under incomplete environmental regulation, the demand for many of these factor inputs will go down, as many major economies reduce their consumption of energy intensive goods. As the demand for energy intensive goods in these regions declines, the demand for many globally-traded factor inputs will decrease, putting negative pressure on the global price for these goods. Regions not subject to environmental regulation will only observe decreased factor input prices. All else equal, these regions will increase their production of energy-intensive goods because the cost of production has declined. Through this mechanism, global emissions can increase when only some regions impose environmental regulation.

Chapter 2

Literature Review

The problem that this thesis examines falls under the broad category of trade and the environment. Trade and the environment have been separate topics of extensive examination within the field of economics. However, the examination of trade's effect on the environment has been a relatively more recent undertaking.[1] Particularly, the relatively recent growth in transboundary pollutants and the spread of globalization have made the relationship between trade and the environment increasingly relevant for public policymaking.

The literature relevant to the policy to contain greenhouse gas emissions for international emission leakage predates this specific problem. Emission leakage is one particular case of the "race to the bottom" or "pollution haven" effect, terms used interchangeably in development economics that refer to the theoretical incentives for regions to decrease environmental regulations (or other types of regulations, such as wages) to attract foreign industry investment. (Kolstad, 2000) This review of the

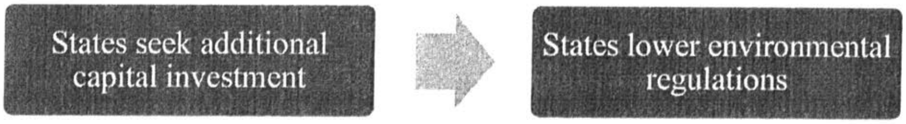
---

[1] Research Papers in Economics (RePEc), a collaboratively maintained database of economics research, identifies 1,083 articles on "trade" since January of 1998. Of the 1,083 articles on trade, RePEc identifies 206 as focused on "trade and the environment."

literature will begin with the race to the bottom theory, adding a level of specificity to describe the problem of greenhouse gas emission leakage from a theoretical economic perspective. Next, this review will examine how these theoretical models have been used in applied case studies to empirically quantify just how large greenhouse gas emission leakage can be. Next, this review will cover proposed policy solutions for greenhouse gas emission leakage before ending with an examination of the higher-order impacts of these proposed policies: the induced incentives for strategic behavior.

2.1 Trade Liberalization and the Environment

One of the essential questions in the body of literature that examines the effect of trade on the environment is, "Would we expect states to weaken their environmental regulations to attract capital and thus jobs?" (Kolstad, 2000, p. 245) This question hypothesizes that regions, usually poorer regions, will reduce their restrictions on environmental quality to reduce the costs of operation for polluting firms, essentially offering a subsidy for investment. Schematically, this hypothesis can be represented as:



A second framing question of this body of literature is, "Will countries with lax environmental regulations end up as 'black holes,' specializing in dirty industries?" (Kolstad, 2000, p. 245)

Combined, these two questions propose the full "race to the bottom hypothesis." In pursuit of capital investment, states lower their environmental regulations, which incentivize polluting firms to relocate to these states. The race to the bottom hypothesis is articulated by the Sierra Club (1999), the oldest and largest environmental grassroots organization in America, as the tendency for trade to "prompt countries to seek international advantage by weakening, not raising, environmental protections."

While the race to the bottom hypothesis has been well articulated in theoretical economic literature, whether or not the race to the bottom exists in reality is a matter of debate. In a briefing paper, the World Bank (2000), an international financial organization charged with relieving poverty in developing countries, claims that, "there is no evidence that the cost of environmental protection has ever been the determining factor in foreign investment decisions." Instead, the World Bank suggests that other factors, such as differences in the cost of labor or raw materials, outweigh the effect of lax environmental regulations in the incidence of foreign capital investment. Further, the World Bank claims that development actually has a positive effect on environmental regulation, instead of the negative relation that the race to the bottom hypothesis suggests. Their claim is supported by an empirical study by Dasgupta, Mody, Roy, and Wheeler (1995).

The World Bank study is concerned with the effect of globalization on environmental regulation, but for particular application to the race to the bottom theory, the specific effect of trade availability on environmental regulations is of more immediate concern. The effect of greater trade opportunities was examined by Antweiler, Copeland, and Taylor (1998), who find that with a theoretical model of international trade with specific application to sulfur-dioxide pollution, "free trade appears to be good for the environment." In a more recent study that seeks to correct several of the weaknesses in the literature, Quiroga, Sterner, and Persson (2007) offer moderate support for the race to the bottom theory in their findings of "some evidence in favor of the pollution-haven effect" in certain industries, but not others. Despite updated methodologies and datasets, Quiroga, et al.'s study does not offer conclusive support for the race to the bottom theory. Kolstad (2000), summarizes, "the general consensus of the empirical literature on pollution havens and the effect of environmental regulations on trade is that the effect is very weak at best."

2.2 Definitions of Emission Leakage

In the mid-1990s, the problem of global climate change reached a milestone with the adoption of the Kyoto Protocol in 1997. The Kyoto Protocol established binding emission targets for developed countries with provisions for emission trading and voluntary assistance for developed countries to reduce their emissions. (Holdren, 2003) Because of the international scope of Kyoto and its provisions for emissions trading (the ability for countries to trade the right to emit between each other for goods), the body of literature examining the effect of trade on the environment was applied rigorously to one environmental problem: global climate change. In the application of this body of literature, the hypothesis of "race to the bottom" was further specified into a case of the race: emission leakage.

Emission leakage is described by Jacoby, et al. (1996) as the phenomenon of "emissions reductions achieved by one set of countries ... partially counteracting increases elsewhere." (p. 3) In more detail, Jacoby, et al. state that "if one set of world regions constrains activities that produce CO_2, then adjustments caused by changes in relative prices and shifts in trade patterns may cause increases in carbon emissions elsewhere, which partially offset the gains achieved." (p. 11) In many ways, emission leakage is an example of the race to the bottom. First, like with the race to the bottom, emission leakage occurs because regions engaging in trade decrease the stringency of their environmental regulations to increase their welfare. Second, in both the race to the bottom and emission leakage, the incentive to degrade the environment is theoretically strong. Third, both theories are driven by firm-level incentives to relocate to regions with weaker environmental protection.

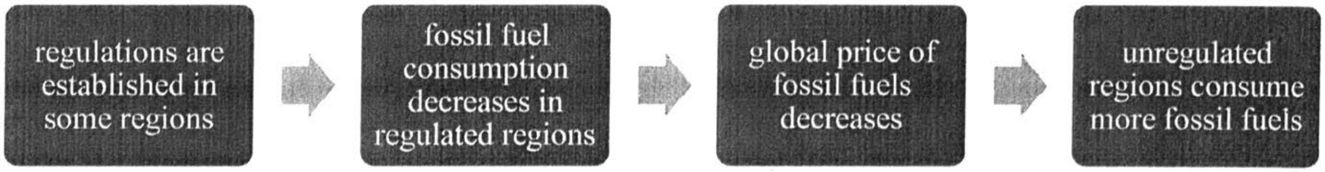
Jacoby, et al. (1997) discuss one of the essential implications of emission leakage beyond the loss of the leaked emissions. They state that once energy-intensive industries are incentivized to develop in non-regulating regions, these regions "will be more reluctant to take actions to curb the CO_2 emissions that have become a more important source of wealth." (p. 7) Therefore, unlike with the traditional cases of races to the bottom, emission leakage, especially as it pertains to greenhouse gases, may increase indefinitely, even as countries become richer. Additionally, the thorough examination of emission leakage may be more relevant for designing effective regional greenhouse gas regulations when political gridlock or ethical grounds prohibit regulation at a higher jurisdiction. (Fowlie, 2008)

In addition to the definition of emission leakage described above, a related, opposite effect relevant to this study is (technology) spillover. A spillover effect is opposite to the leakage effect in that instead of observing higher levels of environmental degradation than expected, in a spillover case, a higher than expected level of environmental quality is observed. The spillover effect is driven by firms adopting technologies that improve performance or efficiency. (Watson, Noble, Bolin, Ravindranath, Verardo, & Dokken, 2007) Emission leakage and spillover effects work in opposite directions, but for clarity, for the remainder of this prospectus I will follow Jacoby, et al.'s definition of leakage: the total increase in emissions in non-regulated regions as a result of a policy change expressed as a percentage of emission reductions in regulated regions due to a policy change. (1996) A spillover effect will reduce the leakage rate, and if the leakage rate is negative, spillover dominates.

2.3 Theoretical Economic Models

In order to gain a thorough understanding of the driving mechanisms in emission leakage, economics and policy analysts have developed formal economic models of emission leakage. These models use traditional microeconomic theory to explain how the incentives for emission leakage are created from global greenhouse gas policy that applies an unequal level of regulation to different regions. These models typically begin from a very broad base of assumptions to capture a more general set of cases. For example, Fowlie examines "incompletely regulated and imperfectly competitive industries" before applying theory to greenhouse gas regulation in California's electricity sector. (2008) From a very general set of initial assumptions, Fowlie finds that as competition increases in an industry, emission leakage rates also increase. However, as competition decreases (towards an oligopoly), the theoretical emission rate declines. (Fowlie, 2008)

In another highly theoretical framework, Ishikawa and Okubo (2008) investigate incentives for firms to relocate, causing emission leakage, under alternative greenhouse gas regulatory mechanisms. In their analysis, Ishikawa and Okubo find that carbon leakage may occur through an additional mechanism besides the one proposed by the race to the bottom hypothesis. They posit that leakage can occur when, under GHG regulation, regulated countries consume less fossil fuel, driving down the price of fossil fuels, making them cheaper for unregulated regions, allowing unregulated regions to consume more fossil fuels. (Ishikawa & Okubo, 2008) This mechanism is illustrated below:



A third mechanism for emission leakage proposed by Watson, et al. (1996) suggests that climate policy may reduce the incomes in countries that adopt regulation. This would induce a reduction in imports, lowering the relative emissions of the regulated region relative to the unregulated region. This mechanism will not be of high significance for this thesis.

As another note, whether or not causality is an important factor in the definition of emission leakage is a point of debate in the literature. Sijm, et al. (2004) states that the "causality condition makes direct measurement of carbon leakage rather difficult." (p. 13) Sijm, et al. emphasize that emission leakage can occur through several different mechanisms, but that changes in greenhouse gas emissions in unregulated regions either are a result of leakage or are not, and that this distinction is important. On the other hand, Cowart (2006), speaking specifically about the Regional Greenhouse Gas Initiative in New England, states that "motivation and causation [of emission leakage] are irrelevant." (p. 4) Cowart continues, "It doesn't matter *why* leakage happens, only *if* it happens." He warns that dwelling on causality is neither in the spirit of a total cap on emissions nor a productive use of time to advance greenhouse gas regulation.

While the theoretical economic modeling work by Fowlie and Ishikawa and Okubo provide insight into the firm-level decision making incentives, they provide weak estimates of the total global emission leakage rate expected under realistic policy assumptions. Global equilibrium modeling, on the other hand, does provide useful estimates of total leakage rates. It is also important to note that equilibrium modeling is not particularly useful for understanding the firm-level decision making incentives that policy induce. Since equilibrium modeling is much more parameter dependent than theoretical models, these models are best used in an applied case study than in theory-building.

2.4 Applied Theory - Regional/Industry Case Studies

The application of global equilibrium models to analyze the Kyoto Protocol has garnered a wide range of estimates, muddling the picture for policymakers. As the policy instrument for international greenhouse gas regulation, insights from an analysis of the Kyoto Protocol will likely be very useful for designing the policy heir to Kyoto after it expires in 2012. (Holdren, 2003) Global equilibrium models of the international economy are useful tools of analysis for emission leakage under the Kyoto Protocol because they capture the inter-economy trade and consumption patterns for the main types of economies in the world.

In one of the first studies of emission leakage under Kyoto using a global equilibrium model, Paltsev (2001) estimates that 10.5% (with an error of about 5%) of emissions will be leaked under the Kyoto Protocol, a significant, but not overwhelming figure. By industry, Paltsev finds the highest emission leakage rates for chemicals and iron/steel, which reach 20% leakage. By region, Paltsev finds the highest emission leakage rates in the European Union, which reach 40%. At 40%, emission leakage is a potentially compromising result of international climate policy. In a similar analysis, Kuik and Gerlagh (2003) calculate that the Kyoto Protocol will induce a 6-17% emission leakage rate. Further, Kuik and Gerlagh specify that the mechanism at play in their model is the decreased fuel price mechanism also proposed by Ishikawa and Okubo, not the race to the bottom theory. However, this may be an artifact of the modeling tool used for analysis, rather than an accurate economic reality. (Babiker, 2004)

One of the weaknesses of the equilibrium modeling framework is its inability to capture the rate at which firms will choose to relocate to another region. Due to complex non-economic factors (such as political pressure), firms may or may not choose to relocate to an unregulated region. Babiker (2004) adopts a computable general equilibrium framework to examine emission leakage while testing the sensitivity of the leakage rate to parameters of market structure. Babiker finds that depending on his assumptions of market structure, global emission leakage rates vary between 25% and nearly 130% under the Kyoto Protocol. On the low end, the emission leakage rate is kept relatively low because Babiker assumes that firms face an increasing returns to scale production method, making production of goods which already are producing large quantities of good even cheaper. This effect deters firm relocation and hence emission leakage rates are low. However, when firms face constant returns to scale, Babiker finds that the net effect of the Kyoto Protocol is the opposite of its intention: greenhouse gas emissions increase. (Babiker, 2004) Interestingly, even Babiker's lowest emission leakage rate is far higher than the leakage rates by Paltsev or Kuik and Gerlagh. While global equilibrium models are useful tools for examining the aggregate outcomes of climate policy, in this case, "real world conditions ... make these outcomes unlikely." (Barker, et al., 2007, p. 666)

In addition to the Kyoto Protocol, applied macroeconomics and microeconomics have been used at a more local level to examine emission leakage in smaller jurisdictional implementation of greenhouse gas regulations. The three jurisdictions which have received the most considerable attention for analysts are: 1) Europe under the European Trading System (ETS), 2) New England states under the Regional Greenhouse Gas Initiative (RGGI), and California electric utilities.

Studies on the effect of emission leakage on the ETS are still in the infant stages. Currently a working.group has been established to investigate leakage further. Their approach is industrially-based. Hopefully, results from these studies will be published soon. (Emission Trading Scheme, 2008)

The Regional Greenhouse Gas Initiative (RGGI) is a policy proposal to establish a cap and trade system of greenhouse gas regulation for electric power plants in New England. In analysis of emission leakage in RGGI, a key point of concern regards the transboundary supply of electricity from unregulated coal-fired power plants in Pennsylvania into the regulated RGGI region. Policymakers in the New England states fear that by implementing RGGI, they are indirectly offering a subsidy to out-of-state coal power plants. Farnsworth, et al. (2007) and Cowart (2006) offer detailed analyses of the potential for emission leakage under RGGI and possible policy solutions to reduce leakage.

California Governor, Schwarzenegger has proposed a cap and trade system of its electric power sector. However, similarly to the RGGI proposal, a cap and trade in California may also drive a leakage effect due to electricity imports from neighboring southwest states. Fowlie (2008) and the Center for Clean Air Policy (2005) analyze the problem of leakage in California and offer policy recommendations. They note that the problem of leakage in California is particularly complex due to the high proportion of electricity imports that occur currently, even without greenhouse gas regulation. Therefore, identifying causality for electricity imports, if it is relevant, becomes more complex.

In addition to region-specific studies, analysts have also examined specific industries to estimate emission leakage. In a study of heavier crude source of petroleum liquid fuels, Reilly, et al. (2007), find that for refinery emissions, leakage is approximately

10% of the reduced emissions. However, for bitumen, leakage rates reach over 80%. This can largely be attributed to the unequal natural resource endowment of bitumen. Because bitumen is in the ground in Canada, bitumen production necessarily occurs in Canada.

2.5 Proposed Policy Solutions

There are two types of policy remedies for emission leakage: border tax adjustments and integrated emissions trading. (Alexeeva-Talebi, Loschel, & Mennel, 2008) Both mechanisms integrate imported products into domestic policy schemes, raising the price of imports proportional to the quantity of greenhouse gases emitted in their production. In effect, by raising the price of imports according to the emissions in production, these policies shift greenhouse gas regulation from the regulation of production or emissions to the regulation of consumption of products that generate emissions. (The differences between these two policies are highly analogous to the differences between cap and trade and a carbon tax.)

In a border tax adjustment policy, the government imposes a tariff on imports of carbon-intensive goods into the domestic economy. (Watson, Zinyowera, & Moss, 1996) This tariff would scale proportionally with the quantity of greenhouse gases emitted in the production of the imported good and should follow the market price of emissions in the domestic economy for maximum efficiency. Integrated emission trading, compared to a border tax adjustment, is a regulation of quantity, not price. In integrated emission trading, importing firms are required to acquire emission permits for their imports, just as power plant operators are required to acquire emission permits for their combustion of fossil fuels. (Alexeeva-Talebi, Loschel, & Mennel, 2008)

In both systems of emission leakage mitigation, Watson, et al. (1996) identifies several practical problems that stand in the way of implementation. First, there is a high accounting challenge to tabulate and sum the total emissions associated with the manufacture of a particular product. Especially because the fuel-mix and production methods vary so greatly between regions, the more accurate an estimate of emissions in production can be, the more fair and efficient policy can be. Second, the implementation of either of these policies may violate existing trade laws. Third, coordinated implementation of these laws would be extremely difficult politically; however, unless policy is implemented in unison, further comparative advantages will be induced, and leakage will occur between regulating regions.

2.6 Strategic Behavior – Firms, Governments, and Voters

When emission leakage occurs in a regulating economy, the individual actors are faced with new incentive schemes that can force them to act strategically. Strategic acting can broadly be defined as taking a conscious action without apparent immediate gain with the intention of making future gains. Specifically, the "individual actors" and their opportunities to act strategically relevant for decision-making are 1) firms who can choose to relocate, 2) governments who can choose whether or not in increase environmental regulation or leakage-specific policy, and 3) voters who can elect representatives and vote for or against greater environmental protection.

In an analysis of a variety of policy scenarios, Ulph (1996) finds that "the impact of environmental policy on strategic behavior can be large." Whether or not a firm chooses to relocate from a regulated region to an unregulated region depends on the industry's mobility. An industry's ability to cross national borders is captured in the Armington elasticity, which is defined as the "elasticity of substitution among imports and competing domestic production." (Welsch, 2007) Together, the Armington elasticity for an industry and the specific new incentives created by greenhouse gas policy and/or emission leakage policy will factor into whether or not firms choose to relocate to unregulated regions. While the empirical evidence to support firms choosing to relocate to regions with weaker environmental regulations is weak (Kolstad, 2000), proposed climate change legislation could potentially induce the largest disparities in environmental regulations between regulated and unregulated regions ever seen.

Governments at the national level may take strategic regulatory action to gain political capital in the international arena to use for an unrelated issue. Proving how such a decision would be made would be quite difficult. While other incentives for governments to act strategically are easy to identify, incorporating these incentives into formal analysis is likely to be a fruitless process.

In the context of international environmental policymaking between democracies, when voters have the opportunity to elect officials to design environmental policy, they may face incentives to act strategically. Hattori (2007) finds that in a constructed political-economy model, voters face "an incentive to deliberately vote for a candidate whose environmental preferences differ from their own." Further, Hattori finds that the regulatory tool that the government chooses highly influences how voters decide which politician to support. While Hattori's results are interesting and generalizable (the model he creates is heavily theoretical), it would be reaffirming to examine an empirical examination of Hattori's hypothesis.

Chapter 3

A Microeconomic Analysis of the Steel Industry

This chapter introduces a model of the United States steel industry which represents domestic and foreign producers as Cournot duopolists who meet the demand in the U.S. market. First a general Cournot model of duopolistic producers of a single emission-intensive good is introduced. The model is then applied to analyze the impact of regulating the emissions of one firm on the leakage of emissions through the unregulated firm. Next, the model is adapted to the steel industry using historical production, consumption, import, and export data. Finally, a large-N Monte Carlo simulation is used to account for uncertainty in the U.S. demand function for steel, domestic steel production costs, foreign steel production costs, and steel production CO_2 emission intensity. The central finding of this simulation is that leakage from CO_2 regulation in the U.S. is met with a 39% leakage rate and that the distribution of likely levels of leaked emissions from the steel industry is strongly right-skewed, indicating a greater-than-normal probability of a high level of leaked emissions.

3.1 The Model

In this section I develop a partial equilibrium one-stage Cournot model of price-taking duopolists producing a single good. The model that I develop is very simple by design to highlight the general principles and outcomes of the problem at hand. This work extends upon Fowlie (2009) who applied a similar model to the California electricity sector. The key feature of the model is that I assume the economy contains exactly two producers of a single good who are both equally aware of their interdependence and who change their production behavior based on a single market demand expectation.

3.1.1 Assumptions of the Firms

In this model, I make several simplifying assumptions regarding the two producing firms. First, I assume that both firms operate at a constant marginal cost of production (which mathematically equals the average cost of production). The production function for firm i with cost of production $C_i(q_i)$, can be written as:

$$C_i(q_i) = \frac{dC_i}{dq_i} q_i \equiv c_i q_i \tag{3.1}$$

where q_i is the quantity produced and c_i is the (constant) marginal cost of production for firm i. Profit for firm i is simply revenue net of cost. The profit function, π_i, for firm i can be written as:

$$\pi_i = P q_i - c_i q_i \tag{3.2}$$

where P is the market price of the good produced by the firm.

Second, I assume that the two firms are the only two firms producing an identical good. Therefore, the goods produced at each firm are perfect substitutes. Further, I assume that no other goods in the economy can substitute for the good produced at the two firms (i.e. there is no market integration) Third, I assume that both firms are profit-maximizing and that they maximize profits by setting their production level (i.e. quantity produced) given the market price of the good and the quantity produced by the other firm. In this sense, the firms can be thought of as strategic actors operating in a game in which the objective is to maximize profits. (Viscusi, Harrington Jr., & Vernon, 2005)

Finally, I assume that each firm pollutes at a constant rate, proportional to its output level. Therefore, the emission level, $E_i(q_i)$ at firm i can be written as:

$$E_i(q_i) = e_i q_i \tag{3.3}$$

where e_i is the emission rate of firm i. Additionally, a firm may or may not have its emissions regulated either by an emission tax or an emission permit system (e.g. cap-and-trade). For the purposes of this analysis, I model both regulatory schemes identically, implicitly assuming that if an emission permit system is implemented that firms do not possess market power to change the emission permit price. Therefore, under both an emission tax system and an emission permit system, firms must pay for each unit of their emissions at a single price which can be defined as either the emission tax level or the emission permit price. The total cost of compliance, ψ_i, for firm i can be written as:

$$\psi_i = r_i \tau\big(E_i(q_i)\big) \tag{3.4}$$

where r_i is a binary variable equal to 1 if firm i is regulated and equal to 0 otherwise, and τ is either the unit emission tax level or the unit emission permit price. Now, accounting for emission regulation, the profit function in Equation 3.2 can be rewritten as:

$$\pi_i = Pq_i - c_i q_i - \psi_i \tag{3.5}$$

Substituting Equations 3.3 and 3.4 into Equation 3.5 yields:

$$\pi_i = Pq_i - c_i q_i - r_i \tau(e_i q_i) \tag{3.6}$$

The next section describes how these two firms behave as duopolists in a closed economy given a single demand function.

3.1.2 Assumptions of the Economy

In the model of the economy, I assume that demand for the good being studied is a linear function of the price of the good. This assumption ignores income effects on demand, an assumption realistic for short-run analysis. Because the goods produced at both firms are perfect substitutes, the quantity demanded by consumers is independent of the relative production by each firm. The demand function can be written as:

$$P = a - b\sum_{i=1}^{2} q_i \tag{3.7}$$

where a and b are constants and firms are indexed by $i = 1, 2$. Because this is a partial-equilibrium model, prices are set by demand and not by the firms. Instead of setting prices, firms set their level of production, q_i, to maximize profits.

I make an additional assumption that firms set their production level simultaneously with perfect knowledge of the production level of the other firm. This is a simplifying assumption which could be relaxed without qualitative changes in the final equilibrium solution.[1] With these assumptions, the profit function for firm $i = 1$ from Equation 3.6 can be combined with Equation 3.7 and rewritten as:

$$\pi_1 = \left(a - b\sum_{j=1}^{2} q_j\right) q_1 - c_1 q_1 - r_1 \tau(e_1 q_1) \tag{3.8}$$

$$\pi_1 = [a - b(q_1 + q_2)]q_1 - c_1 q_1 - r_1 \tau(e_1 q_1) \tag{3.9}$$

Similarly, the profit function for firm $i = 2$ can be written as:

$$\pi_2 = [a - b(q_1 + q_2)]q_2 - c_2 q_2 - r_2 \tau(e_2 q_2) \tag{3.10}$$

Equations 3.9 and 3.10 reveal the duopolistic interdependence of the two firms. The profit of firm 1 is a function of its own production and the production of firm 2. More explicitly, holding firm 1's production constant, increasing firm 2's production decreases firm 1's profits (by decreasing the market price of the good). By symmetry, the same

---

[1] Fowlie (2009) models a two-stage model with other assumptions similar to this study and finds that the economy becomes more competitive when firms sequentially set production levels. In the two-stage model, Fowlie finds that emission leakage increases.

can be said for firm 2's profits. This setup provides the foundation of the Cournot model.

The next step in this formulation is to determine how the two firms behave. I make the assumption that the firm's maximize their own individual profits taking into account the quantity that the other firms produce. To derive the profit maximization functions for each firm, I set marginal profit for each firm to zero using the first-order condition. For firm 1, marginal profit can be found by taking the derivative of π_1 (Equation 3.9) with respect to q_1, which can be written as:

$$\frac{\partial \pi_1}{\partial q_1} = a - 2bq_1 - bq_2 - c_1 - r_1 \tau e_1 \tag{3.11}$$

Applying the first-order condition by setting Equation 3.11 equal to 0, the level of output, q_1, that maximizes profits can be written as:

$$q_1 = \frac{a - bq_2 - c_1 - r_1 \tau e_1}{2b}$$

$$q_1 = -\frac{1}{2} q_2 + \frac{a - c_1 - r_1 \tau e_1}{2b} \tag{3.12}$$

By symmetry, the level of output which maximizes profits for firm 2 can be written as:

$$q_2 = -\frac{1}{2} q_1 + \frac{a - c_2 - r_2 \tau e_2}{2b} \tag{3.13}$$

Equations 3.12 and 3.13 are known as the "best reply functions" for firm 1 and 2, respectively because they give the profit-maximizing behavior for each firm in "reply" to the behavior of the other firm. If both firms follow their best reply functions, the equilibrium level of outputs will be a Nash equilibrium.[2] (Viscusi, Harrington Jr., & Vernon, 2005)

In the next section, the two best reply functions are used to determine the Nash equilibrium level of outputs under the assumption that the two firms do not collude.

3.1.3 Model Formulation

A Nash equilibrium will be defined in the economy when both firms follow their best reply functions. Given the assumptions that I have made regarding the behavior of the firms and the nature of the economy, there will be a unique equilibrium level of q_1 and q_2 that will define the Nash equilibrium. As can be seen from Equations 3.12 and 3.13, output of firm 1, given by its best reply function, is a decreasing function of firm 2's output, and output of firm 2, given by its best reply function, is a decreasing function of firm 1's output. The two firms' best reply functions can be plotted on q_1, q_2 space:

---

[2] The assumption of a Nash equilibrium is a common assumption in game theory literature. A Nash equilibrium is defined as "a set of strategies or actions in which each firm does the best it can given its competitors' actions." For more information, see Pindyck and Rubinfeld (2001).

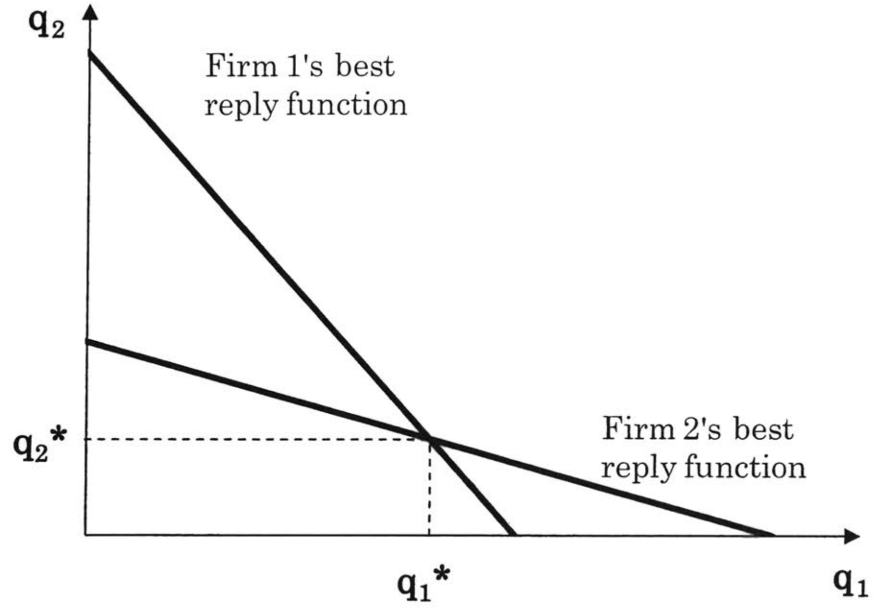


Figure 3.1: A plot of the best reply functions of the two firms. The Nash equilibrium level of output resides at the intersection of the two best reply functions and is marked by levels of output q_1^* and q_2^*. Adopted from Viscusi et al. (2005).

Given a and b, the parameters of the demand function, c_1 and c_2, the production costs of the two firms, e_1 and e_2 the emission intensity of production of the two firms, and r_1, r_2, and τ, the scope and stringency of emission regulation, the equilibrium output levels of each firm and the equilibrium price of the good can be determined.

In the next section, I will examine how the equilibrium level of output for each firm changes with r_1, r_2, and τ, with particular focus on the case where $r_1 \neq r_2$, the case of incomplete environmental regulation.

3.2 The Effect of Emission Regulation and Leakage

In this section I will use the Cournot model of duopolist producers developed in the previous section to analyze the sensitivities of the model for varying scope and stringency of emission regulation. Equation 3.11 reveals that if a firm falls under the jurisdiction of emission regulation, the firm's marginal profits will decrease by the product of the marginal emission rate and the marginal price of emitting one unit of pollution. Applying this observation to Equations 3.12 and 3.13 reveals that if regulated, the best reply function for a firm shifts downward. The plot of best reply functions in Figure 3.1 can be redrawn for regulated polluting firms and unregulated firms:

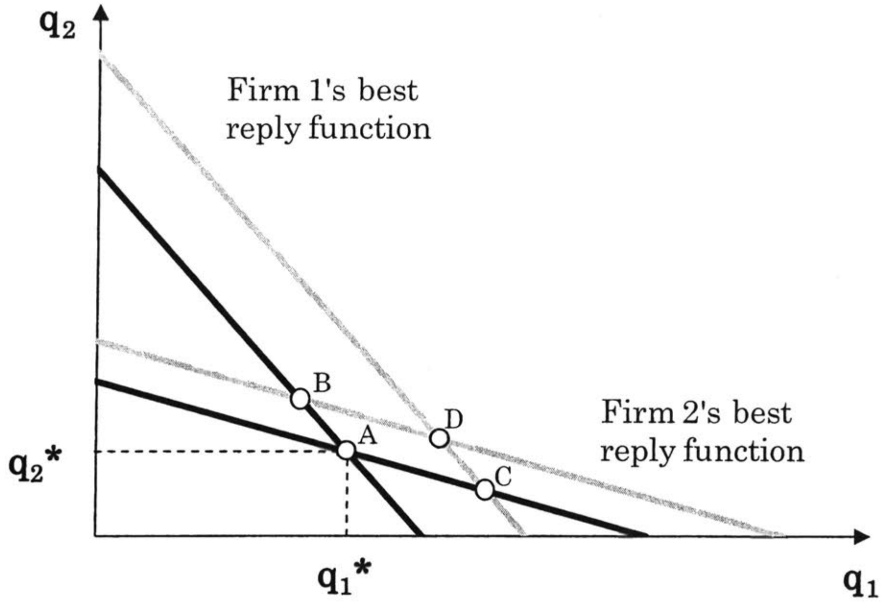


Figure 3.2: A plot of the best reply functions for Cournot duopolists under emission regulation (solid black lines) and without emission regulation (solid grey lines). The new Nash equilibrium level of outputs for $r_1 = r_2 = 1$ is given by point A for q_1^* and q_2^*. Points B and C give the Nash equilibrium levels of output for $r_1 \neq r_2$ and point D gives the Nash equilibrium for $r_1 = r_2 = 0$. Adopted from Fowlie (2009).

3.2.1 Incomplete Regulation and Emission Leakage

When both duopolists are regulated or when both duopolists are unregulated, no emission leakage occurs; either all emissions fall under the jurisdiction of regulation or no emissions do. Therefore, emission leakage will only occur when one duopolist is regulated and one is not ($r_1 \neq r_2$). Thus far, the two duopolist firms only differ in their marginal cost of production, marginal emission intensity of production, and status of regulation. Therefore, the model can be simplified for studying emission leakage by assigning $r_1 = 1$ and $r_2 = 0$. Assuming both firms have positive marginal emission intensities of production, the best reply function for firm 1 will shift downward (this can be seen from Equation 3.12). The new Nash equilibrium will be at point B on Figure 3.2. This case demonstrates that if emission regulations are imposed on firm 1, the equilibrium level of production for firm 1 will decrease and the equilibrium level of production for firm 2 will increase. In effect, regulating emissions from firm 1 gives firm 2 an artificial relative comparative advantage.

The emission leakage rate is defined as the total increase in emissions from unregulated emissions divided by the decrease in emissions in regulated regions. In this model, emission leakage as $[r_1, r_2] = [0,0] \rightarrow [1,0]$ is calculated as:

$$L = -\frac{\Delta E_2(q_2)}{\Delta E_1(q_1)} \tag{3.14}$$

where L is the emission leakage rate. Substituting Equation 3.3 into 3.14 yields:

$$L = -\frac{e_2}{e_1}\left(\frac{\Delta q_2}{\Delta q_1}\right)$$

$$L = -\frac{e_2}{e_1}\left[\frac{q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} - q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix}}{q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} - q_1\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix}}\right] \tag{3.15}$$

Substituting Equations 3.12 and 3.13 into 3.15 with the appropriate values of r_i yields the leakage rate. The calculation is shown in Appendix A and the final result can be written as:

$$L = \frac{e_2}{2e_1} \tag{3.16}$$

This result implies that the leakage rate is only a function of the emission intensities for the two firms.

3.3 Calibrating the Model to the Steel Industry

Globally, the steel industry is responsible for approximately 6 to 7% of total anthropogenic CO_2 emissions, amounting to over 1500 Mt. (IPCC, 2007) In the U.S., 21% of CO_2 emissions not from fossil fuel combustion can be attributed to the iron and steel sector. (U.S. Environmental Protection Agency, 2009) Including fossil fuel combustion emissions, the U.S. iron and steel sector is responsible for approximately 2.5% of total CO_2 emissions. (U.S. Energy Information Administration, 2005) As one of the most energy-intensive sectors of the economy, under climate policy, the steel industry is susceptible to loss of competitiveness and emission leakage concerns. (James, 2009) This section adopts the model described in Sections 3.1 and 3.2 to the U.S. steel market to analyze the emission leakage potential under proposed climate policy legislation.

The model developed in this chapter can be aptly applied for analyzing the steel industry because of the many key characteristics the model and the steel industry share. First, the market for steel is characterized by a highly-unionized labor force, which causes firms to behave as partial oligopolistic producers. (Harris, 1994) Second, competition in the steel industry is likely imperfect because domestic producers and international producers of steel can be reasonably modeled as within-group colluders and across-group competitors. This assumption allows domestic producers and international producers to be represented as competitive duopolists in quantity production. (Harris, 1994) Third, the U.S. demand for steel is relatively inelastic, which makes the inverse linear demand function described by Equation 3.7 appropriate. (Crandall, 1981) Fourth, domestically-produced steel and imported steel are traded in the U.S. market at a common price. (Fenton, 2009)

To calibrate the model of Cournot duopolists operating under environmental regulation developed in sections 3.1 and 3.2, several parameters must be calibrated to the steel industry. This process attempts to solve for the unknown parameters of the model such that the actual observations of the steel industry (which are assumed to be endogenous) result as the predicted equilibrium outputs of the model. (Venables, 1994) The exogenous variables of the Cournot duopolist model that are solved for in this section are:

- The U.S. price elasticity of demand for steel (which reveals total demand)
- The production costs of domestic and international steel producers
- The CO_2 emission intensity of domestic and international steel producers
- The stringency of CO_2 regulation for domestic and international firms

The Cournot duopoly model is calibrated for the steel industry, assuming long-run equilibrium, with data collected by the U.S. Bureau of Labor Statistics, the U.S.

Geological Survey, the Intergovernmental Panel on Climate Change, and Lawrence Berkeley National Laboratory.

3.3.1 Modeling the U.S. Demand for Steel

The functional form of the U.S. demand function for steel is given by Equation 3.7, which relates the market price for a good and the resulting demand for the good. On the surface, it appears that in order to calibrate Equation 3.7 for the U.S. demand for steel, two independent parameters should be solved for, namely a and b. However, given that the model's demand function for steel will be determined by the historical price and demand of steel, there is no basis to assume that parameters a and b are independent. Instead, the relationship between the historical price and demand for steel should be used to approximate the sensitivity of demand to price changes.

To model the U.S. demand for steel, I adopt a two-stage parameterization of inverse linear demand (Equation 3.7). First, I use historical prices and consumption of steel to determine the price elasticity of demand for steel. This step directly measures changing preferences for steel given price changes with the distinct advantage of avoiding the specification of a functional form of the demand function. Second, I calibrate the inverse linear demand function, assuming constant price elasticity of demand, to historical steel prices in the functional form specified in Equation 3.7. Combining these steps yields an estimate for the parameters a and b in Equation 3.7.

3.3.1.1. The U.S. Price Elasticity of Demand for Steel

The price elasticity of demand for a good is the percent decrease in the demand for a good when the price of the good increases by one percent. The price elasticity of demand is a measure of how much consumer preferences for a good will respond to changes in the price of the good. (Pindyck & Rubinfeld, 2001) The price elasticity of demand can be written as:

$$E_d = \frac{\%\ change\ in\ Q}{\%\ change\ in\ P} \tag{3.17}$$

where E_d is the price elasticity of demand, Q is the quantity demanded, and P is the price of the good. Equation 3.17 can be rewritten in differentials as:

$$E_d = \frac{P}{Q}\frac{dQ}{dP} \tag{3.18}$$

Equation 3.18 implies that if the price elasticity of demand is known, then for observable levels of price and quantity, the slope of the demand function (in the case of Equation 3.7, b) can be determined.[3] Equation 3.18 can be rewritten using calculus identities as:

$$E_d = \frac{d \ln Q}{d \ln P} \tag{3.19}$$

I use historical levels of U.S. steel consumption and U.S. steel prices to estimate the price elasticity of demand. Steel consumption data is published in the Minerals Yearbook by the U.S. Geological Survey and relative steel prices are published in the Producer Price Index program by the U.S. Bureau of Labor Statistics. Relative prices

---

[3] This assumes that the supply function stays constant.

are converted to nominal prices using nominal price estimates from the U.S. Geological Survey Minerals Yearbook for 1982[4]. With an extensive history of steel industry data, it is unclear what backwards horizon is appropriate for modeling current demand behavior. To choose an appropriate backwards horizon, I calculate the historical U.S. trade gap in steel production (U.S. steel exports minus U.S. steel imports)[5] Figure 3.3 plots the U.S. steel production and consumption levels and the U.S. steel trade gap from 1900 – 2008.

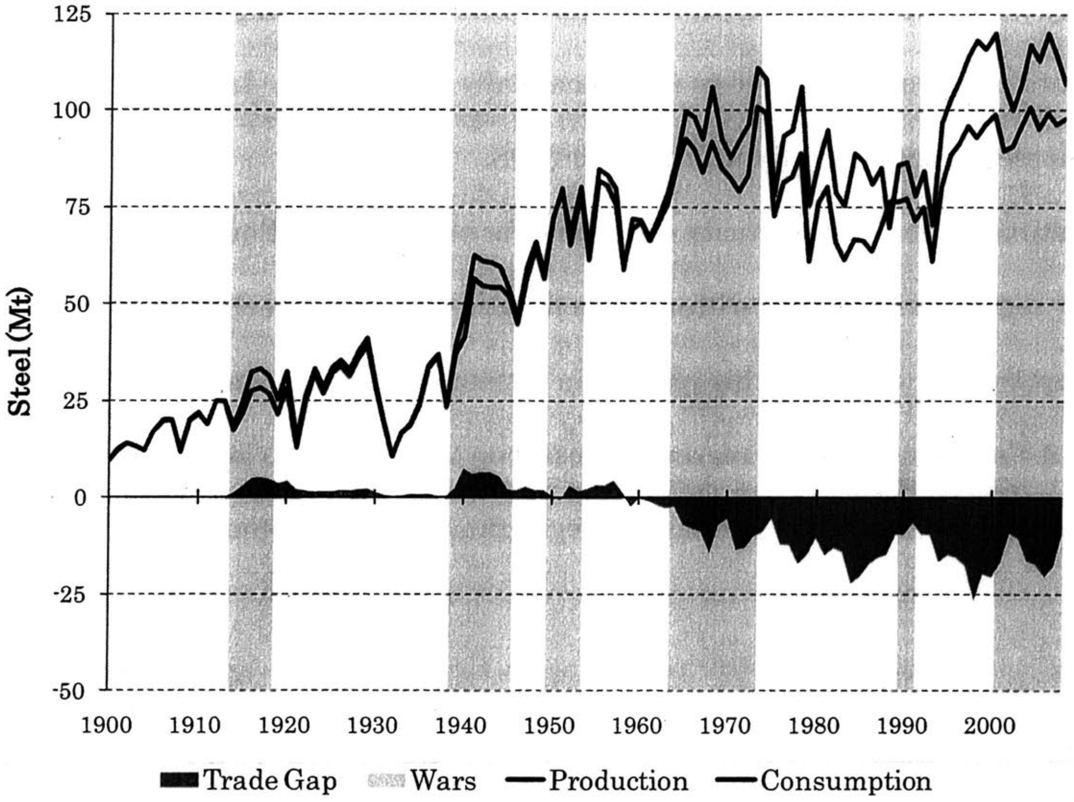


Figure 3.3: A plot of the historic steel production and consumption in the U.S. for 1900-2008. The U.S. trade gap in steel is shown as an area plot. The years in which the U.S. was engaged in a major war are shaded in grey.

---

[4] 1982 is used as the base year in the Producer Price Index; all prices are expressed relative to the 1982 nominal price of steel. Nominal prices for all years are calculated by multiplying the nominal price of steel in 1982 by the relative prices given by the Producer Price Index.

[5] The trade gap in steel is not simply the difference between yearly production and yearly consumption because steel is stored between years.

Figure 3.3 shows that the U.S. has been a net importer of steel since 1960. Additionally, the inclusion of the grey bars indicating U.S. involvement in major wars helps qualitatively explain major shifts in steel production and consumption dynamics. Because the U.S. steel trade balance has remained negative since 1960, choosing to expand the backwards horizon of this analysis to any point since 1960 could be reasonably justified. However, there is a fundamental tradeoff in expanding the backwards horizon: expanding too far back in time includes years when the U.S. economy was more different from its current state, but expanding further back includes more data points and is therefore mathematically more robust. In light of this trade-off, I choose to confine my dataset to 1980-2008.

To estimate the price elasticity of demand for steel, I apply Equation 3.19 to conduct a linear regression of the logarithm of the inflation-adjusted steel price on steel consumption.[6] The slope of this regression estimates the price elasticity of demand. Figure 3.4 superimposes the regression result on the plot of the logarithm of the inflation-adjusted steel price versus the logarithm of steel consumption.

---

[6] Because historical nominal prices are available, I adjusted the nominal prices by the rate of inflation using the Consumer Price Index so that real prices could be compared.

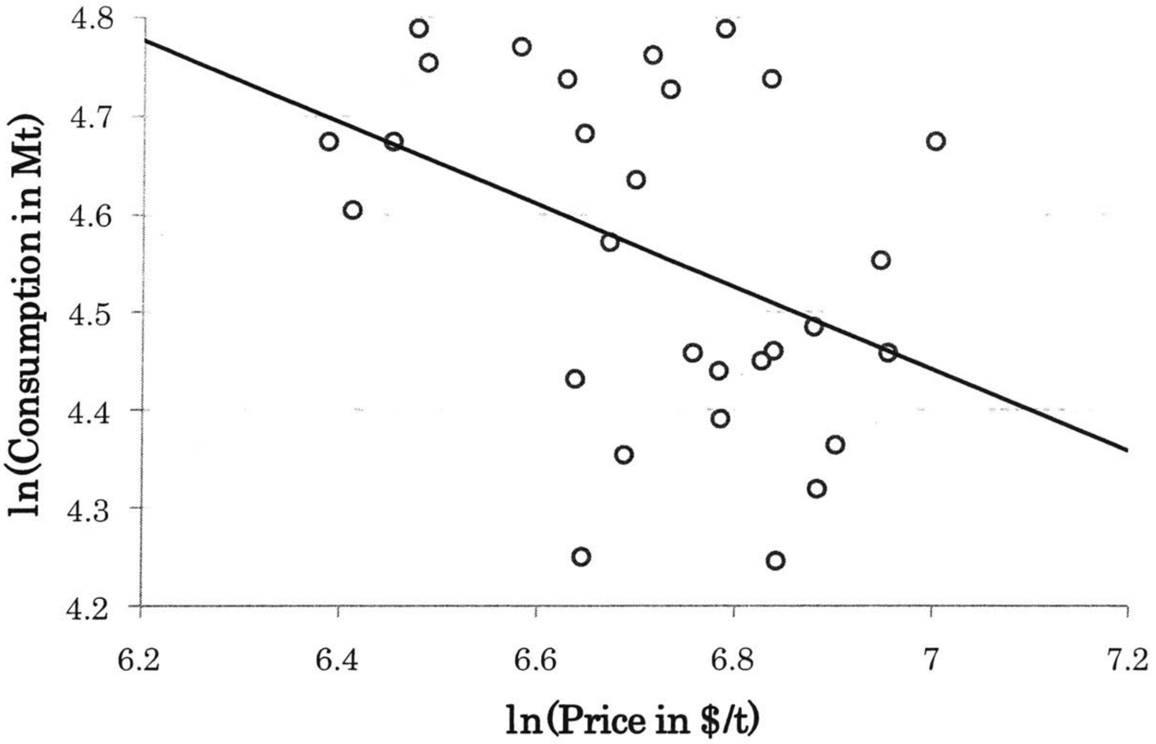


Figure 3.4: A plot of the natural logarithm of steel consumption against the natural logarithm of steel consumption in the U.S. for 1980-2000. The ordinary least squares regression line of the relationship between the two variables is superimposed. The slope of the regression line estimates the price elasticity of demand for steel.

The regression yields a slope of -0.417 with a standard error of 0.179 and a statistically-significant p-value, 0.028. This result provides the requisite information to estimate the price elasticity of demand.

Other estimates in the literature of the steel industry find a negative elasticity less than 1, qualitatively congruent with my finding. (Crandall R. , 1981; Ho, Morgenstern, & Shih, 2008) Harris (1994), surveying the literature, claims that "price elasticities for steel are notoriously low." The low price elasticity for steel is reflective of the lack of other suitable substitutes for steel in manufacturing and construction. Harris (1994) applies a price elasticity for demand of -0.90; however, his time period of analysis is limited to 1990-95.

3.3.1.2. Demand Function Calibration

Taking the estimated price elasticity of demand, I calibrate the model's demand function for steel using the price and consumption data from the last three years, 2006-2008. This process adjusts the model output such that without environmental regulation, the steel price and consumption level will equal the average price and average consumption for 2006-2008. This step is necessary because if only knowledge of the price elasticity of demand is available, only inferences about the relative changes in price and consumption can be made. There is not enough information available in the price elasticity to infer the actual levels of price and consumption, which are of primary interest. This final step completes the derivation of the model's demand function. The mean demand function (i.e. the estimate of the demand function without uncertainty) follows the functional form of Equation 3.7 and is expressed as:

$$P = 3303.4 - 20.5 \sum_{i=1}^{\infty} q_i \qquad (3.20)$$

where P is expressed in chained-2000 US$ per metric ton of steel and q_i is expressed in million metric tons.

3.3.2 Modeling Steel Production Costs

In this model, I have assumed that the steel market is imperfectly competitive such that domestic steel producers and importers exert a degree of market control. Therefore, in equilibrium, both domestic producers and importers raise positive profits.

Domestic producers and importers are able to raise profits by adjusting their output levels such that the demand for steel forces a market price above the production cost of either producer. To calculate the production costs for domestic steel producers and importers, I calibrate the model using domestic production, import, and price data for the U.S. steel industry from 2006-2008. However, before directly calibrating the model, I decided to narrow the scope of domestic production data to adjust for steel production technology heterogeneity.

3.3.2.1. Oxygen vs. Electric Arc Furnaces for Steel Production

Since 1900, steel has been produced from iron or steel scrap through several different processes around the world. Steel production processes can be broadly categorized into four distinct methods: Bessemer, open-hearth, electric arc, and basic oxygen. (Grübler, 2003) The relative production shares for these four steel production processes are displayed in Figure 3.5.

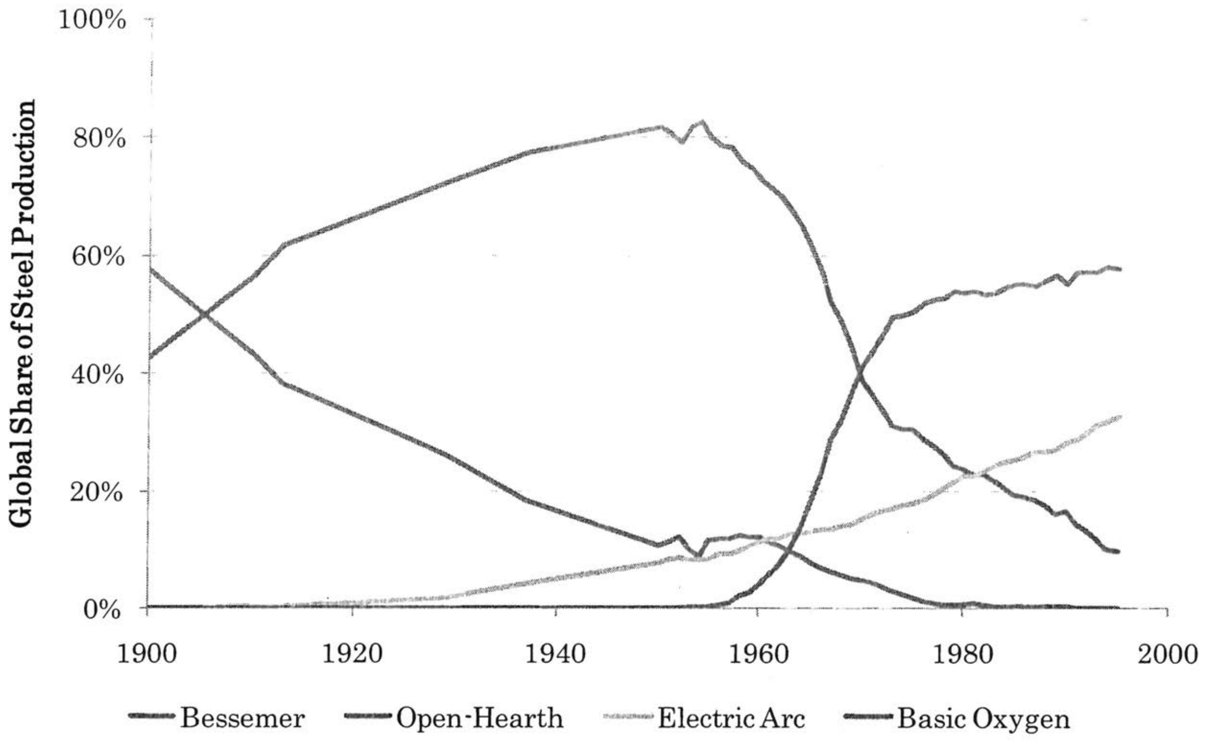


Figure 3.5: Global production shares for the four primary steel production processes for 1900-1995. Data from Grübler (2003). This dataset has been incorrectly cited as U.S. steel production process shares in several sources including Webster and Reiner (1997) and Nakićenvoić (1987).

The production costs, energy inputs, and pollutant emissions for each of these four steel production processes vary significantly. Further, the rate at which each of these four technologies has penetrated and developed in the steel market has been quite different. The political and economic processes which enable technology diffusion in an economy have been modeled in the literature in several different ways, most notably with the "probit" model and the "epidemic" model.[7] (Jaffe, Newell, & Stavins, 2001) For steel production technologies, the rate of technology diffusion has varied considerably: basic oxygen production gained market share very quickly, while electric arc production was considerably slower. (Grübler, 2003)

---

[7] For a further discussion of the microeconomics of technology diffusion with applications for environmental impacts see Jaffe, Newell, and Stavins (2001).

Modeling each of the steel production processes would be quite complicated; therefore, to simplify my analysis, I constrain my dataset of U.S. production to steel produced in basic oxygen furnaces, ignoring steel produced in electric arc furnaces. This simplification is justified because basic oxygen furnaces have over 60% share among international producers (IPCC, 2007), thereby making domestically produced steel through basic oxygen furnaces much closer competitors to imported steel. Further, electric arc production has a lower marginal cost and lower marginal CO_2 emission rate than basic oxygen production (IPCC, 2007), decreasing the validity of the aggregation of the two production processes for the representation of domestic production. Lastly, other studies assessing which industries are most susceptible to loss of competitiveness concerns under climate policy have found that basic oxygen furnace production is much more vulnerable than electric arc furnace production. (McKinsey & Co. and Ecofys, 2006; Reinaud, 2005) Figure 3.6 shows the relative shares of steel production processes in the U.S. for 1992-2008 (older data is not available).

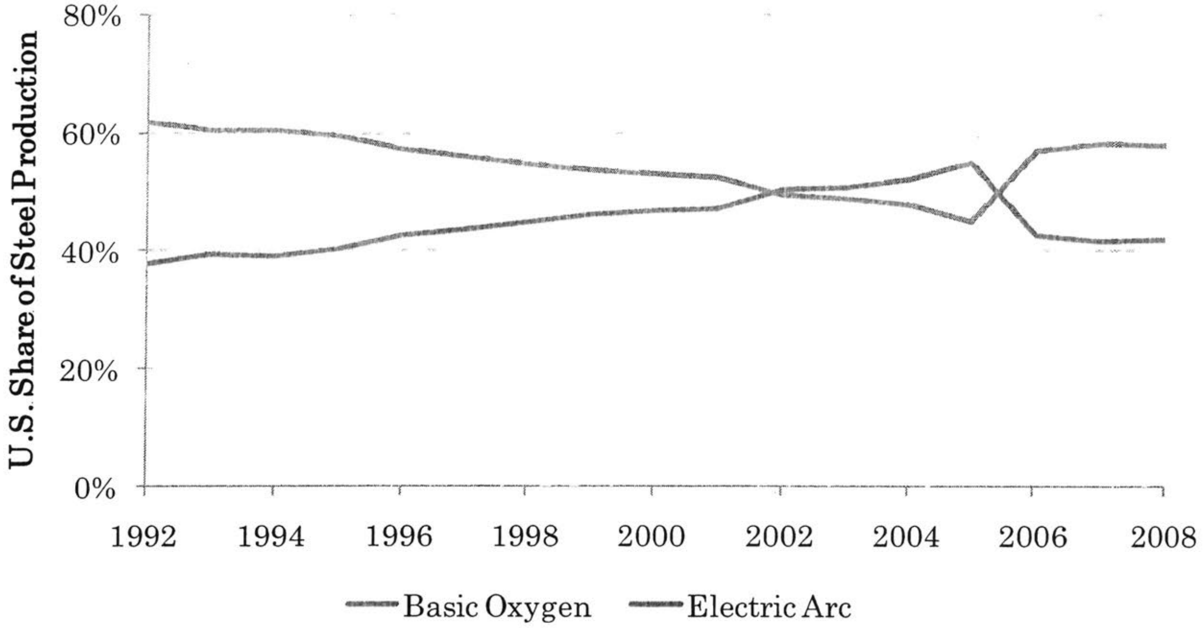


Figure 3.6: U.S. Production shares for the two steel production processes used in the U.S. for 1992-2008. Data from the U.S. Geological Survey (2009)

Because trade effects are of primary concern for this model, it is a reasonable assumption to calculate the demand for steel using all domestically consumed steel, but to calculate the production of steel using a competitive model for only domestic basic oxygen production and imports.

3.3.2.2. Production Cost Calibration

To calibrate the supply side of the model to historic domestic production and import levels, I calculate the production costs that the model estimates to match the historic production and import rates for 2006-2008. A better method to calibrate the model would have been to use actual industry-reported production cost and import cost data, but unfortunately, reliable production cost data is not available. Nevertheless, calibrating the model using levels of output for domestic producers and importers does given production cost results consistent with published cost ratios of domestic production to imports.

Calibrating the model to historic domestic production and import levels involves solving an algebraic backwards-calculation, simultaneously using Equation 3.12 and 3.13. I assume that a and b take their value from Equation 3.20 and solve for c_1 and c_2 using historic levels for q_1 and q_2. I also assume that r_1 and r_2 are zero, representing the historic lack of CO_2 regulation for steel firms. This calculation yields the following approximations for c_1 and c_2:

$$\begin{aligned} c_1 &= 685.2 \\ c_2 &= 1169.4 \end{aligned} \tag{3.21}$$

where c_1 is the average domestic cost of production and c_2 is the total average production cost of imports, including transportation costs, both expressed in chained-2000 US$ per metric ton of steel. Equation 3.21 and 3.20 allows Equations 3.12 and 3.13 to be rewritten as:

$$q_1 = -\frac{1}{2}q_2 + \frac{2618.2 - r_1\tau e_1}{41} \tag{3.22}$$

$$q_2 = -\frac{1}{2}q_1 + \frac{2134.0 - r_2\tau e_2}{41} \tag{3.23}$$

With this information, given values for e_1 and e_2, the market effects of pollution regulatory policy can be deterministically found.[8]

3.3.3 Modeling CO_2 Emission Intensity of Steel Production

---

[8] Pollution regulation would set the values for r_1, r_2, and τ, leaving two equations with two unknown variables, q_1 and q_2. From this, all other market information can be determined.

The last parameters needed to complete the model of U.S. steel domestic production and imports are CO_2 emission intensity estimates. CO_2 emission intensities were calculated by the IPCC (2007) and by Kim and Worrell (2002) for the USA and countries at varying stages of development. Kim and Worrell (2002) estimate that the emission intensity of steel production in the U.S. is 0.54 metric tons of carbon per metric ton of steel produced.

Using import data published by the USGS (2007), the average emission intensity of production for imported steel into the U.S. can be calculated. Figure 3.7a shows the relative import shares of steel into the U.S. in 2007 from OECD countries, transition economies, and developing countries.

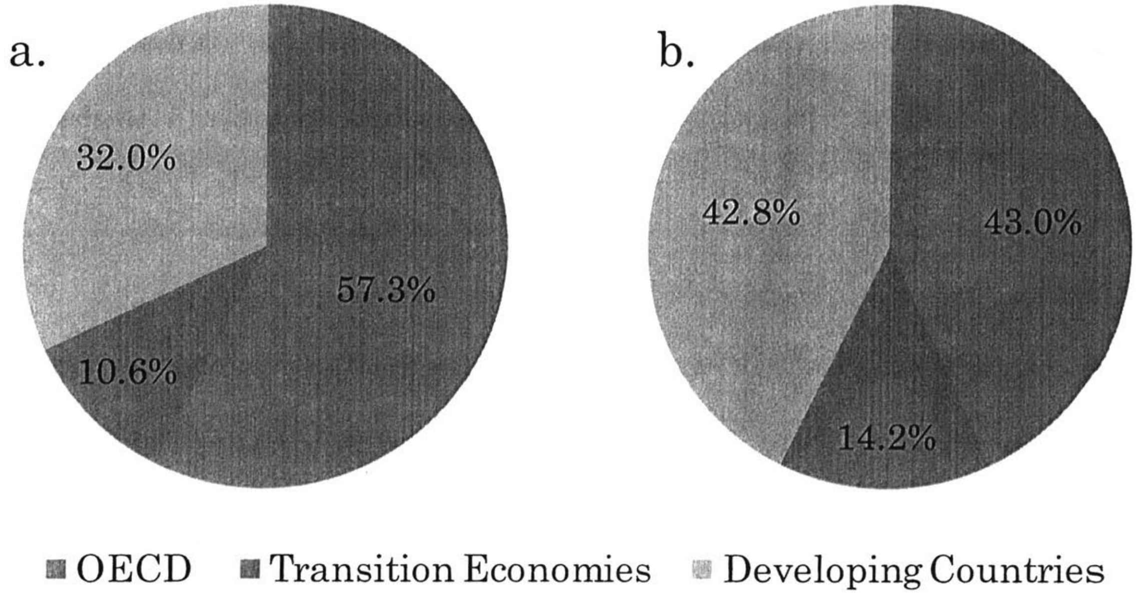


Figure 3.7: Figure 3.7a, on the left, displays the relative steel import shares into the U.S. from OECD countries, transition economies, and developing countries for 2007. Figure 3.7b, on the right, modifies Figure 3.7a by decreasing OECD imports into the U.S. by 25% and increasing imports from transition economies and developing countries proportionally.

Emission intensity data is reported by the IPCC (2007) and Kim and Worrell (2002) in ranges. Therefore, I carry out the calculation for CO_2 emission intensity by finding low and high estimates. By multiplying import shares by low and high estimates of emission intensities, I am able to calculate two estimates of the total emission intensity of steel imports into the U.S. I calculate that the likely range of CO_2 emission intensity of imports into the U.S. is 0.45 – 0.75 metric tons of carbon per metric ton of steel imported. Imports, import shares and emission intensities for OECD countries, transition economies, and developing countries are summarized in Table 3.1.

Exporting Region	Total Imports into U.S. (Mt)	Relative Import Share into U.S.	Steel Production Emission Intensity (t-C / t-steel)	
			Low Estimate	High Estimate
OECD	17.29	0.573	0.44	0.55
Transition Economies	3.21	0.106	0.55	1.04
Developing Countries	9.66	0.320	0.44	1.04
Total	**30.16**	**1.000**	**0.45**	**0.75**

Table 3.1: Steel imports, import shares, and production emission intensities for imports into the U.S. in 2007. Data from the U.S. Geological Survey (2007), IPCC (2007), and Kim and Worrell (2002).

The U.S. import data used in Figure 3.7a and Table 3.1 reflect the level of steel imports into the U.S. when CO_2 regulations were not in place in the U.S. and only weak CO_2 regulations were in place in other OECD regions. In the future, given the Kyoto Protocol and the likelihood of a successor protocol, it is reasonable to expect that many OECD regions will enact stricter CO_2 regulations. If many OECD regions did enact CO_2 regulation, making CO_2 emissions more expensive, it is likely that the U.S. will begin to import more steel from transition economies and developing countries which do not have CO_2 regulation; this is the concept of emission leakage. Therefore, the estimates in Table 3.1 may be too conservative. As an approximation, I have redone the calculation of steel import emission intensities assuming that OECD imports into the U.S. decrease 25% and that this decrease in imports is met by proportional increases in imports from transition economies and developing countries, such that total imports remains constant. Figure 3.7b updates Figure 3.7a to reflect this change in imports. I find that the new range of emission intensities for steel imports increases to 0.45 – 0.83 metric tons of carbon per metric ton of steel imported. Table 3.1 is updated to reflect this change in imports in Table 3.2.

Exporting Region	Total Imports into U.S. (Mt)	Relative Import Share into U.S.	Steel Production Emission Intensity (t-C / t-steel)	
			Low Estimate	High Estimate
OECD	12.97	0.430	0.44	0.55
Transition Economies	4.29	0.142	0.55	1.04
Developing Countries	12.91	0.428	0.44	1.04
Total	**30.16**	**1.000**	**0.45**	**0.83**

Table 3.2: Table 3.1 is revised to reflect a 25% reduction in steel imports from OECD regions into the U.S. met by compensating import increases from transition economies and developing countries. Because steel production in non-OECD regions is more CO_2-intensive, the total CO_2 intensity of imports increases.

I use the low and high estimates of the total emission intensity of imports from Table 3.2 as the values for e_2 in Equation 3.23. This section completes the model's specification of the U.S. domestic steel industry and U.S. steel imports. The final step of the model formulation will be to specify how to model CO_2 emission prices under climate policy.

3.3.4 Modeling CO_2 Regulation

Given the recent policy proposals in the U.S. Congress and the environmental policy stance of President Obama, it is likely that the U.S. will enact a major economy-wide climate policy that uses a market-based mechanism (i.e. a carbon tax or a cap-and-trade system) to regulate greenhouse gas emissions. Under market-based emission regulation, individual firms and sectors without market power to control emission prices will observe carbon prices independent of their production behavior. Ignoring CO_2 emissions from fossil fuel combustion, the steel sector is responsible for approximately 1.2% of U.S. CO_2 emissions. In reality the steel sector is energy-intensive and is responsible for the CO_2 emissions associated with the energy that it consumes, but for gaining market power, the CO_2 emissions that steel production directly emits (i.e. not through purchasing power) is more relevant. Therefore, under future market-based climate policy, it is unlikely that the steel sector will have significant market power to change price levels. Because this model only concerns the steel sector, it is irrelevant to this analysis what type of climate policy is enacted, as long as a carbon price is observed by firms.

For this analysis, I choose to apply a strict climate policy in line with the most aggressive emission reduction goals in Congressional climate policy proposals. The policy I choose to apply is a cap and trade system which begins reducing emissions after 2010 and reduces 2050 greenhouse gas emissions to 80% below 2008 emission levels. (Paltsev, Reilly, Jacoby, & Morris, 2009) To translate this cap and trade emission reduction goal into annual carbon prices, I use the results of the MIT Emissions Prediction and Policy Analysis (EPPA) model. The EPPA model is a computable general equilibrium model that has been adapted to predict the economic effects of climate policy. The EPPA model's predicted carbon prices for 2010 through 2050 are summarized in Table 3.3.

year	CO_2 price 2000$ / tC-eq
2010	0.00
2015	187.51
2020	228.50
2025	279.65
2030	338.23
2035	412.20
2040	500.66
2045	607.80
2050	741.10

Table 3.3: The MIT EPPA model's prediction for CO_2 prices for 2010-2015. Data from Paltsev, Reilly, Jacoby and Morris (2009) and converted using the Consumer Price Index from the Bureau of Labor Statistics (2009).

The CO_2 prices in Table 3.3 are used for values of τ in Equations 3.22 and 3.33. Finally, I assume that steel importers do not fall under CO_2 emission regulation. This sets r_1 to 1 and r_2 to 0.

3.4 Uncertainty Analysis

The parameter estimates described in Section 3.3 carry varying levels of uncertainty due to multiple factors such as measurement error, unknown future economic development, and extrapolative bias. To account for these uncertainties, I use probability density estimates for five uncertain parameter inputs in the model to conduct a Monte Carlo Stochastic Simulation. The five uncertain parameters for which I describe probability density estimates are: the price elasticity of demand for steel, the production cost of domestic steel, the production cost of imported steel, the emission intensity of domestic production, and the emission intensity of imported steel.

The price elasticity of demand for steel is calculated with a linear regression model, described in Section 3.3.1. To estimate a probability density function for the demand elasticity, the logical extension of this method is to assume a normal distribution with the standard error of the regression coefficient as the standard deviation of a normal distribution. Therefore, I use a normal distribution with mean -0.417 and standard deviation 0.179 as the input for the price elasticity of demand.

Production cost estimates for domestic production and imports are calculated by using historic domestic production, import and price levels to infer production costs. These costs are found by taking the average values for 2006-2008. Therefore, I use a probability density function for domestic production costs and import production costs with the mean values for 2006-2008 and standard deviations for 2006-2008, assuming a normal distribution. The domestic production cost probability density function that I use has mean equal to 685.15 and standard deviation equal to 148.89. The import production cost probability density function that I use has mean equal to 1169.44 and standard deviation equal to 229.44.

Emission intensities for steel production from domestic production and imports are found in the literature as ranges. Therefore, to convert ranges in probability density functions, I assume that the maximum and minimum values of emission intensities correspond to the 95th and 5th percentiles of a normal distribution. Therefore, the probability density function for domestic production CO_2 intensity has mean equal to 0.495 and standard deviation equal to 0.033 and the probability density function of the emission intensity of imports has mean equal to 0.640 and standard deviation equal to 0.116.

The probability density functions for the five uncertain variables are each assumed to be normal out of convenience. If more information about the probability density functions was known, other functional forms could have been used. Table 3.4 summarizes the means and standard deviations of the five uncertain variables.

variable	units	mean	st. dev.
price elasticity of demand	N/A	-0.417	0.179
domestic production cost	2000$ / t steel	685.15	148.89
import production cost	2000$ / t steel	1169.44	229.44
domestic emission intensity	t C / t steel	0.495	0.033
import emission intensity	t C / t steel	0.640	0.116

Table 3.4: Probability density function parameters for the five uncertain variables in the model. Each variable is assumed to have a normal distribution.

I conduct a Monte Carlo Stochastic Simulation for 100,000 trials, a sufficiently large size given the number of uncertain variables and computational constraints. I repeat the simulation for each of the carbon prices listed in Table 3.3 to create a projection for steel industry responses to increasingly stringent climate policy.

3.5 Results

Under the climate policy described in Section 3.3.4, I find that emission reductions in the U.S. steel sector amount to 120.1 million metric tons of carbon from 2010 – 2050. This is a 12% reduction from the steel sector's "business as usual" CO_2 emissions. However, in this policy scenario, 45.9 million metric tons of carbon are leaked to steel importing countries. This figure represents a leakage rate over 38%, implying that for every ton of CO_2 avoided in the U.S. steel sector, only 0.62 tons of CO_2 are avoided from reaching the atmosphere. I also find that the U.S. import reliance for steel increases under climate policy. I estimate that annual steel imports into the U.S. increase 22% from 26.8 million metric tons in 2010 to 32.7 million metric tons in 2050. Further, I estimate that total annual steel consumption (excluding domestically produced steel from electric arc furnaces) decreases 8% from 77.3 million metric tons in 2010 to 71.3 million metric tons in 2050.

3.5.1 Steel Consumption and U.S. Steel Competitiveness

Under the CO_2 regulation specified in Section 3.3.4, domestic steel producers face an increase in their marginal production costs which importing firms do not. Over time, the additional cost of complying with the policy, per unit of steel output, increases. In this analysis, technical change and the ability for consumer and producers to substitute to other products or other steel production processes (most notably electric arc furnace production) is held constant. Therefore, this analysis isolates the direct effect of climate policy on domestic steel production competitiveness. I find that given these limiting assumptions, the steel sector does lose a significant portion of its market share in domestic steel consumption, but perhaps not as large of a market share loss as some experts might fear.

I find that for steel produced in basic oxygen furnaces, domestic production loses 11% of its total market share, transitioning from meeting 65% of domestic consumption to meeting 54% of domestic consumption. This represents a loss in domestic annual steel production of 11.9 million metric tons. Assuming a constant labor to output ratio, this loss in domestic production would be associated with the loss of 11,300 American jobs[9].

The movement in domestic steel production and steel imports is shown in Figure 3.8. Uncertainty bands corresponding to the 10th and 90th percentiles are added to the plot.

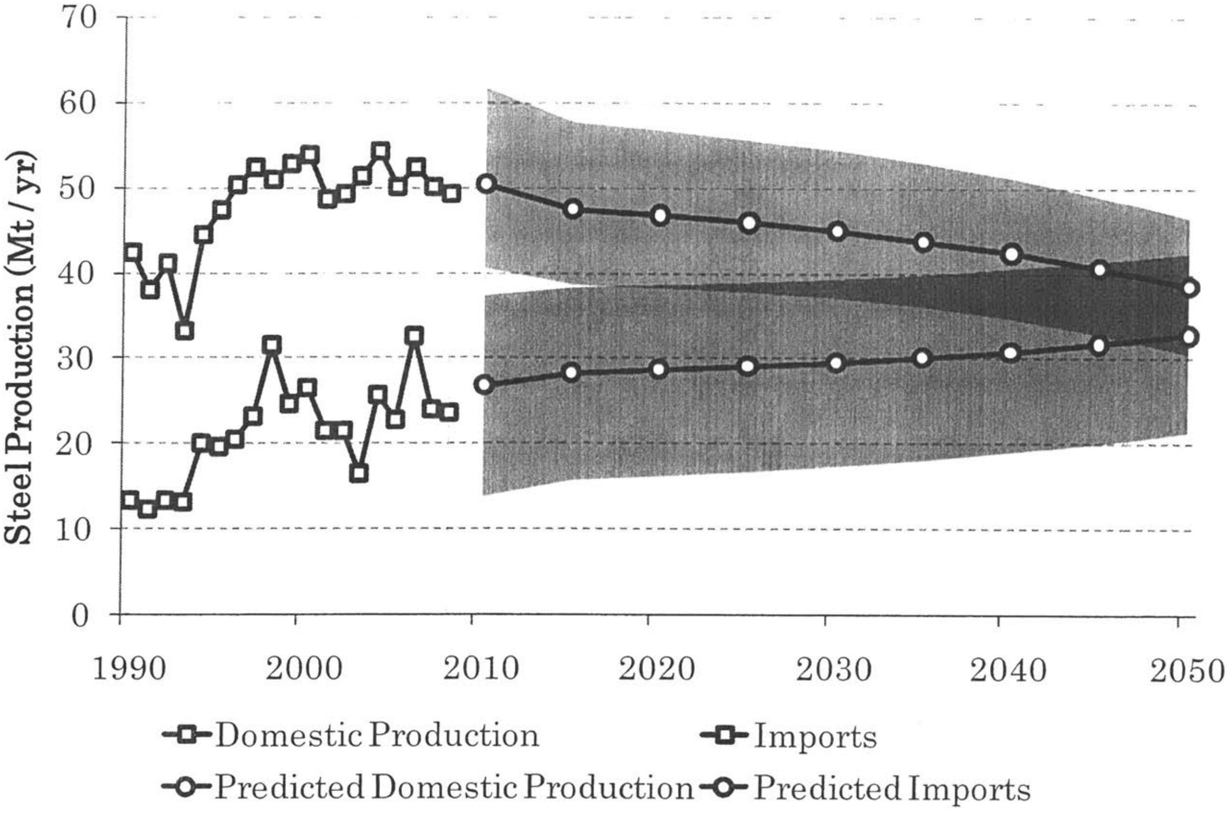


Figure 3.8: Domestic basic oxygen furnace steel production and steel imports for the U.S. Historic data is shown for 1990 – 2008 and mean projections are shown for 2010 – 2050 under climate policy. Uncertainty bands corresponding to the median 80% of values for domestic production and imports are added.

The climate policy effects on domestic steel production, steel imports, and steel consumption (net of electric arc furnace produced steel) are displayed in Table 3.5.

---

[9] Total employment in iron and steel production was 94,000 in 2006. (Bureau of Labor Statistics, 2008) This estimate assumes the labor/output ratio through 2050 remains constant at 2006 levels.

Year	Carbon Price (2000$ / t C)	U.S. Production (Mt Steel / yr)		Imports (Mt Steel / yr)		U.S. Consumption (Mt Steel / yr)	
		mean	st. dev.	mean	st. dev.	mean	st. dev.
2010	0.00	50.47	8.54	26.80	9.76	77.27	4.89
2015	187.51	47.44	7.83	28.32	9.47	75.76	4.85
2020	228.50	46.76	7.67	28.65	9.44	75.41	4.86
2025	279.65	45.91	7.47	29.10	9.30	75.01	4.86
2030	338.23	44.97	7.31	29.56	9.22	74.53	4.87
2035	412.20	43.79	7.13	30.13	9.17	73.92	4.94
2040	500.66	42.38	6.95	30.84	9.08	73.22	4.98
2045	607.80	40.63	6.81	31.71	8.97	72.34	5.08
2050	741.10	38.53	6.72	32.75	8.85	71.28	5.21

Table 3.5: The climate policy effects on U.S. basic oxygen furnace steel production, steel imports, and steel consumption net of electric arc furnace produced steel for 2010 – 2050 under the specified climate policy. Means and standard deviations are shown in 5 year time-steps from the Monte Carlo simulation with n = 100,000.

While Table 3.5 summarizes the general trend and magnitude of uncertainty for domestic production, imports, and total consumption of steel under climate policy, it gives no information to discern asymmetry in each measure's uncertainty. To examine the asymmetry in uncertainty of domestic production and import levels, the skewness of the distribution of production and import levels should be analyzed. Figure 3.9 displays density estimates for domestic production and imports in 2025.

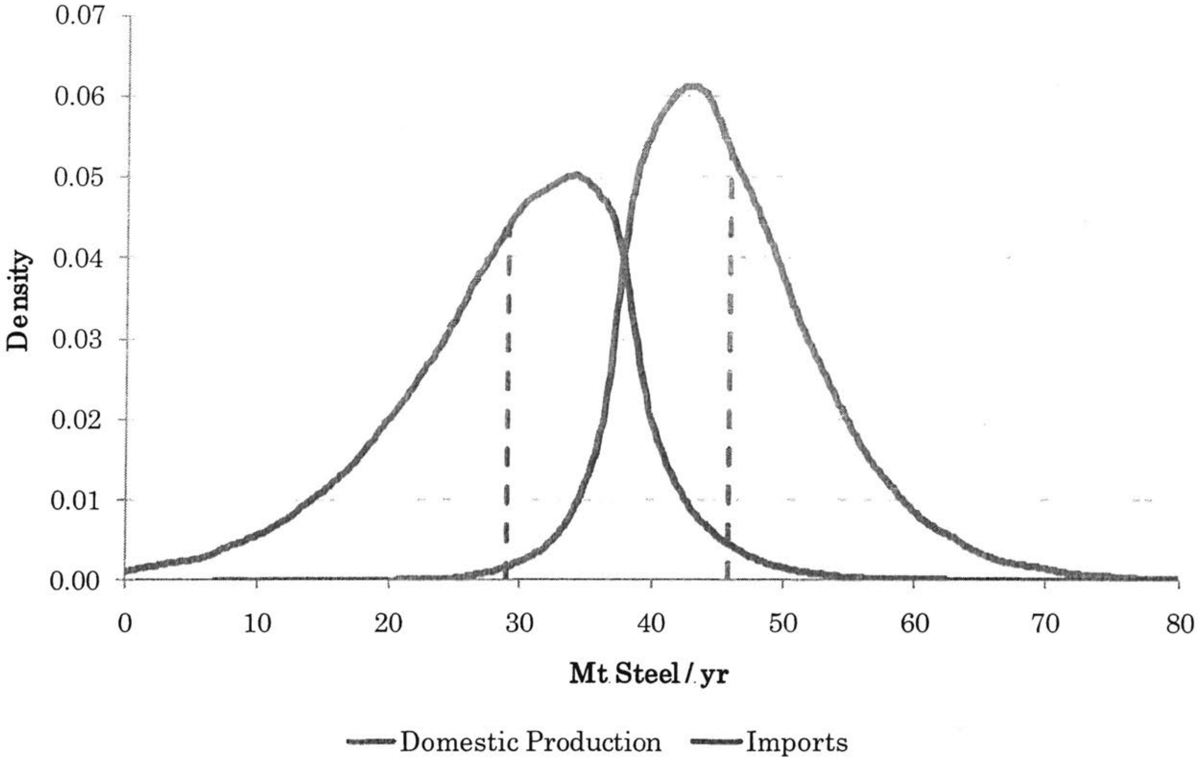


Figure 3.9: Density estimates of domestic production and imports in 2025 using the Epanechnikov kernel function with n = 500. Means for the two functions are shown as dotted lines. The domestic production density function is right-skewed and the imports density function is left-skewed.

Figure 3.9 reveals that the domestic production density function is right-skewed and the imports density function is left-skewed. The direction of skewness of these two density functions is the same for all carbon price levels from 2010-2050. Table 3.6 summarizes the skewness of the domestic production density function and the imports density function for 2010 – 2050.

Year	Domestic Production Skewness	Imports Skewness
2010	0.81	-0.80
2015	0.83	-0.76
2020	0.82	-0.76
2025	0.79	-0.71
2030	0.72	-0.71
2035	0.68	-0.70
2040	0.58	-0.66
2045	0.35	-0.58
2050	0.12	-0.52

Table 3.6: The skewness of the density functions for domestic production and imports. The domestic production function is right-skewed and the imports function is left-skewed for all levels of climate policy, but the magnitude of skewness for both decreases with increasing carbon prices.

The standard deviation estimates from Table 3.5 taken together with the skewness estimates in Table 3.6 suggest that with increasing climate policy stringency, uncertainty in the level of domestic production and imports decreases to a more symmetrically distributed value. The original asymmetry in the model is due to a combination of the formulation of best reply functions and greater uncertainty in production cost of imports. As climate policy increases, a larger fraction of steel production costs can be attributed to compliance with climate policy (for domestic production). Therefore, since the carbon price is taken as a certain value, the total uncertainty in domestic production cost decreases, relative to the total domestic production cost. This decreases both the standard deviation and skewness of the domestic production density function estimate. Because the level of imports is only a partial function of domestic production (this is shown by the best-response functions), the standard deviation and skewness of the imports production function decreases, but at a slower rate.

Asymmetry in the distribution of domestic production and import levels suggests that the mean estimate of the loss of domestic steel production competitiveness are more likely to be too low than too high. In other words, it is more likely that the true level of increased import reliance for steel is greater than the estimate measured in this section. The relevance of high skewness is more important for less-likely outcomes because outcomes will be biased towards either high or low extremes. However, one comparison to highlight skewness in this study is that using mean measures, domestic production of steel meets 60% of consumption from 2010 – 2050, but using median measures, this value falls to 58%.

3.5.2 CO_2 Emission Leakage from the Steel Sector

CO_2 emission leakage arises in this policy context because domestic producers of steel fall under CO_2 regulation and importers do not, creating a system of producers under incomplete regulation. The relevant quantities to assess the magnitude of emission leakage in this policy context are the emission reductions in the U.S. steel sector, the emissions increase in regions where imported steel is produced, and the leakage rate, the ratio of the increase in emissions in the unregulated regions where imports are produced to the decrease in emissions in the regulated region (this is described in Section 3.2.1.) Table 3.7 summarizes the means and standard deviations for these three measures.

Year	Carbon Price (2000$ / t C)	U.S. Emission Reduction (Mt C / yr)		Leaked Emissions (Mt C / yr)		Leakage Rate (%)	
		mean	st. dev.	mean	st. dev.	mean	st. dev.
2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2015	187.51	1.50	0.68	0.57	0.31	0.39	0.12
2020	228.50	1.83	0.83	0.70	0.38	0.38	0.12
2025	279.65	2.24	1.02	0.85	0.47	0.39	0.12
2030	338.23	2.71	1.23	1.03	0.57	0.39	0.12
2035	412.20	3.31	1.50	1.26	0.69	0.39	0.12
2040	500.66	4.01	1.82	1.54	0.84	0.39	0.12
2045	607.80	4.87	2.21	1.86	1.02	0.39	0.12
2050	741.10	5.93	2.69	2.27	1.24	0.39	0.12

Table 3.7: The climate policy effects on emission reductions in U.S. basic oxygen furnace steel production, leaked emissions to unregulated regions where imports are produced, and the emission leakage rate for 2010 – 2050 under the specified climate policy. Means and standard deviations are shown in 5 year time-steps from the Monte Carlo simulation with n = 100,000.

The Monte Carlo simulation confirms the intuition that with more stringent climate policy, the quantity of emission leakage increases. However, the leakage rate stays constant, independent of the level of climate policy, at approximately 39%. In other words, for every 1 ton of CO_2 reduced in the U.S. steel sector, 0.39 additional ton of CO_2 emitted in a region producing steel for consumption in the U.S. This result was shown algebraically with Equation 3.16 and the calculation in Appendix A. Further, because the leakage rate is dependent on the ratio of two normally distributed variables, the distribution of leakage rates is also normal. Figure 3.10 shows the distribution of CO_2 leakage rates.

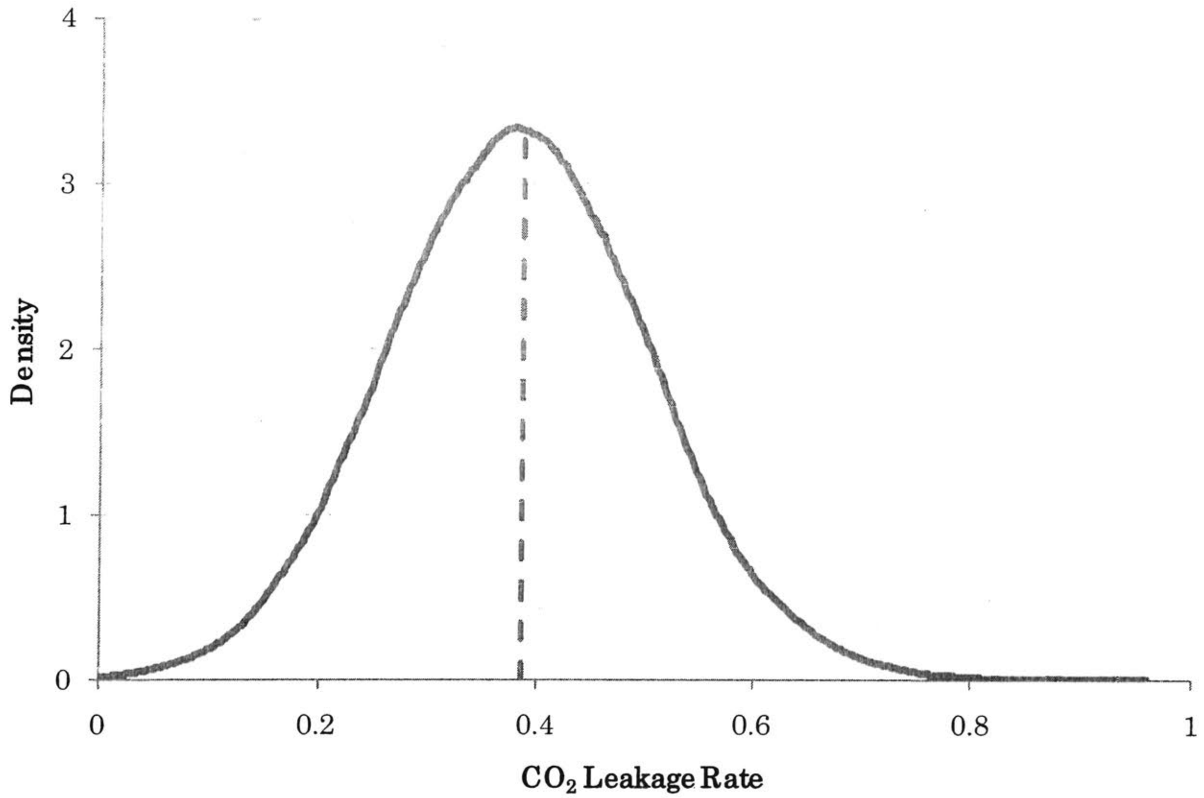


Figure 3.10: Density estimate of the CO_2 leakage rate using the Epanechnikov kernel function with n = 500. The mean of the function is shown as a dotted line. The distribution is approximately normal.

In 2050, the climate policy analyzed in this study reduces CO_2 emissions in the domestic steel sector by 5.9 million metric tons of carbon per year. However, this policy is also responsible for increasing CO_2 emissions from foreign steel producers by 2.3 million metric tons of carbon per year. Further, the quantity of leaked emissions is right skewed. This skewness arises in the distribution of leaked emission values because of the skewness in production costs described in Section 3.5.1 and because of greater uncertainty in the emission intensity of steel production from imports than the emission intensity of domestic steel production. Density estimates for the quantity of leaked emissions for 2020, 2030, 2040, and 2050 are plotted in Figure 3.11.

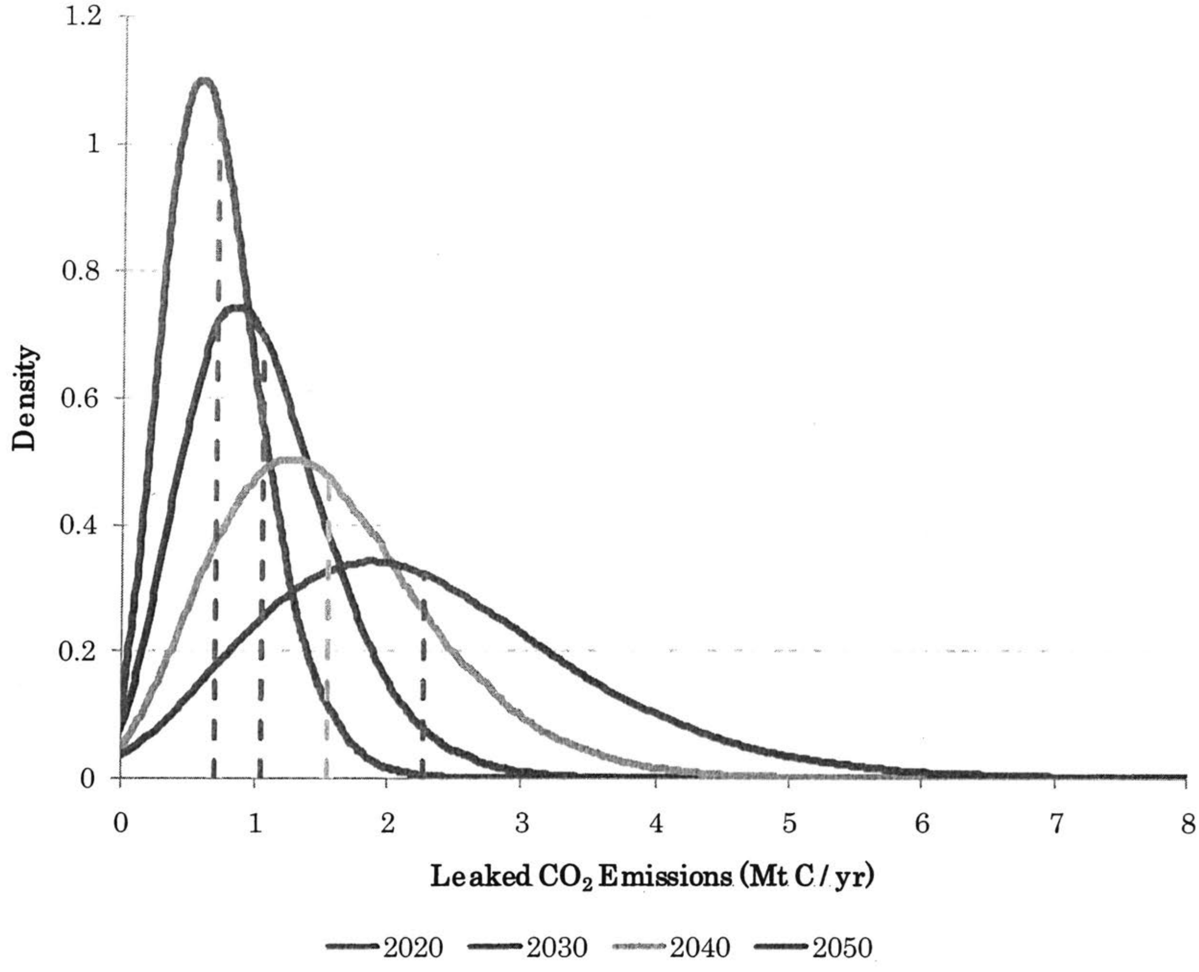


Figure 3.11: Density estimates of total leaked CO_2 emissions for 2020, 2030, 2040, and 2050 estimated using the Epanechnikov kernel function with n = 500. The mean of each function is shown as a dotted line of the same color. Each distribution is right-skewed.

Over time, as the carbon price increases, the mean quantity of leaked emissions increases. Additionally, the variance of leaked emissions increases while the skewness of the estimated density of leaked emissions stays positive and relatively constant at approximately 0.68.

3.6 Analysis

The model described in this chapter and then calibrated to the steel industry makes several assumptions about producer and consumer behavior in the steel market which may not be consistent with reality. At best, applying the duopoly model described in Sections 3.1 and 3.2 to the steel industry provides insight for understanding how market parameters of interest, such as emission leakage, qualitatively respond to general trends in climate policy. Large uncertainties in parameter estimation are but one of the several reasons why this model does not comprehensively capture behavior of the steel industry. In reality, domestic producers compete with each other and cannot perfectly collude with each other to reap maximum profits, as assumed in this model. Further, under climate policy, energy-intensive firms will seek to make efficiency gains or innovate new technologies to reduce their greenhouse gas emissions. For the steel industry in particular, the availability of electric arc furnaces to displace the more emission-intensive basic oxygen furnaces appears to be a viable strategy for steel producers to reduce their CO_2 emissions in the short-run. In fact, even without climate policy, the steel industry has significantly reduced its CO_2 emissions in the last two decades, partially as a result of rising energy prices and the shift from basic oxygen furnace production to electric arc furnace production. (James, 2009)

Compared to other studies of emission leakage in the steel industry, this model does quite well. Ho, Morgenstern, and Shih (2008), using four different time horizons, estimate that emission leakage from energy-intensive industries, such as steel production is "more than 40 percent." The ability of this model to closely replicate the results of the models that Ho, et al. develop with a considerably more simplistic approach is reaffirming of this methodology.

Moving forward, this model can be improved in three major ways: 1) uncertainty in parameter values can be decreased, 2) the model can be formulated to more accurately represent competition in the steel sector, 3) the model should account for technical change and the ability of steel producers to adopt more efficient practices, either by switching to electric arc furnaces or increasing energy use efficiency. With these three improvements, the model would better represent reality, perhaps at the expense of computational simplicity. By design, this model was left computationally simplistic so that a more robust uncertainty analysis could be conducted for a wider range of uncertainty in the input parameters. If the model were refined (with the exception of better estimates of parameter inputs) the insight gained from the Monte Carlo stochastic simulation that I conducted may be muted.

Chapter 4

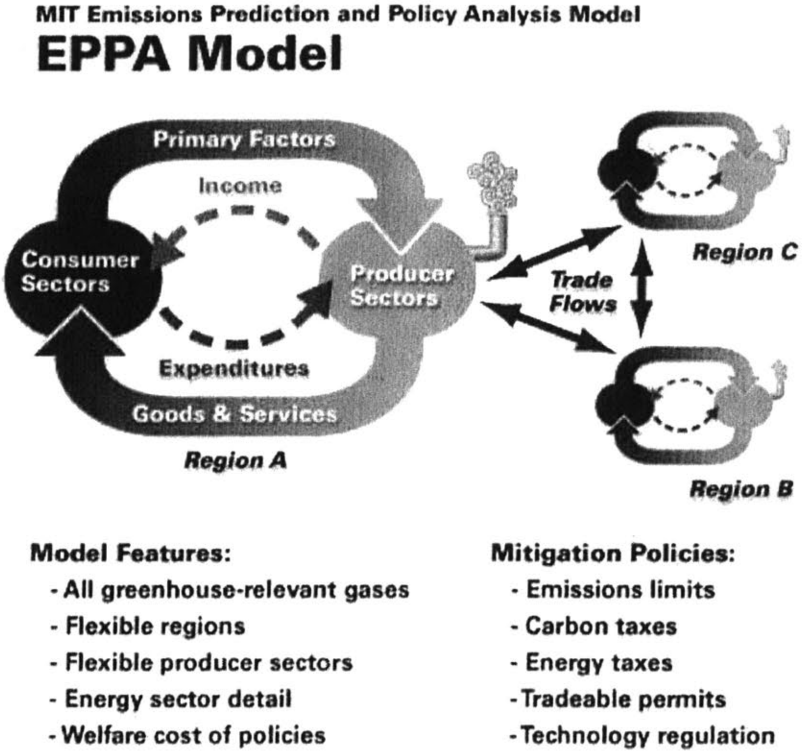
A Macroeconomic Analysis of Canadian Oil Sands

This chapter introduces the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy designed to analyze the macroeconomic impacts of greenhouse gas regulation. For this analysis, EPPA-ROIL, a version of the EPPA model modified for more detailed analysis of the refining sector, is used. The EPPA-ROIL model includes detailed specification for the oil sands industry, but before analyzing the effects of climate policy on the oil sands industry, the model is modified to include two new technologies. A detailed specification of two new carbon capture and sequestration (CCS) technologies specific to the oil sands industry are developed and incorporated into the EPPA-ROIL model. Next, the EPPA-ROIL model is run through a suite of climate policy regulations to estimate the emission leakage from the Canadian oil sands industry. The central finding of this suite of simulations is that increasing stringency of CO_2 regulation in Canada drives increasing levels of CO_2 leakage from oil sands emissions to developing countries until Canadian climate policy becomes so strict as to begin to shut down oil sands production completely. Additionally, the potential for CCS technology to be applied to oil sands dampens the total level of CO_2 leakage for weak Canadian climate policy and enhances CO_2 emission leakage at strict levels of Canadian climate policy, allowing the oil sands industry to thrive even under strict CO_2 emission regulation.

4.1 The MIT EPPA Model

The MIT Emissions Predication and Policy Analysis (EPPA) model is a "recursive-dynamic multi-regional general equilibrium model of the world economy." (Paltsev, et al., 2005) The EPPA model uses data from the Global Trade Analysis Project (GTAP), supplemented with additional greenhouse gas and urban gas emission data, to model economic growth and emissions of greenhouse gases and other pollutants. The EPPA model is one component of the MIT Integrated Systems Model (IGSM). In the IGSM, the anthropogenic emissions output by EPPA are fed into a model of the Earth's natural systems to estimate climate change and other environmental impacts. However, on its own, the EPPA model can act as a stand-alone model of the global economy to study the levels of greenhouse gas emissions and the economic impacts of greenhouse gas emission regulation. (Paltsev, et al., 2005)

The EPPA model divides the world into 16 geographic regions. Each region is modeled as an open economy with two main components: a consumer sector and a producer sector. The consumer sector of each region supplies primary factors such as labor and capital for the producer sector, which provides income for consumers. The producer sector of each region provides supplies goods and services for the consumer sector, which provides expenditures for producers. (Paltsev, et al., 2005) Figure 4.1 illustrates the relationship between the consumer and producer sector and lists some of the other features of the EPPA model.



Model Features:
- All greenhouse-relevant gases
- Flexible regions
- Flexible producer sectors
- Energy sector detail
- Welfare cost of policies

Mitigation Policies:
- Emissions limits
- Carbon taxes
- Energy taxes
- Tradeable permits
- Technology regulation

Figure 4.1: A depiction of the MIT EPPA model's primary components, highlighted model features, and mitigation policy inputs. (MIT Joint Program on the Science and Policy of Global Change, 2009)

4.1.1 EPPA-ROIL Modification

EPPA4 draws on the GTAP dataset for data on the energy commodities in model, crude oil, natural gas, coal, electricity, and an aggregate commodity which represents many different petroleum products which result from crude oil refining. To improve EPPA's capacity to analyze how climate policy affects the supply and demand for refined oil products, Choumert, Paltsev and Reilly (2006) modified the refining sector in EPPA by disaggregating both the downstream and upstream oil industries so that more granular research could be conducted. Their modified version of the EPPA model is EPPA-ROIL, the primary tool for analysis in this chapter.

The most substantial changes done to EPPA's energy supply and conversion sectors are to disaggregate output from the downstream refining sector into the six categories:

- refinery gases,
- gasoline,
- diesel,
- heavy fuel oil,
- petroleum coke, and
- other petroleum products

The physical flows of these refined products are disaggregated using the International Energy Agency (IEA) Databases. (International Energy Agency, 2005) Prices for these products are determined for EPPA regions and sectors using both the IEA price data and data from Energy Information Administration (EIA). (Energy Information Administration, Annual Energy Review) Finally, the model is calibrated to overcome gaps in the trade data for non-OECD regions. (Choumert, Paltsev, & Reilly, 2006)

In addition to disaggregating the output of the refining sector, EPPA-ROIL also modifies EPPA by introducing new multi-output production functions for each of the new outputs of the refining sector. Specifically, the new multi-output production functions assume a constant elasticity of transformation (CET) on outputs, and constant elasticity of substitution (CES) on inputs. (Choumert, Paltsev, & Reilly, 2006)

EPPA-ROIL also improves EPPA's representation of several technologies relevant to the refining sector. EPPA-ROIL adds explicit representation of two new technologies:

- residue upgrading technology which allows heavy fuel oil to be upgraded into the other five categories of refined products
- the gasification technology which can turn residual fuel oil (such as heavy fuel oil) and petroleum coke into synthetic gas

EPPA-ROIL also improves the technology characterization of biofuels, a potentially important substitute for many fossil fuel refinery sector outputs. In EPPA, biofuel technology is represented as a single technology which produces one refined oil product. In EPPA-ROIL, this characterization is improved by elaborating details on the outputs of biofuel technology, allowing the technology to now output two types of fuel: biodiesel and a gasoline-like biofuel.

Additionally, EPPA-ROIL also improves the representation of oil reserves and resources. EPPA-ROIL adds explicit representation of non-conventional oil reserves for Canada and Latin America to represent the large oil sands resources which may come into play at scale in the future. Further, to utilize non-conventional oil reserves, EPPA-ROIL introduces two new technologies which will be of central importance for this chapter:

- extra-heavy oil production (e.g. oil sands production)
- extra-heavy oil upgrading (e.g. oil sands upgrading to synthetic crude oil)

The new representation of non-conventional oil reserves in EPPA-ROIL along with EPPA-ROIL's estimate of conventional oil reserves is shown in Figure 4.2.

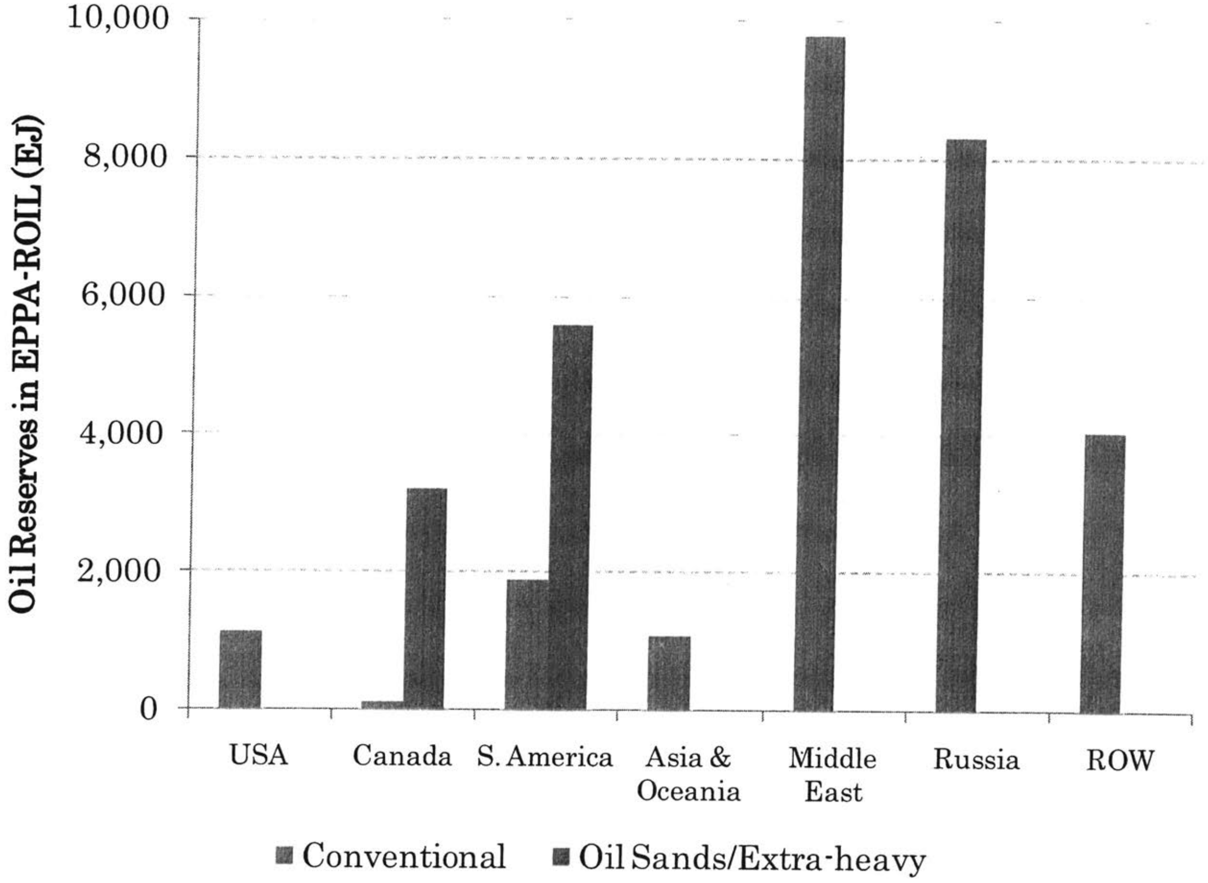


Figure 4.2: The oil reserve estimates in EPPA-ROIL for conventional and non-conventional resources. Data is broken down by EPPA region. "ROW" = rest of the world. (Choumert, Paltsev, & Reilly, 2006)

Finally, EPPA-ROIL improves upon EPPA's representation of CO_2 emissions for the refinery sector's activities. EPPA-ROIL's CO_2 emission representation modifications are relevant to the bitumen industry in two ways. First, the upstream disaggregation of the oil industry in EPPA-ROIL allows me to consider the significant quantity of CO_2 emissions generating in producing and upgrading non-conventional oil reserves, such as the oil sands in Canada. Second, the downstream disaggregation of the oil industry allows me to more granularly analyze the emissions of the diversified refined oil products from consumption, upgrading (such as upgrading the oil sands in Canada into other refined products), and gasification. The improvements in the representation of CO_2 emissions from refined products in EPPA-ROIL generate new estimates of regional CO_2 emissions. However, on net, these improvements do not change global CO_2 emissions. (Choumert, Paltsev, & Reilly, 2006)

4.2 Canadian Oil Sands

Oil sands deposits of bitumen, a highly viscous oil which flows when heated or diluted with less viscous hydrocarbons. (Government of Alberta, 2005) Oil sands cover over 50,000 square miles in Alberta, Canada, and, at 174.5 billion barrels of oil equivalent, contain the second largest proven oil reserve on the planet, second to Saudi Arabia. (Government of Alberta, 2005) Fueled in part by American imports, the oil sands industry in Canada is booming. In 2006, Alberta's oil sands accounted for nearly half of all crude oil output from Canada. Currently, the bitumen extracted from Canadian oil sands contributes over 1.1 million barrels of oil per day (bbl/d), with projections for growth expecting the industry to reach 3 million bbl/d and 5 million bbl/d by 2020 and 2030, respectively. (Government of Alberta, 2009) Bitumen and synthetic crude oil production from Canada's oil sands have increased by 229% between 1990 and 2006, but whether this growth can continue, will depend strongly on whether the oil sands industry can comply with environmental regulations. (Environment Canada, 2008)

4.2.1 Bitumen Production from Oil Sands

There are two ways which bitumen is currently recovered from oil sands: surface mining and in-situ (or "in place") techniques. Surface mining uses open pits to extract oil sands near the surface. After being mined, the oil sands are moved by trucks to cleaning facilities where the intermediate is mixed with hot water to separate the bitumen from the sand. In-situ techniques, such as Cyclic Steam Stimulation (CSS) and Steam Assisted Gravity Drainage (SAGD), on the other hand, are used to extract the oil sands residing deeper in the ground. In-situ processes are very similar to conventional oil extraction, which primarily uses wells to reach the oil reserve deep underground. In-situ techniques use steam, pressure, solvents or thermal energy to make the bitumen flow to a point that can be pumped to the surface. (Government of Alberta, 2005; Government of Alberta, 2009)

4.2.2 Oil Sands Production and CO_2 Emissions

Today, 60% of Alberta's bitumen output from oil sands comes from surface mining; the remaining 40% is extracted with in-situ techniques. (Energy Resources and Conservation Board, 2009) In-situ techniques are less harmful to the environment than surface mining because in-situ techniques use less water and occupy less land. However, greenhouse gas emissions produced during both the bitumen production and upgrading processes for both extraction techniques remains an issue of concern. (Government of Alberta, 2009) Depending on the production process and the viscosity of the bitumen deposit, bitumen production from oil sands emits between 5 to 100 kg of CO_2 per barrel of oil equivalent produced. In Canada, oil sands extraction with SAGD, an in-situ technique, can cause emissions as high as 100 kg CO_2 per barrel of oil equivalent produced. Once bitumen is extracted from the oil sands, it is upgraded in a refinery, a process which emits an additional 100-120 kg per barrel of processed bitumen. (Choumert, Paltsev, & Reilly, 2006)

Together, the combined emissions of bitumen production (5 – 100 kg CO_2 per barrel of oil equivalent) and bitumen upgrading (100-120 kg CO_2 per barrel of oil equivalent) amount to two to three times the quantity of emission associated with the extraction and refining of conventional oil reserves to gasoline and diesel. (The Economist, 2008) Despite recent efficiency gains, the bitumen industry is still a heavily polluting sector of Canada's economy which could be adversely affected under future greenhouse gas regulation. Driven primarily by more efficient use of fuels by producers and refineries, the average CO_2 emission intensity of operations in the oil sands production and upgrading industries declined 23% from 1990 to 2003. (Environment Canada, 2008)

4.2.3 The Oil Sands Industry, Climate Policy, and CO_2 Leakage

In 2006, the greenhouse gas emissions of Canada reached 721 million metric tons of carbon dioxide equivalent (Mt CO_2-eq), 29% above the target set for Canada under the Kyoto Protocol (Environment Canada, 2008b). The profitability of bitumen production and upgrading has put increased pressure on Canadian CO_2 emissions, making it less attractive for Canada to reduce its CO_2 emissions. A large reason why Canadian oil sands production is so profitable is because other countries, with excess demand for oil, have begun to import petroleum products derived from Canadian oil sands. In 2004, 12% of U.S. crude oil imports were from Alberta (an additional 4% of U.S. imports were from other Canadian provinces). (Government of Alberta, 2005)

In the future, as regions of the world develop, open themselves to international trade, and implement new environmental regulations, it is feasible that Canada will begin to export raw bitumen and / or upgraded bitumen to other regions of the world. While exporting upgraded bitumen is not of interest for studying emission leakage (because all associated emissions are contained within Canada, a regulated region), exporting raw bitumen for upgrading abroad is a compelling case study for emission leakage. In the production of synthetic crude oil from Canadian oil sands, approximately 40% of CO_2 emissions are emitted in the extraction (production) of bitumen. The remaining 60% of CO_2 emissions are generated in upgrading bitumen to synthetic crude oil. If upgrading shifts from Canada to unregulated regions when Canada enacts CO_2 emission regulation, the 60% of CO_2 emissions from bitumen upgrading will be leaked.

In the next section, I describe the policy and technology assumptions I used to assess the potential leakage rate from bitumen upgrading from enacting climate policy on Canada.

4.3 Scenario Analysis: Policy & Technology Factors

CO_2 emission leakage from oil sands is a dynamic problem to study because CO_2 emissions are generated in two steps in the production chain of synthetic crude oil. (See section 4.2.3) Because emissions are generated in two-steps, Canadian climate policy puts negative pressure on synthetic crude oil production from oil sands in two ways: by making bitumen production more expensive and by making domestic bitumen upgrading more expensive. Because of fixed resource constraints (oil sands are in the ground and therefore, must be produced in Canada) no bitumen production emissions can be leaked. CO_2 emissions from upgrading can be leaked because the intermediate crude bitumen can be transported to unregulated regions and upgraded there. However, leakage through upgrading becomes complex as the climate policy enacted decreases bitumen production, decreasing the quantity of available crude bitumen for upgrading. This mechanism lowers the marginal cost of upgrading and introduces non-linearity to the quantity of emission leakage. Because of this complexity in operation costs and the complexity in oil markets, the computable general equilibrium framework of EPPA-ROIL is particularly apt.

4.3.1 The Canadian Climate Policy Envelope

In my analysis of Canadian climate policy, I begin with the policy proposal of Canada's current majority party, the Conservative Party, as outlined in the 2007 document "Action on Climate Change and Air Pollution." The plan calls for an 18% reduction in Canadian emission intensity, the ratio of greenhouse gas emissions to gross domestic product, by 2010. Additionally, the plan calls for reducing greenhouse gas emissions to 20% below 2006 emission levels by 2020. Finally, in a December 2007 speech, Canada's Minister of the Environment and member of the Conservative Party, John Baird, called for a 50% reduction in greenhouse gas emissions by 2050. This is also in line with the 2008 Group of Eight (G8) statement to reduce greenhouse gas emissions by 50% by 2050. The G8 statement did not include the baseline year for the emission reductions, but for this analysis I impose the Canadian 2006 emission level as the baseline for reductions. I impose linearly interpolated emission constraints for years without explicit emission targets. Table 4.1 outlines these CO_2 emission constraints.

year	CO_2 Reduction Goal	Baseline	Reduction
2010	Emission Intensity (CO_2/GDP)	2006	18%
2020	Total CO_2	Ambiguous, 2006	20%
2050	Total CO_2	Ambiguous, 2006	50%

Table 4.1: The Canadian Conservative Party CO2 emission reduction goals used as the baseline policy case in this analysis. Example: In 2010, reduce CO2/GDP by 18% from 2006 levels.

In addition to the baseline policy, I also generate a suite of CO_2 emission constraints that span the envelope of CO_2 emission profiles from 110% of the emission reduction goal of the baseline policy case to the emissions of the no-policy (or "business as usual") case. In my suite of CO_2 emission constraints, I generate 12 emission profiles: business as usual, and 10% - 110% of the baseline policy case in 10% increments. These policy cases are numbered from 0 to 110 (in increments of 10). Table 4.2 tabulates the total CO_2 emissions and emission reductions from 2000 – 2050 of these 12 policies.

Policy Name	2000 - 2050 CO_2 Emissions (GtC)	2000 - 2050 CO_2 Emission Reduction (GtC)
110	7.24	15.61
100	8.66	14.19
90	10.08	12.77
80	11.50	11.35
70	12.92	9.93
60	14.34	8.52
50	15.76	7.10
40	17.18	5.68
30	18.60	4.26
20	20.02	2.84
10	21.44	1.42
0	22.85	0.00

Table 4.2: The total cumulative CO_2 emissions and emission reductions for the 12 Canadian policies analyzed in this study. Policy 100 is consistent with the Canadian Conservative Party's policy proposal and Policy 0 is consistent with the no policy or "business as usual" case.

Figure 4.3 displays the emission reduction profiles for the twelve policies.

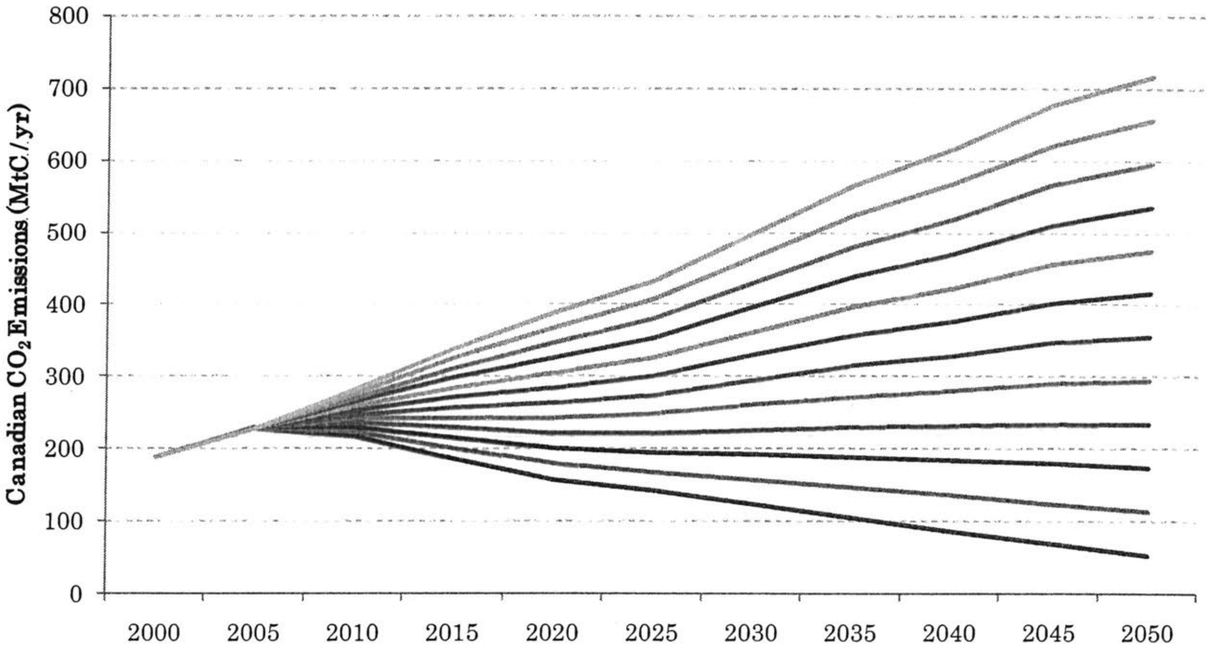


Figure 4.3: The CO_2 emission profiles for the 12 policies analyzed in this study. The top line is the emission profile for Policy 0 and the bottom line is the emission profile for Policy 110.

4.3.2 Climate Policy in the Rest of the World

4.3.2.1. Annex I Policy

I apply a climate policy to the United States that closely approximates the cap-and-trade emission targets of the proposed Lieberman-Warner Climate Security Act of 2008 bill (S.2191). For the United States, climate policy is initiated in 2015, approximating the emission constraints stated in the Lieberman-Warner bill and including the provision for up to 15% of emission allowances to be met through international emission offsets. For the remaining countries of the Annex I parties to the United Nations Framework Convention on Climate Change (UNFCC) (Canada and the USA are modeled in more detail), we use the officially stated goal of a 20% reduction in carbon-dioxide emissions by 2020 relative to 1990 emissions and a 50% reduction in carbon-dioxide emissions by 2050 relative to 1990 emissions. In these countries, climate policy is phased in beginning in 2010, representing the carbon-dioxide emission reductions initiated by the Kyoto Protocol. Additionally, carbon-dioxide emission caps are interpolated linearly for the years with no explicitly stated emission goals. Table 4.3 details the carbon-dioxide emission caps for the USA and the other Annex I countries (not including Canada).

year	USA	Other Annex I
2010		emission reductions begin
2015	emission reductions begin	
2020	2005 emission + 5%	1990 emissions - 20%
2050	2005 emissions - 54%	1990 emissions - 50%

Table 4.3: CO_2 emission reduction goals for the USA and other Annex I countries.

Figure 4.4 displays the emissions path projected by EPPA-ROIL for the business-as-usual case over time (in grey). If developing countries do not participate in CO_2 regulation, they will account for 86% of total world emissions by 2050 in the baseline policy scenario (11.1 GtC/yr out of 12.9 GtC/yr). By 2050, climate policy in the Annex I countries (including emission leakage) reduces global annual CO_2 emissions from the "business as usual" scenario by 30% (5.9 GtC/yr).

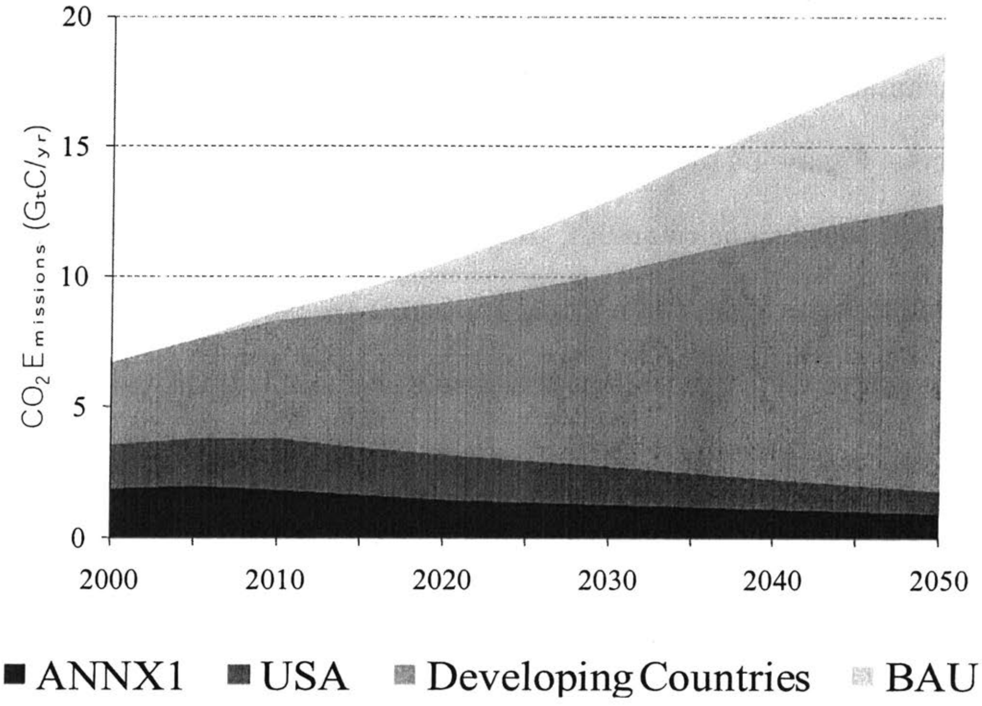


Figure 4.4: CO_2 emissions in the baseline policy case. Annex I countries reduce CO_2 emissions while developing countries are left unconstrained. "BAU" = business as usual.

4.3.3 Developing Country Policy

If left unconstrained, the emissions of developing countries grow substantially through 2050, when they account for 86% of global emissions. It is clear that without emission reductions from developing countries, emissions will not stabilize in the first half of the century. Therefore, in several of my policy simulations I constrain the emissions of developing countries. The policy I apply for developing countries represents a significant departure from business-as-usual, but since the developing countries have made few official climate policy statements, the policy I apply is largely speculative. The emission targets that I apply begin in 2025, and force developing country regions to meet their 2015 annual emission level by 2025 and their 2000 annual emission level by 2050. Between 2025 and 2050, developing countries meet emission benchmarks determined by the linear interpolation of their 2025 and 2050 emission targets. Figure 4.5 plots global emission targets for the USA, other Annex I countries, and the developing countries. Beginning in 2021, global CO2 emissions steadily decline through 2050, when global emissions are nearly one-fourth of what they would have been under the business-as-usual scenario (4.9 GtC/yr instead of 18.7 GtC/yr).

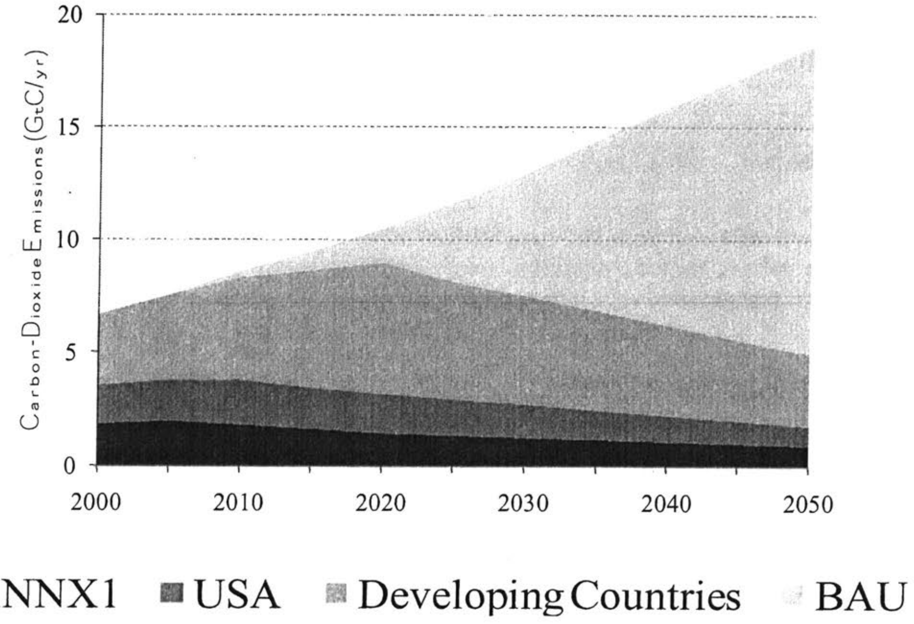


Figure 4.5: CO_2 emissions in the policy case with developing country participation. "BAU" = business as usual.

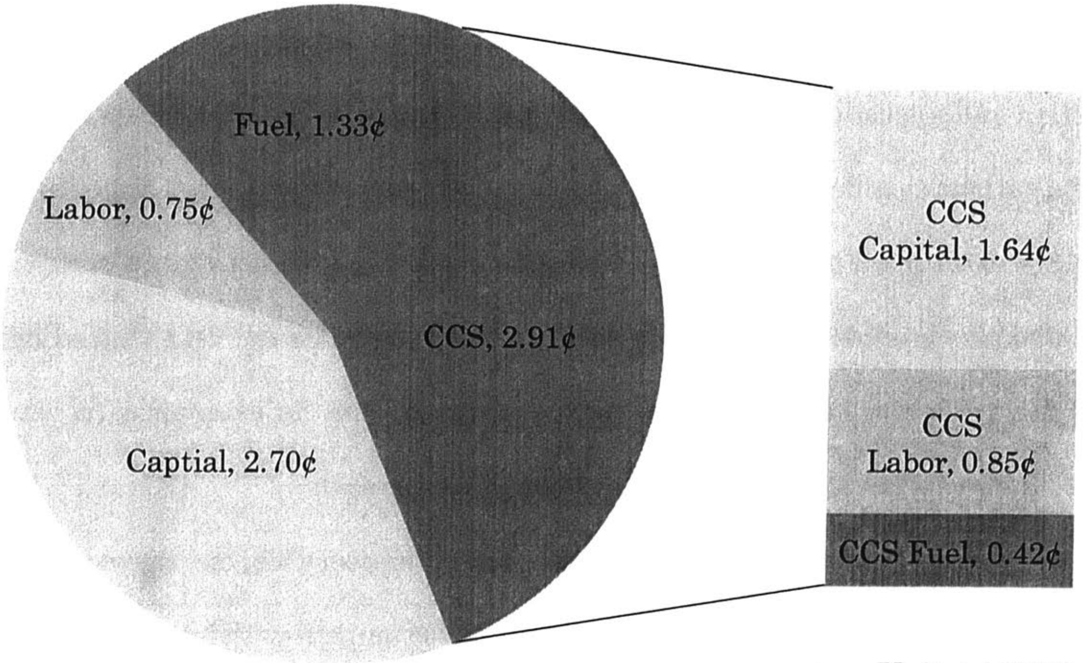
If developing countries participate in CO_2 regulation, the potential for emission leakage is very small. Therefore, for this analysis, developing regions are left completely unconstrained.

4.3.4 Low-Carbon Technology: Carbon Capture and Storage

Carbon capture and sequestration (CCS) technology is a potential option for the production and upgrading of bitumen which would increase operating costs while lowering carbon dioxide emissions compared to existing technologies. Applying CCS technology to bitumen production and upgrading could help abate a large portion of carbon dioxide emissions otherwise created in bitumen production and upgrading. This section describes how I developed the analytical framework for evaluating oil sands CCS production and bitumen upgrading costs and emissions.

I model two new technologies that capture and sequester CO_2, one to compete with existing bitumen production technologies and one to compete with bitumen upgrading technologies. A key challenge in properly characterizing these CCS technologies in the primarily top-down EPPA-ROIL model is adapting and integrating bottom-up engineering cost estimates into the EPPA structure. I integrate these new technologies by calculating the CCS cost mark-ups, the percent cost increases of capital, labor, and fuel for each technology with CCS compared to the technology without CCS.

I calculate the CCS cost mark-ups by determining the final costs and carbon-dioxide emissions of CCS technologies for bitumen production and upgrading. Given the lack of rigorous engineering studies of CCS technology applied to bitumen production or upgrading, I base my cost and capture efficiency estimates on the engineering estimates of CCS technology applied to pulverized coal electric power plants by Ansolabehere, et al. (2007). Figure A shows the costs of capital, labor, and fuel in pulverized coal electricity generation and the cost increases in capital, labor, and fuel associated with CCS applied to pulverized coal electric power plants.



Units: ¢ / kWh

Figure 4.6: Cost of pulverized coal electric power generation and cost of CCS add-on broken down by capital, labor, and fuel costs. (Ansolabehere, et al., 2007)

In adapting the cost and emission estimates for a coal power plant to bitumen production and upgrading technology, I make the assumption that all flue gas capture technology follows a constant cost to CO2-captured ratio, which is independent of the fuel combusted. From Ansolabehere, et al. I determine the capital, labor, and fuel costs per metric ton of CO2 captured required to apply CCS technology in a post-combustion capture pulverized coal plant. I hold these three quantities constant to calculate the additional costs to capital, labor, and fuel that would be required to apply CCS to bitumen production and upgrading. I use the cost estimates for the inputs to bitumen production and upgrading from Choumert, et al. (2006) (see tables in the Appendix B). However, the "fuel" mark-up is only applied to the bitumen production and upgrading inputs which are combusted, natural gas and heavy fuel oil. The other inputs to bitumen production and upgrading are refinery gas, transportation, energy-intensive industrial inputs (e.g. steel and petrochemicals used in plant construction), and services (e.g. banks and insurance). These inputs are not combusted and do not produce CO2 emissions; therefore I do not apply a mark-up to these inputs and assume that they follow a constant input to output ratio whether or not CCS is applied.

Table 4.4 shows the detailed cost estimates from Ansolabehere, et al. for applying CCS technology to pulverized coal power plants and the new cost mark-up estimates for applying CCS to bitumen production and upgrading. Figures 4.7 and 4.8 provide insight into the relative costs of CCS technology capital, labor, and fuel inputs for bitumen production and upgrading.

Technology	Total Cost		CO_2 Emissions		Cost Ratio of CCS to Conventional Technology				Carbon Entry Price for CCS
	w/o CCS	w/ CCS	w/o CCS	w/ CCS	Capital	Labor	Fuel	Total	
	(¢/kWh)		(g-CO_2/kWh)			(Mark-up)			($/t-$CO_2$)
Pulverized Coal for Electric Power	4.78	7.69	830	109	1.61	2.13	1.32	1.61	40.36
	($/boe)		(kg-CO_2/boe)			(Mark-up)			($/t-$CO_2$)
Bitumen Production	10.00	11.93	55	7	1.38	1.27	1.13	1.19	40.36
Bitumen Upgrading	12.78	15.76	85	11	1.26	1.80	1.12	1.23	40.36

Table 4.4: Cost of CCS for Pulverized Coal Power Plants, Bitumen Production and Upgrading

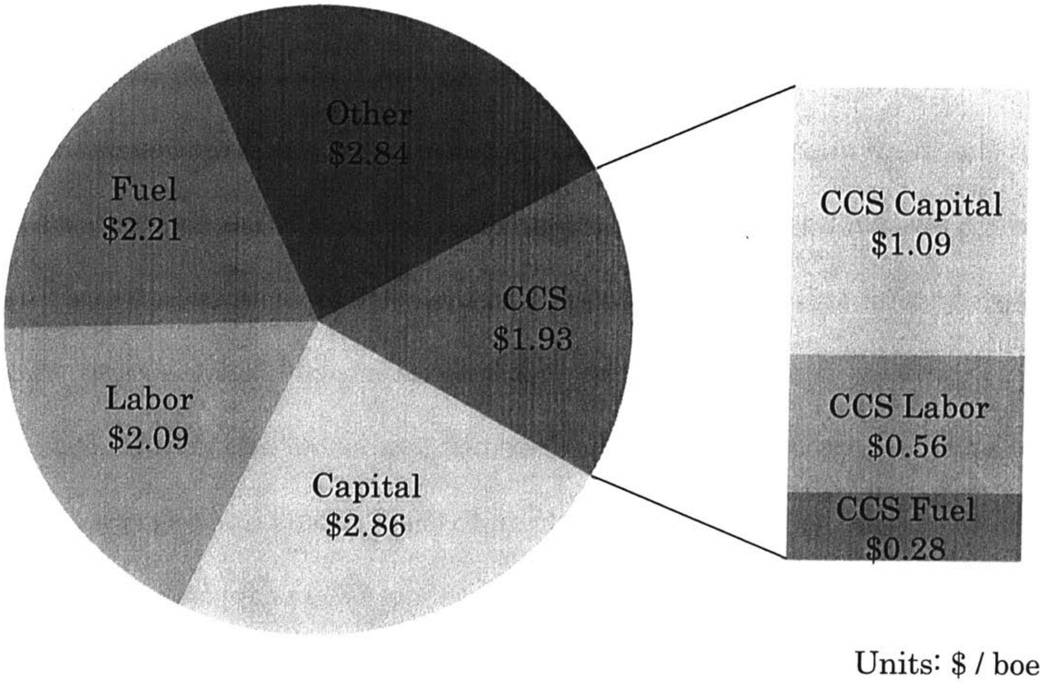


Figure 4.7: Cost of bitumen production & cost of CCS add-on broken down by capital, labor, and fuel costs.

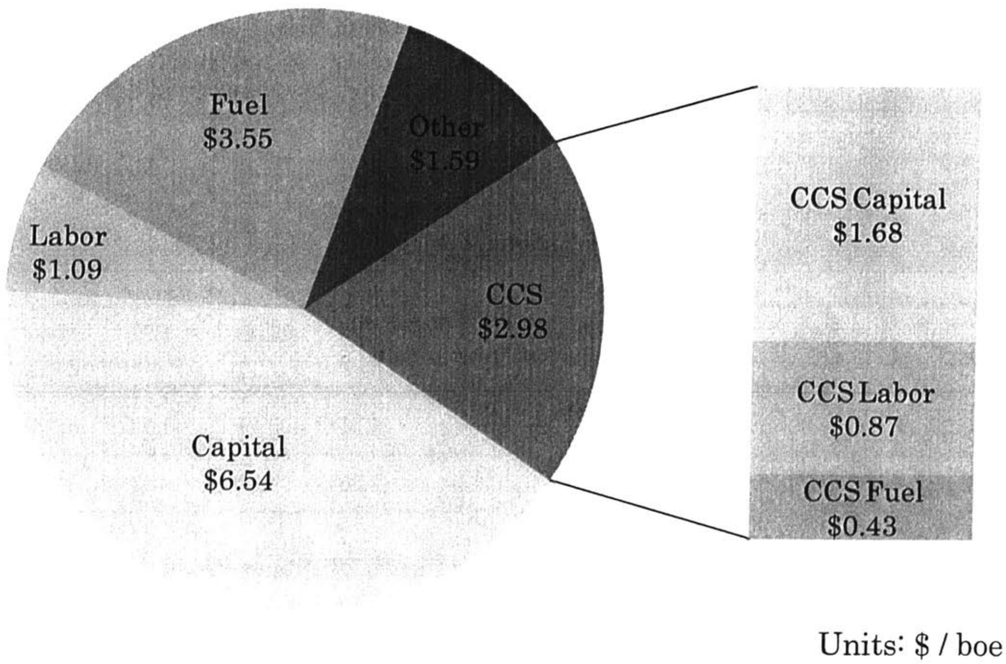


Figure 4.8: Cost of bitumen upgrading & CCS add-on broken down by capital, labor, and fuel costs.

4.4 Results and Analysis

4.4.1 Analysis of the Baseline Policy Case

If Canada adopts the Conservative Party's proposed climate policy (described in Table 4.1), bitumen production could expand significantly, conditional on the availability of unregulated markets to import raw bitumen for upgrading. Under the Conservative Party's climate plan, the gradual rise in the Canadian carbon price erodes bitumen production from 2010 through 2030. Under the policy, the carbon price reaches approximately \$40 / metric ton CO_2 in 2025 and rises through 2050 when the carbon price reaches \$85 / metric ton CO_2. Beginning in 2030, even though the carbon price continues to rise, bitumen production in Canada begins to expand, driven by increasing demand for relatively cheap liquid fuels from unregulated developing countries. This influx of bitumen purchases from developing countries actually helps drive major welfare improvements in Canada. In 2025, Canadian welfare reaches 2.5% below the business as usual predicted welfare, but by 2050, as bitumen production grows, welfare reaches just 0.8% below the projection for business as usual. Figure 4.9 displays the development of the bitumen production industry in Canada.

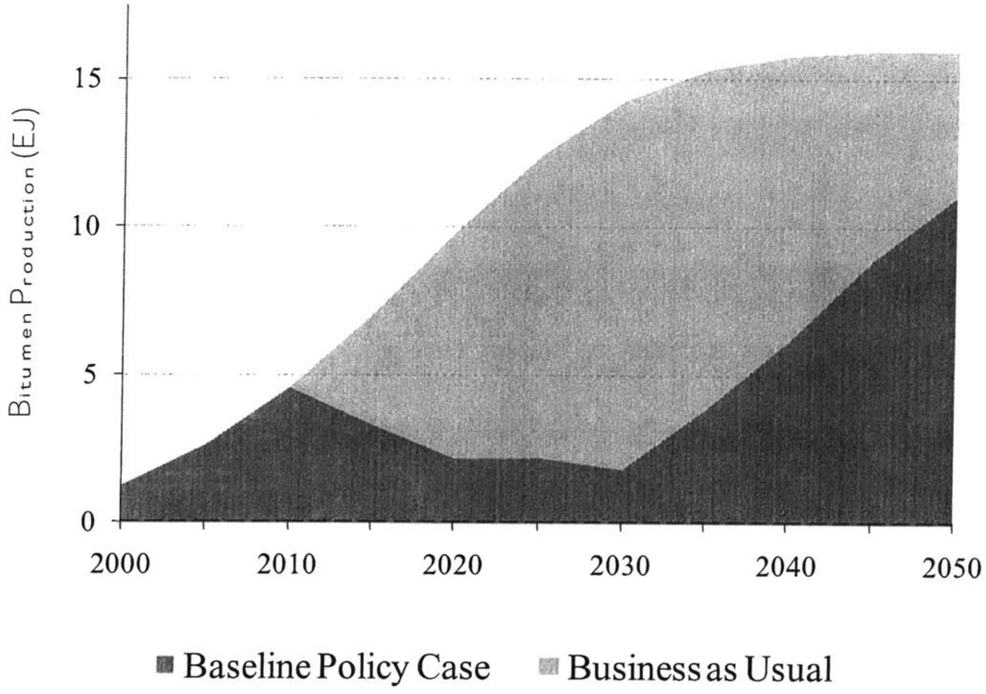


Figure 4.9: Bitumen production from Canadian oil sands from 2000 – 2050. Although bitumen production drops significantly by 2030, from 2030 – 2050, production expands quickly.

Bitumen production from oil sands is economically viable in Canada because of the availability of unregulated regions to purchase bitumen for their own domestic upgrading. Even though shipping bitumen long distances comes at a cost, see Table B.3 in Appendix B, by 2030, bitumen exports from Canada are an attractive option to meet liquid fuel demand in many developing countries. In the baseline policy case, bitumen is upgraded in the Former Soviet Union, Southeast Asia, and China. Figure 4.10 displays the quantity of upgraded bitumen by region from 2000 – 2050. Every unit of bitumen upgraded outside of Canada is associated with leaked CO_2 emissions.

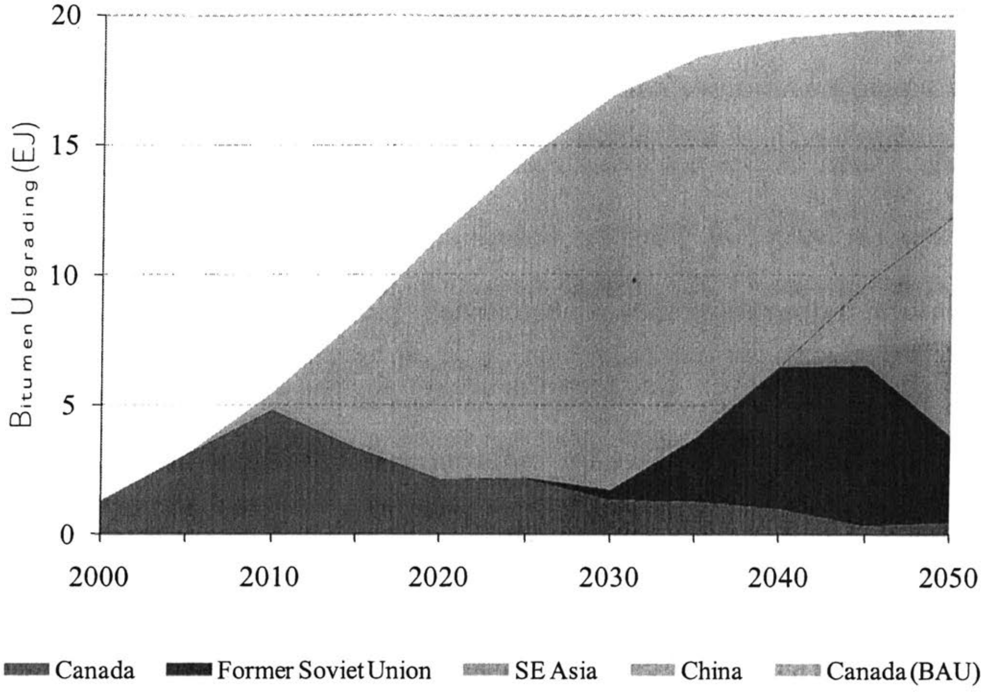


Figure 4.10: Bitumen upgrading by region from 2000 – 2050. By 2050, almost all of Canadian-produced bitumen is upgraded outside of Canada, represented leaked CO_2 emissions.

In this analysis, Canadian bitumen production relies heavily on developing countries as consumers of non-upgraded bitumen who will upgrade bitumen themselves. In Figure 4.10, Canadian bitumen production is plotted over time broken down by the EPPA region where bitumen is upgraded. In the baseline policy case, assuming carbon dioxide is emitted proportionally across regions to the energy content of bitumen upgraded, in 2045 over 95% of bitumen upgrading emissions are leaked to developing countries (32% to the Former Soviet Union, 37% to China, and 26% to India). In 2050, Canada again leaks over 95% of bitumen upgrading emissions (17% to South East Asia, 49% to China, and 29% to India).

4.4.2 Sensitivity Analysis to Canadian Policy without CCS

In this section I apply the Canadian policy scenarios described in Section 4.3.1. These policy scenarios assume that developing countries do not enact any level of climate policy. When CCS is not available, bitumen upgrading begins to shift abroad at policy cases stricter than Policy 50. As Canadian policy becomes stricter, a larger quantity of bitumen upgrading moves abroad as it becomes more expensive to upgraded bitumen in Canada. However, this trend is broken for the strictest Canadian policy case, Policy 110. In order to achieve the emission reduction goals in Policy 110, the Canadian carbon price is set higher enough to make the extraction of bitumen from tar sand prohibitively expensive. In Policy 110, the revenue from extracting bitumen is actually less than the cost of extraction and the climate policy compliance cost (i.e. permit price multiplied by emissions). This finding suggests that as long as developing countries do not enact climate policy, the Canadian oil sands industry can remain economically viable for more levels of Canadian climate policy stringency. Figure 4.11 shows the quantity of leaked crude bitumen leaked to developing countries for upgrading there.

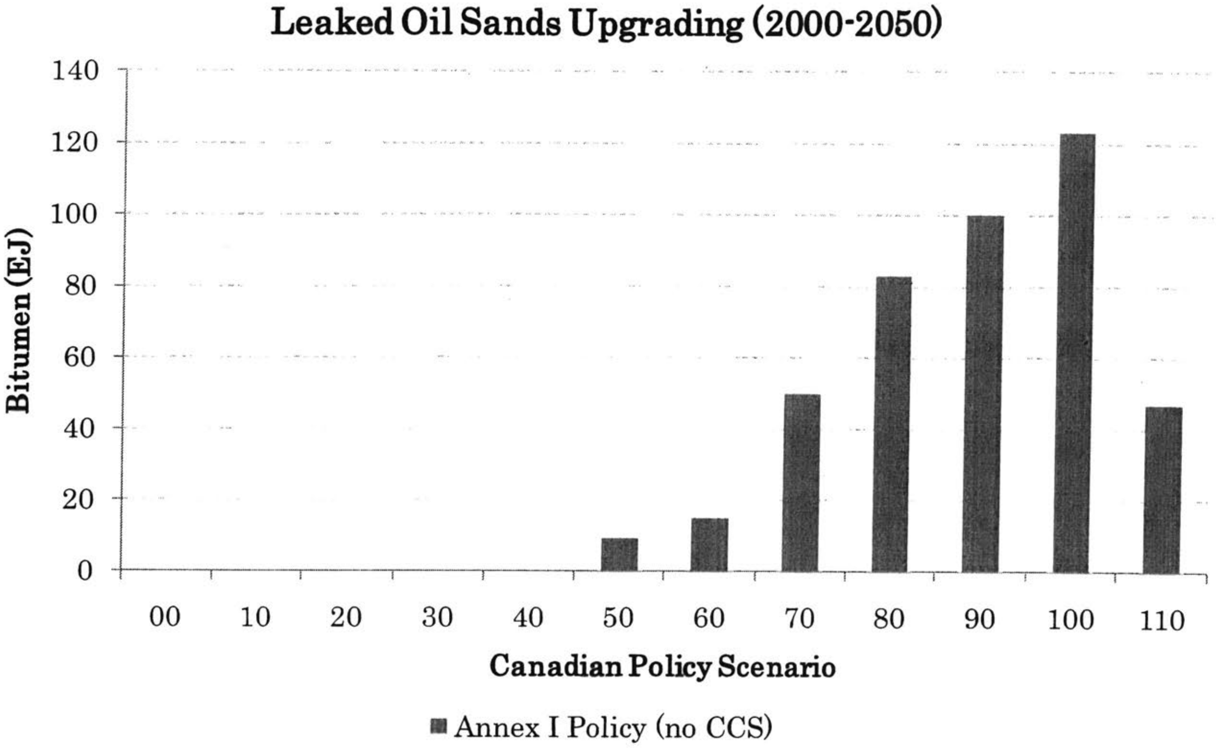


Figure 4.11: Quantity of leaked bitumen upgrading to developing countries from Canada. Canadian climate policy stringency is increasing to the right. The positive relationship between Canadian climate policy stringency and leaked bitumen upgrading is reversed for Policy 110.

Emission leakage from bitumen upgrading can also be expressed as a percentage of total bitumen upgraded in Canada and abroad. Assuming that CO_2 emissions are proportional to the energy content of final upgraded bitumen, this percentage will be the emission leakage rate.[1] Figure 4.12 replicates Figure 4.11 but for the annual emission leakage rate for Canadian bitumen upgrading in 2050 and for cumulative leakage from 2000 – 2050.

---

[1] In reality, the emission intensity of bitumen upgrading is likely higher in developing technologies. This would make my estimate of emission leakage too low.

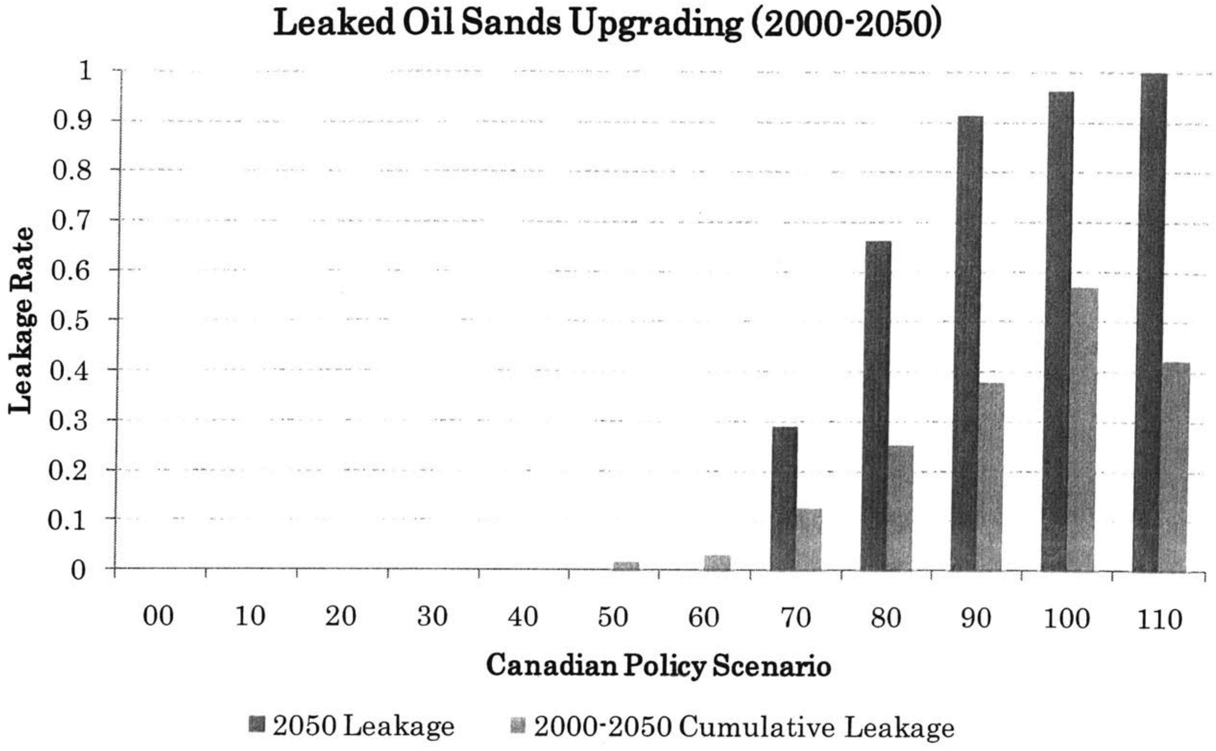


Figure 4.12: The CO_2 emission leakage rate for Canadian-produced bitumen upgrading expressed as 2050 leakage rate and the cumulative leakage rate from 2000-2050. Leakage occurs in developing countries, particularly to China and Southeast Asia.

Cumulative emission leakage is the greatest under Policy 100, when cumulative CO_2 leakage from 2000 – 2050 is 60%. 2050 leakage rates are over 90% for Policies 90, 100, and 110.

4.4.3 Sensitivity to Canadian Policy with CCS

CCS provides a low carbon substitute for traditional bitumen production and upgrading. The availability of CCS provides a means for bitumen to be produced or upgraded at a higher cost but with lower CO_2 emissions. Therefore, CCS becomes economical at certain carbon prices and unambiguously increases welfare; merely having the option of a new technology can't be bad.

Because the availability of CCS lowers the marginal cost of bitumen upgrading in Canada for the same climate policy stringency, it becomes cheaper to retain bitumen for domestic upgrading. Therefore, the total leakage rate decreases for most levels of climate policy. When CCS was not available, the carbon price in Policy 110 was so strict that bitumen production was no longer economical. However, with CCS available, this constraint is lifted from bitumen production because bitumen can be produced at significantly lower cost. Therefore, because more bitumen can be produced, emission leakage actually increases when Canada adopts Policy 110. Figure 4.13 displays the quantity of leaked bitumen upgrading when CCS is not available and when CCS is made available.

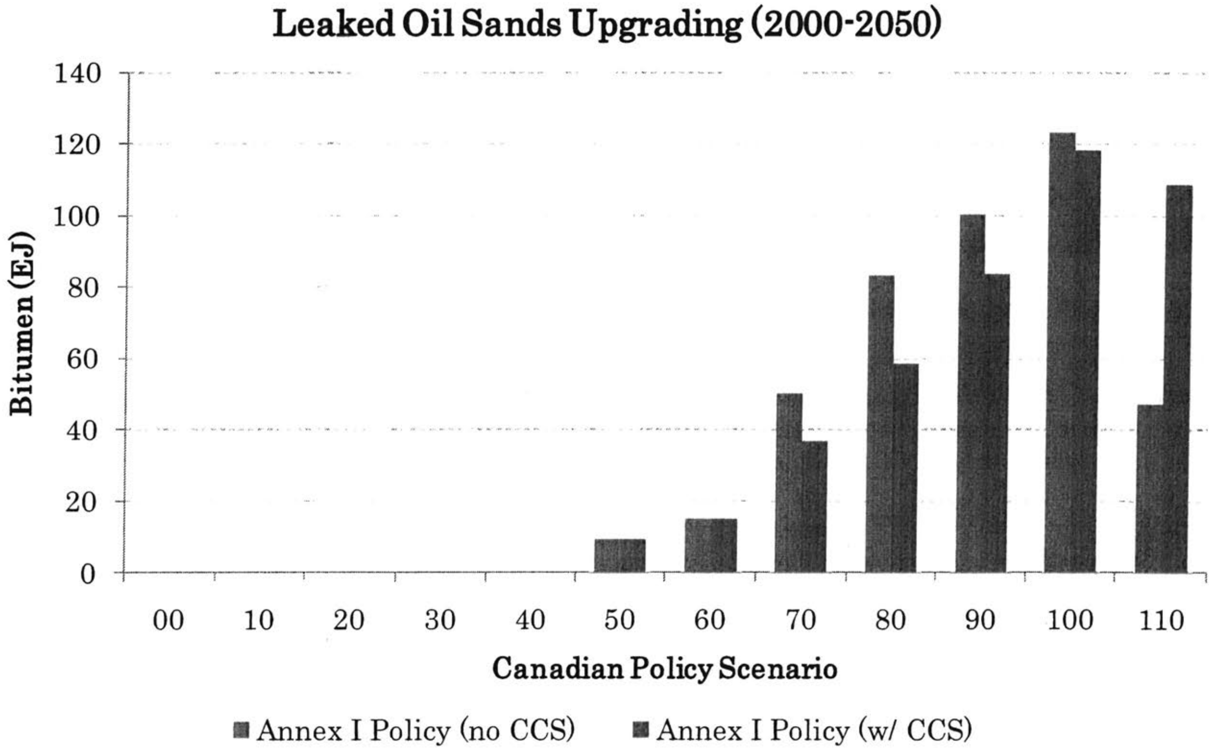


Figure 4.13: Quantity of leaked bitumen upgrading to developing countries from Canada with and without CCS availability. Canadian climate policy stringency is increasing to the right. CCS

availability decreases emission leakage for all climate policies except Policy 110.

Bitumen upgrading leakage when CCS is available is also expressed as leakage rates in figure 4.14. Again, the reversal in the positive relationship between Canadian policy stringency and emission leakage is not present when CCS is available.

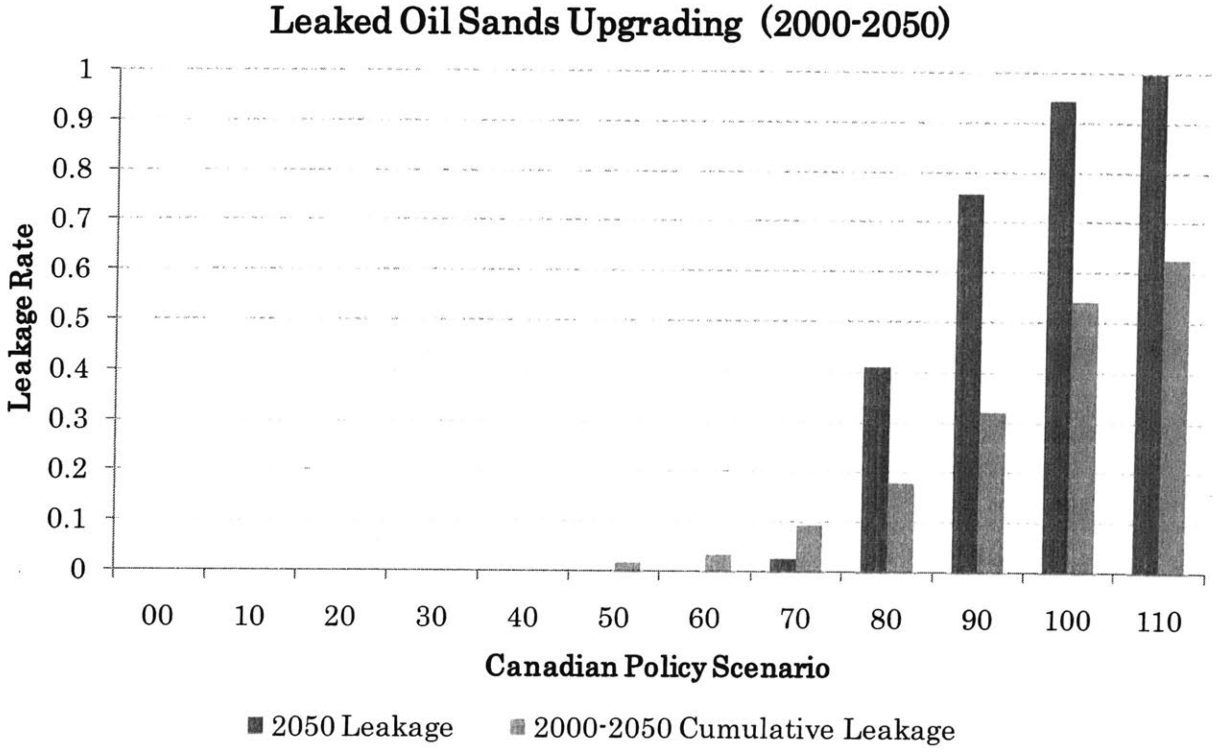


Figure 4.14: CO_2 emission leakage rate when CCS is available for Canadian-produced bitumen expressed as 2050 leakage rate and the cumulative leakage rate from 2000-2050. The leakage rate is always a positive function of Canadian climate policy stringency.

Carbon capture and storage technology could potentially offer a very low-cost option for reducing CO_2 emissions. However, the effect of CCS availability on the effectiveness of climate policy is ambiguous. For weaker climate policy, CCS increases the effectiveness of climate policy by decreasing CO_2 emission leakage. However, for very strict climate policy, CCS increases leakage by providing low-cost options for regulated regions, such as Canada, to increase their production of fossil fuels for consumption both domestically and elsewhere.

Chapter 5

Conclusion and Policy Recommendations

This thesis has provided two distinct methods for quantifying the magnitude of CO_2 emission leakage under prospective climate policy. Based on this analysis, CO_2 emission leakage will make climate policy substantially less effective. In the steel industry, I estimate that for every 1 unit of CO_2 avoided in the U.S. steel industry, an additional 0.4 unit of CO_2 is emitted elsewhere in the world. In the Canadian oil sands industry, I estimate that for every unit of bitumen produced from the Canadian oil sands, over 90% of CO_2 emissions from upgrading that bitumen to synthetic crude oil are leaked to developing countries.

In order for climate policy to be effective, policymakers should address the issue of emission leakage. However, the policy options to address emission leakage can easily be hijacked by protectionist ideological fervor. In designing climate policy to mitigate emission leakage and make domestic action more effective, several guidelines should be practiced by policymakers (Frankel, 2009):

- Terms of trade agreements should be made multilaterally so that they are perceived as fair in the eyes of regulators (i.e. the WTO) and the economic “losers.”
- Judgments of factual statistics in other regions, such as emission intensities of production from imports, should be made by an independent body to avoid the perception of bias.
- Import and export restrictions should only be levied on a few specific energy-intensive industries and fossil fuel industries to lessen the costs of implementation and increase the chances of success.

Appendix A

Emission Leakage in an Incompletely Regulated Cournot Duopoly

Relevant equations from Chapter 3:

$$q_1 = -\frac{1}{2}q_2 + \frac{a - c_1 - r_1\tau e_1}{2b} \tag{3.12}$$

$$q_2 = -\frac{1}{2}q_1 + \frac{a - c_2 - r_2\tau e_2}{2b} \tag{3.13}$$

$$L = -\frac{e_2}{e_1}\left[\frac{q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0\end{pmatrix} - q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0\end{pmatrix}}{q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0\end{pmatrix} - q_1\begin{pmatrix} r_1 = 0 \\ r_2 = 0\end{pmatrix}}\right] \tag{3.15}$$

To solve for Equation 3.15, I solve for each quantity in 3.15 individually by substituting Equations 3.12 and 3.13 into 3.15. First, solve for $q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0\end{pmatrix}$:

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}q_1 + \frac{a - c_2 - r_2\tau e_2}{2b} \tag{A.1}$$

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}q_1 + \frac{a - c_2}{2b} \tag{A.2}$$

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}\left[-\frac{1}{2}q_2 + \frac{a - c_1 - r_1\tau e_1}{2b}\right] + \frac{a - c_2}{2b} \tag{A.3}$$

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{1}{4}q_2 - \frac{a - c_1 - \tau e_1}{4b} + \frac{a - c_2}{2b} \tag{A.4}$$

$$\frac{3}{4}q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{a - c_1 - \tau e_1}{4b} + \frac{2a - 2c_2}{4b} \tag{A.5}$$

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{4}{3}\left[\frac{a + c_1 + \tau e_1 - 2c_2}{4b}\right] \tag{A.6}$$

$$q_2\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{a + c_1 + \tau e_1 - 2c_2}{3b} \tag{A.7}$$

Next, solve for $q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix}$ beginning with Equation A.3:

$$q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}\left[-\frac{1}{2}q_2 + \frac{a - c_1}{2b}\right] + \frac{a - c_2}{2b} \tag{A.8}$$

$$q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = \frac{1}{4}q_2 - \frac{a - c_1}{4b} + \frac{a - c_2}{2b} \tag{A.9}$$

$$\frac{3}{4}q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = -\frac{a - c_1}{4b} + \frac{2a - 2c_2}{4b} \tag{A.10}$$

$$q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = \frac{4}{3}\left[\frac{a + c_1 - 2c_2}{4b}\right] \tag{A.11}$$

$$q_2\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = \frac{a + c_1 - 2c_2}{3b} \tag{A.12}$$

Next, solve for $q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix}$:

$$q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}q_2 + \frac{a - c_1 - \tau e_1}{2b} \tag{A.13}$$

$$q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{1}{2}\left[-\frac{1}{2}q_1 + \frac{a - c_2 - r_2\tau e_2}{2b}\right] + \frac{a - c_1 - \tau e_1}{2b} \tag{A.14}$$

$$q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{1}{4}q_1 - \frac{a - c_2}{4b} + \frac{a - c_1 - \tau e_1}{2b} \tag{A.15}$$

$$\frac{3}{4}q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = -\frac{a - c_2}{4b} + \frac{2a - 2c_1 - 2\tau e_1}{4b} \tag{A.16}$$

$$q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{4}{3}\left[\frac{a - 2c_1 - 2\tau e_1 + c_2}{4b}\right] \tag{A.17}$$

$$q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix} = \frac{a - 2c_1 - 2\tau e_1 + c_2}{3b} \tag{A.18}$$

Next, solve for $q_1\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix}$ using A.18 and noting that $q_1\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix}$ will be highly related to $q_1\begin{pmatrix} r_1 = 1 \\ r_2 = 0 \end{pmatrix}$:

$$q_1\begin{pmatrix} r_1 = 0 \\ r_2 = 0 \end{pmatrix} = \frac{a - 2c_1 + c_2}{3b} \tag{A.19}$$

Finally, plug Equations A.7, A.12, A.18, and A.19 into Equation 3.15 to find L:

$$L = -\frac{e_2}{e_1}\left[\frac{\frac{a + c_1 + \tau e_1 - 2c_2}{3b} - \frac{a + c_1 - 2c_2}{3b}}{\frac{a - 2c_1 - 2\tau e_1 + c_2}{3b} - \frac{a - 2c_1 + c_2}{3b}}\right] \tag{A.20}$$

$$L = -\frac{e_2}{e_1}\left[\frac{\frac{\tau e_1}{3b}}{-\frac{2\tau e_1}{3b}}\right] \tag{A.21}$$

$$L = \frac{e_2}{2e_1} \tag{A.22}$$

Appendix B

Bitumen CCS Cost Input/Cost Shares

Input	Canada (w/o CCS)		Canada (w/ CCS)	
	Bitumen Production	Bitumen Upgrading	Bitumen Production	Bitumen Upgrading
GAS	2.16	2.89	2.43	3.24
RGAS	0.18	0.18	0.18	0.18
HFOL	0.05	0.66	0.06	0.74
ELEC	0.14	0.16	0.14	0.16
K	2.86	6.54	3.95	8.22
L	2.09	1.09	2.65	1.97
EINT	0.35	0.75	0.35	0.75
SERV	0.15	0.09	0.15	0.09
TRAN	0.92	0.41	0.92	0.41
Non-conventional Resource	1.00	-	1.00	-
Bitumen	-	10.00	-	10.00
Fixed Factor	0.10	-	0.10	-
Resulting CO_2 emissions (kg/boe produced)	55.00	85.00	7.15	11.05
Production Cost ($/boe produced)	10.00	22.78	11.93	25.76

Table B.1: Bitumen CCS cost shares for Canada

Input	Canada (w/o CCS)		Canada (w/ CCS)	
	Bitumen Production	Bitumen Upgrading	Bitumen Production	Bitumen Upgrading
GAS	0.216	0.127	0.204	0.126
RGAS	0.018	0.008	0.015	0.007
HFOL	0.005	0.029	0.005	0.029
ELEC	0.014	0.007	0.012	0.006
K	0.286	0.287	0.331	0.319
L	0.209	0.048	0.222	0.076
EINT	0.035	0.033	0.029	0.029
SERV	0.015	0.004	0.013	0.004
TRAN	0.092	0.018	0.077	0.016
Non-conventional Resource	0.100	-	0.084	-
Bitumen	-	0.439	-	0.388
Fixed Factor	0.010	-	0.008	-
Resulting CO_2 emissions (kg/boe produced)	55.00	85.00	7.15	11.05
Production Cost ($/boe produced)	10.00	22.78	11.93	25.76

Table B.2: Bitumen CCS Input shares for Canada

Upgrading Region	Mark-up Factor
U.S.	1.25
Canada	1.08
Japan	1.30
Former Soviet Union	1.30
East Asia	1.30
India	1.35
Latin America	1.05

Table B.3: Cost mark-ups of upgrading bitumen in other regions. This mark-up represents the additional costs of physically transporting bitumen from the oil fields where they are extracted to the refineries where they are upgraded.

References

Ansolabehere, S., Beer, J., Deutch, J., Ellerman, D., Friedmann, J., Herzog, H., et al. (2007). *The Future of Coal.* Cambrdige: MIT.

Benabou, R. (1996). Unequal Societies. *NBER Working Paper No. W5583* .

Blasing, T., & Smith, K. (2006, July). *Recent Greenhouse Gas Concentrations.* Retrieved from http://cdiac.ornl.gov/pns/current_ghg.html

Bohm, M., Herzog, H., Parsons, J., & Sekar, R. (2007). Capture-Ready Coal Plants -- Options, Technologies and Economics. *International Journal of Greenhouse Gas Control* .

BP. (2007). *Statistical Review of World Energy 2007.* BP Global.

Bureau of Labor Statistics. (2008, March 12). *Career Guide to Industries.* Retrieved from Steel Manufacturing: http://www.bls.gov/oco/cg/cgs014.htm

Bureau of Mines (USGS). (1982). Metals and Minerals. *Minerals Yearkbook 1982* . Washington, D.C.: US Department of the Interior.

Choumert, F., Paltsev, S., & Reilly, J. (2006). *Improving the Refining Sector in EPPA, Technical Note No. 9.* Cambridge: MIT Joint Program on the Science and Policy of Global Change.

Cox, S., & Vadon, R. (2007, January 26). Running the Rule Over Stern's Numbers. *BBC News: The Investigation* .

Crandall, R. W. (1981). *The U.S. Steel Industry in Recurrent Crisis.* Washington, D.C.: Brookings Institute.

Deutch, J. M., & Lester, R. K. (2004). *Making Technology Work: Applications in Energy and the Environment.* Cambridge: Cambridge University Press.

Eilperin, J. (2006, January 29). Debate on Climate Shifts to Issue of Irreparable Change. *Washington Post* , p. A01.

Energy Information Administration. (Annual Energy Review). *2004.* Washington, D.C.: US Department of Energy.

Energy Information Administration. (n.d.). *Receipts, Average Cost, and Quality of Fossil Fuels for the Electric Power Industry".* Retrieved from http://www.eia.doe.gov/cneaf/electricity/epa/epat4p5.html

Energy Resources and Conservation Board. (2009). *Frequently Asked Questions on the Development of Alberta's Energy Resources.* Retrieved 2009, from Calgary, Canada: http://www.ercb.ca/docs/public/EnerFAQs/PDF/EnerFAQs12-OilSands.pdf

Environment Canada. (2008). *National Inventory Report 1990-2006: Greenhouse Gas Sources and Sinks in Canada.* Gatineau, Quebec: Environment Canada.

Esber III, G. S. (2006). *Carbon Dioxide Capture Technology for the Coal-Powered Electricity Industry: A Systematic Prioritization of Research Needs.* Cambridge: MIT.

Fenton, M. D. (2009). *Mineral Commodity Summaries: Iron and Steel.* Washington, D.C.: U.S. Geological Survey.

Fowlie, M. (2009). Incomplete Environmental Regulation, Imperfect Competition, and Emissions Leakage. *MIT Department of Economics Public Economics Seminar* (pp. 6-12). Cambridge: University of Michigan.

Frankel, J. (2009). *Environmental Effects of International Trade.* Stockholm: Globalization Council.

Galor, O., & Zeira, J. (1993). Income Distribution and Macroeconomics. *Review of Economic Studies* , 35-52.

Government of Alberta. (2009). *About the Oil Sands.* Retrieved from Alberta, Canada: http://oilsands.alberta.ca/1.cfm

Grübler, A. (2003). *Technology and Global Change.* Cambridge: Cambridge University Press.

Harris, R. G. (1994). Trade and Industrial Policy for a 'Declining' Industry: The Case of the U.S. Steel Industry. In P. Krugman, & A. Smith, *Empirical Studies of Strategic Trade Policy* (pp. 131-156). Chicago: The University of Chicago Press.

Ho, M. S., Morgenstern, R., & Shih, J.-S. (2008). *Impact of Carbon Price Policies on U.S. Industry.* Washington, D.C.: Resources for the Future.

Intergovernmental Panel on Climate Change. (2007). *Climate Change 2007.* Cambridge: Cambridge University Press.

International Energy Agency. (2005). *Extended Energy Statistics.* Paris: International Energy Agency.

International Energy Agency. (2007). *World Energy Outlook 2007.* IEA.

IPCC. (2007). *Industry in Climate Change 2007: Mitigation.* Cambridge: Cambridge University Press.

Jaffe, A., Newell, R., & Stavins, R. (2001). *Technological Change and the Environment.* Washington, D.C.: Resources for the Future.

James, S. (2009, May 14). U.S. Steelmakers Fear Burden in Climate Rules. *Reuters* .

McKinsey & Co. and Ecofys. (2006). *EU ETS Review: Report on the International Competitiveness.* Brussels: European Commission (Directorate General for Environment).

MIT Joint Program on the Science and Policy of Global Change. (2009). *Economics, Emissions, and Policy Cost - The EPPA Model.* Retrieved 2009, from MIT Global Change Program: http://globalchange.mit.edu/igsm/eppa.html

Paltsev, S., Reilly, J. M., Jacoby, H. D., & Morris, J. F. (2009). *The Cost of Climate Policy in the United States.* Cambridge: MIT Joint Program on the Science and Policy of Global Change.

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J., Sarofim, M., et al. (2005). *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4.* Cambridge: MIT Joint Program on the Science and Policy of Global Change.

Pindyck, R. S., & Rubinfeld, D. L. (2001). *Microeconomics* (5th ed.). Upper Saddle River, New Jersey: Prentice Hall.

Raupach, M., Marland, G., Ciais, P., Le Quere, C., Canadell, J., Klepper, G., et al. (2007). Global and Regional Drivers of Accelerated CO2 Emissions. *104* (24), 10288-10293.

Reinaud, J. (2005). *Industrial Competitiveness under the European Union Emissions Trading Scheme.* Paris: International Energy Agency.

Schmalensee, R., Joskow, P. L., Ellerman, D. A., Montero, J. P., & Bailey, E. M. (1998). An Interim Evaluation of Sulfur Dioxide Emissions Trading. *Journal of Economic Perspectives , 12* (3), 53-68.

Stern, N. (2006). *Stern Review on the Economics of Climate Change.* Cambridge: Cambridge University Press.

Stigler, G. (1971). The Theory of Economic Regulation. *The Bell Journal of Economics and Management Science , 2* (1).

The Economist. (2008, August 25). The Politics of Sand. *The Economist* .

The World Bank. (2009). *Measuring Income Ineqaulity Database.* Retrieved April 1, 2009, from http://go.worldbank.org/UVPO9KSJJ0

U.S. Bureau of Labor Statistics. (2009). Consumer Price Index. Washington, D.C.: U.S. Department of Labor.

U.S. Bureau of Labor Statistics. (2009). Iron and Steel. *Producer Price Index-Commodities* . Washington, D.C.: U.S. Department of Labor.

U.S. Bureau of Labor Statistics. (2009). Producer Price Index. *Commodity Data* . Washington, D.C.: U.S. Department of Labor.

U.S. Central Intelligence Agency. (2009). *The World Factbook [online].* Washington, DC.

U.S. Central Intelligence Agency. (2008, April 15). *The World Factbook.* Retrieved from https://www.cia.gov/library/publications/the-world-factbook/geos/us.html

U.S. Climate Change Science Program. (2007). *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations.* Washington DC: US Department of Energy.

U.S. Climate Change Technology Program. (2006). *Strategic Plan.* Washington DC: U.S. Department of Energy.

U.S. Environmental Protection Agency. (2009). *2009 U.S. Greenhouse Gas Inventory Report.* Washington, D.C.: U.S. Environmental Protection Agency.

U.S. Geological Survey. (2008). Iron and Steel. *Historical Statistics for Mineral and Material Commodities in the United States* . Washington, D.C.: U.S. Department of the Interior.

U.S. Geological Survey. (2007). *Minerals Yearbook 2007, Iron and Steel.* Washington, D.C.: U.S. Department of the Interior.

US Department of Energy. (2008, January). *Fact Sheet: Bush Administration Requests $648 Million for Coal Programs in FY09.* Retrieved from US Department of Energy Office of Fossil Energy: http://www.fossil.energy.gov/programs/powersystems/futuregen/fy09_coal_budget.pdf

Venables, A. J. (1994). Trade Policy under Imperfect Competition: A Numerical Assessment. In P. Krugman, & A. Smith, *Empirical Studies of Strategic Trade Policy* (pp. 41-66). Chicago: The University of Chicago Press.

Viscusi, W. K., Harrington Jr., J. E., & Vernon, J. M. (2005). *Economics of Regulation and Antitrust* (4th Edition ed.). Cambridge, Massachusetts: The MIT Press.