MODELING THE STATE-LEVEL IMPACTS OF CARBON POLICY:
THE CASE OF COLORADO

by
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ABSTRACT

This study analyzes the impacts, at the state-level, of policies that limit carbon dioxide (CO$_2$) emissions. A multi-sector, dynamic general equilibrium model of the Colorado economy, based on forward-looking agent behavior and capital accumulation, is utilized. Data sources include the state-level IMPLAN social accounts (Minnesota Implan Group, Inc.) and emissions estimates from the Energy Information Administration of the Department of Energy. This model is used to examine Colorado’s stated long-term goal of an 80% reduction in CO$_2$ emissions from 2005 levels by 2050. The central case, which relies on tradable emissions allowances to meet the desired reduction, results in permit prices rising from $4 to $167 over the period 2020-2060, with consumer welfare declining by 0.62% and consumption declining by 4%, relative to baseline levels. The rate of emissions leakage peaks at 7%, driven by high leakage rates in electricity generation. When this policy is used with the state’s existing renewable portfolio standard, the interaction is found to further depress consumer welfare while decreasing emissions leakage and increasing the net tons of emissions reduction achieved.
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A.1 Elasticities used in nested CES production and utility functions.
LIST OF ABBREVIATIONS

AGR  Agriculture
BAU  Business-as-usual
CCX  Chicago Climate Exchange
CDM  Clean Development Mechanism
CES  Constant Elasticity of Substitution
CGE  Computable General Equilibrium
CO₂  Carbon Dioxide
COL  Coal mining
CRU  Crude oil and gas extraction
EIA  Energy Information Agency
ELE  Electricity generation
EPA  Environmental Protection Agency
ERMS Emissions Reduction Market System
EU-ETS European Union Emissions Trading System
GAMS General Algebraic Modeling System
GAS  Natural Gas
GHG  Greenhouse Gas
K    Capital
L    Labor
MAC  Marginal Abatement Cost
MAN  Manufacturing
MPSGE Mathematical Programming System for General Equilibrium (Analysis)
NAP  National Allocation Plan
OIL  Oil products
OTH  Other sectors (non-coal mining, transportation, and others)
RGGI Regional Greenhouse Gas Initiative
RPS  Renewable Portfolio Standard
SAM  Social Accounting Matrix
SO$_2$ Sulfur Dioxide
SRV  Services
WCI  Western Climate Initiative
Chapter 1

INTRODUCTION AND RELEVANT LITERATURE

ABSTRACT

Within the US, in the absence of a national greenhouse gas emissions reduction policy, many state and local governments have committed to their own emissions restrictions. These restrictions include state-level renewable portfolio standards or efficiency requirements, or emissions trading programs involving coalitions of states. The state of Colorado has a goal of reducing CO$_2$ emissions by 80% of 2005 levels by 2050. In order to investigate how such a goal can be met, this chapter explores how tradable emissions permits have been used historically to reduce the emissions of various pollutants, and how these systems are currently being used to reduce GHG emissions. The chapter also introduces computable general equilibrium (CGE) modeling, a tool used in later chapters to model the state of Colorado.

1.1 Introduction

The purpose of this dissertation is to measure the impacts on the Colorado state economy of a proposed reduction in carbon dioxide (CO$_2$) emissions, by use of an emissions permit policy. The proposal calls for an 80% reduction below 2005 emissions levels by 2050. Chapter 2 measures these impacts under some basic assumptions: Colorado is a small, open economy that acts unilaterally to reduce its emissions; consumers and producers are forward-looking and exhibit optimizing behavior; and
renewable electricity production is available, but not required. Under these assumptions, we find that welfare falls by 0.62%, compared with a business-as-usual scenario, between 2005 and 2060. Note that this measure of welfare focuses solely on the costs of the policy; any benefits of the policy are not considered. Consumption falls by 4% relative to the baseline by the end of this time period and permit prices peak at $167.34 in the year 2050.

Chapter 3 investigates the effectiveness of the policy by considering the “leakage” of emissions to other states. Because Colorado is assumed to act unilaterally, productive activities can move out of state to avoid purchasing emissions permits. The final goods can be imported back to Colorado, weakening the effectiveness of the emissions reduction policy. We find peak leakage rates of 21.6% for the electricity sector and 7% economy-wide, meaning that for every ton of CO₂ emissions avoided within Colorado, 0.07 tons are added outside of the state. These leakage rates depend on the flexibility to substitute imported electricity, or to substitute between electricity and fuels.

In Chapter 4, we investigate how the existing renewable portfolio standard (RPS) in Colorado affects the outcome of the permit system. The standard requires that 20% of electricity sold in Colorado be generated by renewable sources by 2020. While the RPS aims to reduce emissions of CO₂, the policy imposes an additional constraint on emissions reduction. We find that using these policies together reduces permit prices and emissions leakage in early periods, and the reduction in emissions leakage means that Colorado achieves a larger net emissions reduction. The RPS adds a binding constraint in early periods that forces investments in renewable technology. This technology would have become economical in later periods without the RPS requirement, and the suboptimal allocation in early periods leads to lower levels of
consumer welfare.

This chapter serves as an introduction to the areas of emissions trading, state-level emissions policy, and relevant modeling techniques. Section 1.2 discusses the potential impacts of climate change for the state of Colorado and some policies already in place to reduce CO$_2$ emissions. Advantages of using a permit system to achieve the emissions reduction goal are discussed in Section 1.3, as well as some lessons from other existing permit systems. The modeling techniques are introduced in Section 1.4, along with some related studies. Finally, Section 1.5 outlines the rest of the dissertation.

1.2 Motivation

The theory that global climate change is occurring due to the accumulation of greenhouse gasses (GHGs), such as CO$_2$, in the atmosphere has been proposed by the scientific community for decades. Because of the efforts of high profile politicians and members of the media (and the occasional polar bear), the American public has recently turned its attention to this issue. Many citizens have personally taken steps to reduce their carbon footprints, and the list of private firms offering ways for consumers to offset and reduce their use of fossil fuels grows longer by the day. Although the consequences of climate change are difficult to predict, the potential exists for massive environmental changes that could endanger human lives and cause economic and political instability. In light of these risks, lawmakers are being called upon to come up with strategies to reduce GHG emissions on a global scale.

In 2001, the U.S. declined to join the Kyoto Protocol, an international agreement limiting member nations’ greenhouse gas emissions. This agreement would have required the US to reduce GHG emissions to 93% of their 1993 levels by 2012 (Anderson
Since this decision, in the absence of a national GHG emissions reduction policy, many state and local governments have committed to similar goals or passed other legislation to restrict GHG emissions. These governments include the ten northeastern states committed to the Regional Greenhouse Gas Initiative (RGGI) and the seven states collaborating as partners in the Western Climate Initiative (WCI). Although GHG emissions are pollutants which act on a global scale, residents of these regions are concerned enough about the problem of climate change to demand action. Within the state of Colorado, several measures for reducing emissions have been enacted or are currently under consideration.

1.2.1 Concerns for Colorado

Colorado residents have reason to be especially concerned about climate change. According to the Rocky Mountain Climate Organization, the American West is especially vulnerable to rising temperatures, and is experiencing faster warming than the global average (Saunders et al. (2008)). Recent years have seen less precipitation, shorter winters, and a reduced snowpack (Ritter (2007)). Obviously, the state’s famed mountain resorts will suffer from a lack of snow, but the state depends on this snowpack throughout the year to replenish reservoirs and aquifers. Colorado is already prone to drought and wildfires, and these conditions may become more severe as temperatures rise. Industries important to the state’s identity, such as farming and ranching may be threatened by additional warming. Wild animals are expected to move to higher altitudes, seeking cooler temperatures. This loss of habitat for plant and animal species will not only affect the state’s ecology, but also the wildlife viewing and hunting activities popular with residents and tourists alike.

One highly publicized threat to Colorado is the mountain pine beetle. With
warmer winters, fewer of these insects are killed by severe freezing temperatures, and the insects can move to higher altitudes, compounding the risk for wildfires. The mountain pine beetle affects several types of pine found in Colorado forests and are controlled in the following manner:

For freezing temperatures to affect a large number of larvae during the middle of winter, temperatures of at least 30 degrees below zero (Fahrenheit) must be sustained for at least five days... Once MPB infests a tree, nothing practical can be done to save that tree. (Leatherman et al. (2007)).

The affected area is quite large, and some camping and wilderness areas have been closed because of fire danger.

Their favorite meal: the majestic lodgepole pine, which makes up 8 percent of Colorado’s 22 million acres of forests... So far, say state foresters, the beetles have eaten through 1.5 million acres, about 70 percent of the all the state’s lodgepole pines. The tree’s entire population will be wiped out in the next few years, Colorado state foresters predict, leaving behind a deforested area about the size of Rhode Island. (Moscou (2008)).

The loss of these trees is not merely aesthetic; the potential for fire caused by these dead pines endangers property and public safety. The burning or rotting of these logs will release more carbon emissions. Kurz et al. (2008) suggest that recent beetle outbreaks in British Columbia, Canada have turned that region from a “small net carbon sink to a large net carbon source.”

These threats to Colorado – risks to valuable crops, destruction of animal habitat, loss of life and property to wildfires, reduced demand for tourism, deforestation, and
drought conditions – have led citizens of the state to demand legislative action to reduce GHG emissions. These actions are being undertaken in spite of the fact that Colorado’s contribution to global atmospheric concentrations of CO$_2$ are small, and a reduction in emissions on the part of Colorado residents will do little to change Colorado’s future without national and international commitments. The next section details a variety of policies, both existing and under consideration, which are designed to reduce emissions in the state of Colorado.

1.2.2 Greenhouse Gas Reduction Policies in Colorado

In 2004, Colorado voters became the first in the nation to use a ballot initiative to pass a renewable portfolio standard (RPS). Amendment 37 mandates that 10% of electricity sold in the state come from renewable sources by 2015. These requirements were increased by the legislature in 2007, to a 20% requirement by 2020.$^1$ Much of this electricity is currently produced by wind and solar energy; other options such as biomass and fuel cell production are also allowed. More information about this policy can be found in Chapter 4.

Cities such as Boulder, Denver, and Aspen have evaluated their emissions output and have set goals for reduction of emissions. Several counties and municipalities offer rebates or subsidies for energy-efficient appliances or solar panels. Other current initiatives call for greater use of natural gas in electricity generation instead of coal, the implementation of cleaner coal technologies, green building requirements, higher energy efficiency standards, and an even greater reliance on renewable energy.

The state has founded the Colorado Climate Project, an initiative supported

\[^1\text{The full text of this amendment is available at}\]
\[\text{http://www.dsireusa.org/documents/Incentives/O26R.htm}\]
by the Center for Climate Strategies, and is an Observer in the Western Climate Initiative (WCI). The governor has announced that if no progress is made toward nationwide emissions reduction legislation in 2008, the state will consider becoming a trading member of the WCI. In the meantime, the governor has suggested a reduction in GHG emissions by 20 percent from 2005 levels by 2020 and then by 80 percent by 2050. To help accomplish these goals, the governor has also called for reporting of GHG emissions and for both the Climate Advisory Panel and the Public Utilities Commission to make recommendations on how this reduction can be achieved (Ritter (2007)).

1.2.3 National Policy Goals

The governor's announced goals are similar to those in the Waxman-Markey American Clean Energy and Security Act. This bill was passed in the House of Representatives in June 2009 and is awaiting action by the Senate. The bill calls for a 14% reduction in GHG emissions from 2005 levels by 2020, and by 83% by 2050. President Obama has endorsed such a policy, which would be achieved through a cap-and-trade system with some permit auctioning. The revenues from these auctions would be used to fund development of cleaner and more efficient technology, restore wildlife habitat, and provide assistance to low-income consumers. The president has also joined G-8 leaders in committing to an 80% emissions reduction as a means to limit the increase in global average temperatures to less than two degrees Celsius.

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2Observer states have not committed to the WCI’s proposed cap-and-trade system.
3http://thomas.loc.gov/cgi-bin/query/D?c111:3.:/temp/ c111WNbRFM::
1.3 Tradable Emissions Permits

The proposals discussed in the previous section utilize tradable emissions permits, originally proposed by Crocker (1966) and Dales (1968), which have been successfully used to reduce or eliminate many pollutants in the US and other nations. The European Union is currently using emissions permits to limit output of GHGs, and such policies have been used nationally and sub-nationally within the US to reduce emissions of other pollutants. This section discusses the benefits of emissions permits over other policies, and reviews the outcomes of existing permit schemes.

1.3.1 Basics of Permit Markets

As pointed out by Hanley et al. (1997), a negative externality, such as air pollution, occurs when there is a lack of property rights for environmental resources. A tradable permit system establishes these property rights and a market price for the right to pollute. Montgomery (1972) shows that a competitive market for permits results in a price that minimizes the cost of emissions reduction.

Figure 1.1 shows the Marginal Abatement Cost (MAC) curve, which gives the cost to firms of avoiding pollution. This cost rises with each unit of emissions reduction undertaken. A firm’s abatement activities may include reducing output of goods and services, using less polluting production processes, or using technology to collect pollutants before they are released into the atmosphere (Hanley et al. (1997)). Each firm chooses to minimize their abatement costs, subject to regulation. In the case of a permit policy, a firm’s MAC curve represents its demand for permits, and the horizontal sum across all firms gives the market demand for permits. The regulator chooses the acceptable level of emissions (over a given time frame), and the market determines a price of $P^*$, as shown in the figure.
Alternatives to tradable permits include emissions taxes or command-and-control policies, which require a particular technology be adopted or set maximum emissions per source. In contrast with tradable permits, to achieve the same level of emissions shown in Figure 1.1 through a tax, the regulator must estimate the MAC curve and choose a tax rate equal to $P^*$, so that the effective price intersects the MAC at the desired level of emissions. Estimating the MAC may require that the regulator gather large amounts of information on the costs of pollution abatement (Tietenberg (2006)). This process can be expensive, and the regulation may be inefficient if a tax, penalty, or emissions cap is set at the wrong level. Monitoring emissions and enforcing penalties add to the costs of these traditional policies.

Goulder et al. (1997), Goulder (1998), and Goulder et al. (1999) argue that the cost savings from market-based instruments depend on pre-existing factor taxes.
These taxes raise the cost of all environmental policy instruments, due to tax-interaction effects. The increase in cost may be offset by revenue-recycling, the use of the value of auctioned permits to offset other distortionary taxes. Parry (2003) shows that with these existing taxes, revenue raising instruments, such as auctioned permits or emissions taxes, are preferable to freely allocated permits. Fisher et al. (2003) show that there is no clear preference between taxes, quotas, and permits in the case of endogenous technological innovation.

Permit schemes also have benefits over command-and-control regulation. With a technology requirement, the total emissions reduction may not be known. These requirements focus on emissions per unit of output, not total emissions. Firms either install the equipment or meet their cap and have no incentive to reduce emissions further. With a permit system, the total emissions are known, and emissions are reduced where it is most efficient to do so.

Technology requirements can also be difficult to implement if a large variety of technologies are used in producing emissions. This is the case for CO\textsubscript{2} emissions, which are produced by such diverse sources as passenger vehicles, coal-fired power plants, cement kilns, and other diverse industrial and residential uses. Clearly, no one technology standard or monitoring system can be useful for such varied sources. Allowing a single market for emissions eliminates the need for an inefficient patchwork of regulations, and allows emissions to be reduced in the cheapest manner available.

The variety of emissions sources also makes monitoring of CO\textsubscript{2} emissions difficult. In this case, a system in which permits are purchased with fuel inputs is preferable to one in which permits are presented to offset a measured level of emissions. Some pollutants, such as SO\textsubscript{2}, do not have a simple link between inputs and emissions output. Fortunately, CO\textsubscript{2} emissions are closely and predictably related to the carbon
content of fuels, making them well suited to a system in which permits are purchased based on the carbon content of fuels (Fischer et al. (2001)).

1.3.2 The US Sulfur Dioxide Market

The first large-scale tradable emissions allowance program to be implemented was the US market for sulfur dioxide (SO\(_2\)). This program aimed to reduce SO\(_2\) emissions by 10 million tons from 1980 levels by 2010, in response to concerns about acid rain (Tietenberg (2006)). Stavins (1998) uses the experience of this market to offers some lessons for evaluating which pollutants are best suited to this type of regulation. Schmalensee et al. (1998) suggest how aspects of such a policy’s design can make it more successful. These lessons from the SO\(_2\) market can be applied to the design of permit policy for other pollutants, such as CO\(_2\).

The SO\(_2\) market was implemented in two phases: Phase I ran from 1995 to 2000, and capped emissions from the 263 largest polluters; Phase II began in 2000 and tightened the cap on all polluters. Several additional firms entered Phase I as “Table A” units to prevent the large emitters from shifting production to unregulated plants. Allowances were given away freely at first, and new entrants could buy allowances from other regulated producers or at auction.

Permit prices were lower than expected throughout the history of the program. Firms over-invested in abatement technology, such as scrubbers, in anticipation of high predicted permit prices. In addition, deregulation of the rail industry lowered transportation costs for low-sulfur coal available in Wyoming, and allowed emitters of SO\(_2\) to switch to this fuel. This switch, combined with the over-investment in abatement technology, meant that emissions were reduced by more than expected in a shorter time period. Schmalensee et al. (1998) estimate that this was achieved at a
25 - 34% lower cost than other regulation.

The experience of the SO\textsubscript{2} market showed that permit schemes can adapt quickly to unexpected events in the market. The decline in rail costs during the first few years of SO\textsubscript{2} trading led quickly to a switch to low-sulfur coal, with no legislative action required to make this input attractive. Plants switched to the less-polluting coal, knowing that they would require fewer permits with its use. Stavins (1998) points out that simply requiring plants to install scrubbers would not have led to any additional reduction in emissions after this event.

For a tradable permit system to be successful, there must be enough participants to create a well-functioning market. The speed at which an efficient market for permits develops depends on the design of the policy. While SO\textsubscript{2} permits were initially given away freely, the EPA conducted auctions periodically for small numbers of permits, helping to establish a market price. The difference between the highest and lowest winning bids was reduced over time as the market became more efficient. Schmalensee et al. (1998) describe the SO\textsubscript{2} market as efficient by mid-1994, only a few months after trading began. The current outlook for national CO\textsubscript{2} permit distribution in the US is that close to half of the permits will be auctioned off initially. The initial auction, as well as information from other international and subnational markets can help to provide information about permit prices which may help an efficient market emerge quickly.

The potential market for CO\textsubscript{2} is much larger than that of SO\textsubscript{2}; In 2002, the US produced 5,880.5 million metric tons of CO\textsubscript{2} emissions (United States Energy Information Agency (2008a)) and 10.4 million tons of SO\textsubscript{2} (United States Environmental Protection Agency (2002)). Schmalensee et al. (1998) point out that SO\textsubscript{2} emissions output is larger in particular areas that are responsible for acid rain in other parts of
the country. In this case, some regional trading restrictions may be desirable to ensure that these regions make appropriate reductions. However, these restrictions were not employed due to fears that the permit market would be too thin. CO₂ emissions do not cause localized damages, implying that trading regulations are unnecessary.

1.3.3 Permit Markets for Other Pollutants

Tietenberg (2006) discusses many of the earlier emissions trading markets, starting with the US EPA’s offset policy. This policy became necessary in the 1970s when many so-called “non-attainment” regions were unable to meet their air quality standards. Rather than deny permits for new facilities on environmental grounds and slow economic growth, the EPA offered to certify emissions reductions by existing polluters. These certified emissions credits could be sold to new entrants in the area. The offset policy evolved into the US Emissions Trading Program, which included banking of credits.

The next instance of a permit approach was used to eliminate lead from gasoline. This policy was favored because those refineries that could eliminate lead more cheaply would have an incentive to do so faster than under traditional regulation. Tietenberg (2006) points out three innovative features of this policy: instead of monitoring emissions, an input to emissions was regulated; the program was designed to eliminate the pollutant rather than reduce it to an acceptable level; and the flexibility allowed the pollutant to be eliminated faster than would be possible under a traditional deadline.

The US also decided to use a permit system to reduce its use of ozone-depleting chemicals and meet its obligations under the Montreal Protocol, signed in 1988. Allowances were given away freely to producers and consumers, in accordance with their
1986 usage level. With EPA approval, the allowances could be traded internationally. The windfall profits earned by the industry led to the use of a tax on the sale of these chemicals. This tax redirected some of the profits to the government and provided an additional incentive for producers and consumers to use less of these harmful chemicals.

The RECLAIM program, begun in 1994, is the one of the first examples of a state-level permit scheme. This program was enacted to meet the Southern California area’s requirements for air quality by regulating \( \text{NO}_x \) and \( \text{SO}_2 \). In the first years of the program, there were excess credits, but electricity deregulation in 2000 caused the price of permits to rise more than tenfold. This dramatic rise in prices led to the introduction of a “safety valve” policy, or maximum permit price. When the safety valve was exceeded, more emissions were allowed. Spatial restrictions were also used to differentiate coastal and inland regions (Johnson and Pekelney (1996), Tietenberg (2006)).

Other sub-national emissions permit programs include the seasonal \( \text{NO}_x \) reduction used in the US Northeast and The Chicago Emissions Reduction Market System (ERMS), used to reduce seasonal \( \text{NO}_x \) levels as well as volatile organic materials. Santiago, Chile, implemented a permit system to reduce suspended particulate emissions in 1992. The Clean Air Interstate Rule, used in the Eastern US beginning in 2005, is used to reduce ozone and particulates.

1.3.4 European Union Emissions Trading System

The European Union began its Emissions Trading System (EU-ETS) in 2005 to meet its \( \text{CO}_2 \) emissions reduction responsibilities under the Kyoto protocol. The restrictions agreed to under Kyoto run from 2008-2012, but the EU began trading in
2005, as part of a preliminary phase. This first trading period was designed to ensure that a working market would be established before the Kyoto agreement period. The second period will run from 2008-2012, and a 2013-2020 period is planned for after the Kyoto agreement expires (Ellerman and Joskow (2008)).

In this system, each member country submits its own cap for EU approval. The total cap is not set at a particular level, so the amount of reduction depends on the total of the individual country caps. For the third trading period and onwards, the total cap will be set, and this total will be reduced each year, ensuring a 20% reduction from 1990 levels in 2020. The sectors included in the EU-ETS system include electricity generation; oil refineries; coke ovens; metal ore & steel; cement kilns, glass, ceramics; paper & pulp mills (Pew Center for Global Climate Change (2005)). Transportation is notably absent, although it is the fastest growing emissions source. These emissions may be included in future phases of the program. Targets can be met through the purchase of permits or through the Kyoto Protocol’s Clean Development Mechanism (CDM), in which states cooperate with developing countries on specific projects. These projects are limited in availability and can take years to be developed and approved.

The EU-ETS demonstrated the speed at which an international permit trading system can be established. The establishment of the EU-ETS system followed an ambitions timeline. From a general idea in 2000, the program was approved in 2003, and required national allocation plans (NAPs) to be submitted by March 2004. Only five of fifteen of these plans were submitted on time. When the program began in January 2005, only Denmark had an operating registry to record permit trades; another year and six months passed before all member nations were operational (Ellerman and Joskow (2008)).
Within trading periods, permits may be banked or traded with other nations. However, permits could not be traded between the first and second phases of the program, to keep problems from the trial period from spilling into Phase II. Because of this expiration date, prices of phase one permits fell to near zero in 2006 following the release of 2005 emissions information. These emissions were lower than expected, and firms that had been banking permits for a rainy day began releasing permits into the market. With less than two years remaining to use the additional permits, prices fell dramatically.

While the first period may not have achieved significant emissions reductions, it provided a well-functioning market for emissions permits with competing exchanges offering spot, forward, and futures contracts and other instruments. Twenty-eight nations are now participating in the system, with Norway linked as an outside trading partner. Challenges for future periods include concerns over windfall profits, and harmonization of policies, such as allocation to the different sectors and across nations (Pew Center for Global Climate Change (2005)).

1.3.5 Other Currently Existing and Proposed Schemes

Within the US, several regional initiatives are currently implementing policies to reduce GHG emissions. The Regional Greenhouse Gas Initiative (RGGI) includes 10 Eastern states: Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont (Regional Greenhouse Gas Initiative (2007)). Their goal is a 10% reduction in CO$_2$ emissions from the electric power sector by 2018. The compliance period began January 1, 2009, and permits are currently scheduled for quarterly auction. The last auction on December 17, 2008, resulted in a clearing prices of $3.38 per ton CO$_2$, with all 31,505,898 offered
permits sold. Ruth et al. (2008) analyzes the impact of this agreement on the state of Maryland. They predict that electricity demand will fall by 3% by 2025 compared to a baseline scenario, mainly due to increases in energy efficiency. Exports of fuels and investment in generation capacity both decline. No significant change in electricity prices is projected, and Maryland is predicted to be a net exporter of allowances.

The Western Climate Initiative (WCI) is another regional collaboration of US states and Canadian provinces working toward a cap-and-trade system for GHG emissions reduction. The trading Partners include Arizona, British Columbia, California, Manitoba, Montana, New Mexico, Ontario, Oregon, Quebec, Utah, and Washington. These states and provinces have committed to a trading scheme; six additional states, including Colorado, one Canadian province, and six Mexican states are Observers, not committed to a trading system. The current goal is a 15% reduction from 2005 levels by 2020. Reporting will begin in 2011, a three year trading period will begin in 2012, and a second period will begin in 2015, and will include transportation and household emissions (Western Climate Initiative (2008a), Western Climate Initiative (2008b)).

The Chicago Climate Exchange offers “voluntary, but legally binding” Chicago Climate Exchange (2007) contracts for emissions reduction. The exchange trades in six greenhouse gases. Members agree to a phased reduction program. From 2003-2006, emissions were reduced by 1% per year, and the second phase requires all members to be 6% below the baseline by 2010. The baseline is the member’s average emissions between 1998-2001. As with EU-ETS, the modest goals of these two phases are intended to provide experience about emissions trading.

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5The major greenhouse gases are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulfur hexafluoride (SF₆), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).
1.4 Emissions Reduction Policy Analysis

The increasing number of proposals for market-based legislation have led to the development of several economic models for evaluating the impacts of these policies. Often, these take the form of computable general equilibrium (CGE) models of an international, national, regional, or local economy. Balistreri and Rutherford (2004) point out several reasons why a computable general equilibrium (CGE) model is useful for analyzing carbon policy: the general equilibrium structure captures relationships between markets; large policy changes can be considered, which may not be reliably estimated econometrically; and the relative sizes of markets are considered. The model can produce estimates of macroeconomic variables such as economic growth, state-wide income, and economy-wide welfare, as measured by equivalent variation. The effects on specific industries, such as those involved in energy production or that use energy intensively can also be investigated.

The model of Colorado presented in Chapter 2 and in Appendix A uses computable general equilibrium methodology. In such a model, consumers maximize their utility subject to a budget constraint. The utility function represents the consumers' preferences for the goods available, and the consumers' incomes are determined by sales of their endowments of factors of production. Firms maximize profits according to available technology. Their output can be sold to consumers, or to other firms as inputs to production. Both consumer utility and production functions are modeled as nested constant elasticity of substitution (CES) functions that feature detailed energy nesting. In an equilibrium solution, supply equals demand for each good and factor of production, income equals expenditure, and firms earn zero economic profits.

This model is calibrated to a base year data set, consisting of a balanced Social Accounting Matrix (SAM), which includes payments between all sectors and agents.
within the economy. The SAM represents a snapshot of the economy at a given point in its dynamic path. The baseline scenario represents a balanced growth continuation of this snapshot. After a benchmark equilibrium is found, a scenario can be introduced, such as the emissions reduction described above.

Examples of CGE models used to examine policy changes at the international and US level include MIT’s Emissions Prediction and Policy Analysis (EPPA) model, which ties in with a climate model to allow climate impacts to influence economic outcomes (Babiker et al. (2008)). The Applied Dynamic Analysis of the Global Economy (ADAGE) model is used to produce estimates for the US Environmental Protection Agency (EPA) of proposed legislation such as the 2009 American Clean Energy and Security Act. This model can be used to investigate policy impacts on a particular focus state, as in Ross et al. (2004). Recent efforts to study the impacts of GHG emissions reduction policies in other specific countries include the ECOGEM model of Chile and IMAGE of Ireland (O’Ryan et al. (2003), Wissema and Dellink (2007)).

State-level analyses are less common. Li and Rose (1995) study the effects of a carbon tax on the Pennsylvania economy using a long-run, static model. Because of the importance of coal mining and heavy industry to the state economy, the effect on GDP in the state is negative for three different tax rates corresponding to proposed carbon emissions targets. Balistreri and Rutherford (2004) criticize this paper on the basis that their long-run equilibrium is less accurate than a dynamic model, and that the results are exaggerated because the state is assumed to act unilaterally.

Other recent studies on CO₂ trading include Bohringer et al. (2004), which suggests that incorporating a variety of GHG pollutants will reduce the cost of abatement. Hanley et al. (2006) finds that in Scotland, policies that encourage greater energy ef-
ficiency cause both energy consumption and pollution levels to rise as energy prices fall. Jensen and Rasmussen (2000) use a CGE model to compare allocation policies. Earlier relevant works are surveyed by Partridge and Rickman (1998) (state-level applications, including models focusing on energy and the environment) and Bhattacharyya (1996) (models focused on energy, mostly at the national level).

1.5 Outline

The rest of this dissertation is structured as follows. Chapter 2 presents the impacts of the emissions permit policy alone. The CGE model is described in more detail, and the methodology is explained more fully. Chapter 3 explains the issue of emissions leakage, and gives estimates of leakage rates under the proposed policy. The sensitivity of these leakage rates with different model assumptions is investigated. Chapter 4 considers the interactions between the state’s current renewable portfolio standard and the proposed emissions reduction policy. The estimates of permit prices, leakage rates, and other economic indicators for the different policy scenarios are discussed. Conclusions are offered in Chapter 5. Appendix A provides detailed model documentation, and Appendix B contains model code.
Chapter 2

MEASURING THE STATE-LEVEL IMPACTS OF CLIMATE POLICY IN COLORADO

ABSTRACT

This chapter examines the impacts on the Colorado economy of a proposed carbon emissions reduction policy. A dynamic, multi-sector, computable general equilibrium model, based on forward-looking agent behavior and capital accumulation, is used to predict these impacts. A benchmark forecast is constructed by calibrating the model to projections of emissions from the Energy Information Agency (EIA) and 2002 data from IMPLAN (Minnesota IMPLAN Group, Inc.). This baseline forecast is compared to a scenario in which the proposed goal of an 80% reduction in emissions from 2005 levels by 2050 is achieved with tradable allowances. The model predicts permit prices will rise from $4/ton CO$_2$ to $167/ton CO$_2$, in real terms, over the reduction period. Other economic indicators, as well as impacts on specific sectors of the state economy under this policy, are discussed.

2.1 Introduction

Several US states have enacted legislation aimed at reducing greenhouse gas (GHG) emissions, such as CO$_2$. These regulations include command-and-control policies that limit emissions or require certain technologies, renewable portfolio standards (RPS) that require a specified portion of a state’s electricity supply be generated
from renewable sources, or simply measures designed to catalog emissions. Although many state governments and large businesses support a nationwide emissions trading scheme, such a measure has not yet been enacted. In response, many states have worked together to form groups, such as the Regional Greenhouse Gas Initiative (RGGI) in the Northeast, or the Western Climate Initiative (WCI) in the West, to pursue trading schemes.

Colorado has announced its own goals for the reduction of CO$_2$ emissions. Without a federal policy, these reductions could be achieved through the use of a state-level permit system. In this chapter, we measure the economic impacts within the state of such a system. We present forecasts of permit prices, as well as changes in macroeconomic indicators compared to a baseline projection. These estimates are generated by a computable general equilibrium (CGE) model of the state. We find that in order to achieve an 85% reduction in 2050 baseline emissions, permit prices rise from $4 CO$_2$ per ton to a peak of $167 per ton CO$_2$, in real terms. Consumption of goods and services by Colorado residents declines by 4% and consumer welfare falls by 0.62% over the period 2005 to 2060, compared to the baseline projection. While some sectors of the economy are not impacted greatly, others such as coal mining are virtually eliminated.

Keep in mind that the model results presented in the following chapters attempt to quantify the economic impacts of Colorado’s proposed and existing emissions reduction policies without attempting to estimate the benefits. Welfare measures do not include improvements in human or ecosystem health associated with a cleaner environment. The satisfaction Colorado residents recieve from working to stop climate change is not included, nor is welfare explicitly linked to emissions.

This chapter is structured as follows. The next section highlights Colorado’s
specific concerns and current policies, and describes the emissions reduction scenario. Next, the methodology used is presented, and then in Section 2.4 the data are described. Section 2.5 presents the model results, and Section 2.6 offers conclusions.

2.1.1 Colorado’s Current Strategies

The state of Colorado is particularly sensitive to the effects of climate change, with the American West currently warming faster than the global average. Residents of Colorado rely on a mountain snowpack for water supplies throughout the year. Current forecasts indicate that less snowfall and warmer winters can be expected, leading to drought conditions and increasing the number and intensity of wildfires. Winter sports seasons may be shortened, wildlife habitat may be reduced as animals move to higher elevations, and forests may be more prone to insect damage. These impacts would lead to reductions in the tourism and sporting activities for which the state is famed, as well as agricultural activities important to the state’s identity. Sensitivity to water concerns, enjoyment of outdoor activities, and a respect for wildlife lead many Coloradans to request action on this problem.

Currently, a variety of measures are in place to promote cleaner energy sources and make the state more energy efficient. These measures include subsidies for clean energy, research funding, technology standards, and other incentives. Colorado voters were the first in the nation to enact a renewable portfolio standard (RPS) by voter initiative. This standard now mandates that 20% of electricity sold in the state come from renewable sources by 2020. Much of this renewable electricity is currently produced by wind, solar, and hydroelectric energy; other options such as biomass and fuel cell production are also allowed. Table 2.1 gives the current electricity production profile for Colorado.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>% of CO production</th>
<th>% of national production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum Fired</td>
<td>0.04%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Coal Fired</td>
<td>66%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Natural Gas Fired</td>
<td>25%</td>
<td>1.7%</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>2%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Other Renewables</td>
<td>7%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Total Renewables</td>
<td>9%</td>
<td></td>
</tr>
<tr>
<td>Total MWh</td>
<td>4,159</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

In 2008, Governor Bill Ritter announced goals for the state to reduce its CO₂ emissions by 20 percent by 2020, and by 80 percent by 2050, based on 2005 levels (Ritter (2007)). We refer to these goals as the “Ritter Plan” throughout this chapter. The goal of an 80% reduction by 2050 was chosen first, with the 20% reduction by 2020 selected as an intermediate goal. Currently, these goals are not binding, but these, or similar reductions, may be pursued in the future. If the state were to become a trading partner in the WCI, for instance, emissions would have to be reduced by 15% from 2005 levels by 2020 (Western Climate Initiative (2008a)). See Chapter 1 for more information on this organization and other state policies.
Figure 2.1. Carbon Emissions under Business-as-usual (BAU) and Ritter Plan scenarios. The suggested 80% reduction of emissions from 2005 levels in 2050 corresponds to an 85% reduction from BAU levels by 2060. Source: United States Energy Information Agency (2008b).

From the Ritter Plan’s recommendations, we have constructed a model scenario for emissions reduction. In this scenario, emissions are reduced linearly starting with the 20 percent goal in 2020 and continuing to 80 percent of 2005 levels in 2050. Figure 2.1 shows the scenario emissions compared to the baseline projection. In the scenario, we assume that permits are not traded until 2020, the first year in which a reduction in emissions is made. After 2020, emissions are reduced linearly by 10% every five years until 2050. Between 2050 and the end of the model period in 2060, emissions are held constant at their 2050 level. By the end of the period, emissions are reduced by 85% of the projected business-as-usual level, which is consistent with an 80% reduction relative to 2005 emissions.
2.1.2 Existing Systems

The current efforts within the US to reduce greenhouse gas emissions draw on years of experience at the national, state, and local levels with permit schemes for other pollutants, as well as international experience in reducing GHGs. Chapter 1 provides further details on many of these existing and proposed systems. A short summary is presented here, as this chapter focuses solely on the permit policy.

Emissions allowance schemes are popular for a number of reasons. As Tietenberg (2006) points out, other regulations, such as command-and-control requirements, demand much more data in order to assign emissions to producers efficiently. Permit schemes can, in most cases, achieve a given level of emissions reduction at a lower cost than traditional regulation. Also, the level of emissions reduction can be chosen explicitly, whereas with technology requirements or emissions taxes, the total emissions reduction achieved may be uncertain. Sales of permits can raise revenues used to subsidize renewable energy technology, or provide aid to those who can no longer afford higher energy prices. Businesses tend to favor permit schemes when the permits are given away freely, and they have incentives to reduce emissions beyond what is required. In the case of CO$_2$ emissions, the damages are not localized, so emissions reductions at any location have the same benefit. This allows for greater flexibility and lower costs for a given reduction in emissions.

The US market for SO$_2$ emissions has proven very successful since its introduction in 1995. This two phase program first capped emissions for five years, then tightened the cap in the years that followed. The program was the largest permit scheme attempted at that time, and its success at reducing acid rain more cheaply than expected has led to market-based policies for the reduction of many other air pollutants (Stavins (1998)), both nationally and on a more local level.
The Regional Greenhouse Gas Initiative (RGGI) began trading GHG emissions permits on January 1, 2009 (Regional Greenhouse Gas Initiative (2007)). The RGGI requires its 10 member states to cap their emissions from 2009 through 2014, then reduce emissions by 10% of the cap by 2018. Permit trading began in September 2008, and as of this writing, two permit auctions have been held. The Western Climate Initiative (WCI) is an agreement between seven US states and four Canadian provinces to use a trading scheme to reduce CO$_2$ emissions by 15% from 2005 levels by 2020, with a second period to begin in 2015. Colorado is currently an uncommitted “Observer” to this agreement. The state of California has also investigated its own permit scheme to reduce CO$_2$ emissions (Bushnell et al. (2008), Goulder (2007)). Permit systems have been used at the state or local level to reduce other pollutants, such as the RECLAIM program in California, or the Chicago ERMS, both of which aimed to improve air quality to meet EPA standards (Tietenberg (2006)).

2.2 Methodology

Significant emissions reductions will likely lead to substantial economic impacts. In studying the impact of CO$_2$ emissions regulation on the Colorado economy, understanding the effects on economic variables such as consumer welfare, consumption, and investment is necessary. Also of interest are the effects on specific industries, such as those involved in energy production or those that use energy intensively. Estimates of permit prices can give a sense of the costs of the program. A CGE model can help to investigate these economic impacts by considering the interactions among several markets.

CGE models are commonly used to investigate changes in tax policy, international trade agreements, or environmental policy, at the regional, national, or state
level. Within the CGE model, the economy is described by its endowments of factors of production, the available technologies (represented by the production functions), consumer preferences (represented by the consumers' utility functions), and the assumption that all agents exhibit optimizing behavior. This optimization, and the interaction of consumers and producers, results in three types of fundamental equations that are solved simultaneously to find a set of prices that form a general equilibrium solution. These equations include market clearance (supply = demand) for each good, zero economic profits for each activity, and income balance (consumers spend their entire income). In a dynamic model, these equations are satisfied in each period and across periods, with the capital stock available in one period depending on the level of investment in previous periods.

2.2.1 Zero-Profits Conditions

In the following description of the model, variable definitions are found in Table 2.2. Firms producing commodity \( s \in G \) at time \( t \) seek to maximize their profits, \( \Pi_{st} \), subject to their constant-returns-to-scale production function \( F_s(x_{st}, k_{st}) \), where \( x_{sgt} \in x_{st} \) are intermediate inputs of commodity \( g \in G \) and \( k_{sft} \in k_{st} \) are inputs of capital or labor indexed by \( f \in \{K, L\} \). Firms are assumed to take input and output commodity prices, denoted \( p_{st} \), and factor prices, \( w_{ft} \), as given. Let the output quantity be given by \( y_{st} \) such that the production problem is given by the following:

\[
\text{Max } \Pi_{st} = p_{st}y_{st} - \sum_g p_{gt}x_{sgt} - \sum_f w_{ft}k_{ft}
\]

subject to: \( y_{st} = F_s(x_{sgt}, k_{ft}) \).

Solving this problem, assuming free entry and free access to the technology, gives
Table 2.2. Variable definitions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \delta )</td>
<td>Depreciation rate,</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Elasticity of intertemporal substitution,</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Discount rate,</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Factors</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( K )</td>
<td>Capital,</td>
</tr>
<tr>
<td>( L )</td>
<td>Labor,</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Sets</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s \in {1, \ldots , G} )</td>
<td>Sectors,</td>
</tr>
<tr>
<td>( g \in {1, \ldots , G} )</td>
<td>Commodities,</td>
</tr>
<tr>
<td>( t \in {1, \ldots , T} )</td>
<td>Solution periods,</td>
</tr>
<tr>
<td>( f \in {K, L} )</td>
<td>Factors,</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Functions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_s(x_{st}, k_{st}) )</td>
<td>Production function for sector ( s ),</td>
</tr>
<tr>
<td>( \pi_s(p_t, w_t) )</td>
<td>Optimized unit profits for sector ( s ),</td>
</tr>
<tr>
<td>( P_t(p_t) )</td>
<td>Unit expenditure function in period ( t ),</td>
</tr>
<tr>
<td>( E(P_1, P_2, \ldots , P_T, W, \rho, \sigma) )</td>
<td>Minimized intertemporal expenditure,</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Pi_{s,t} )</td>
<td>Profits earned by sector ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( x_{sgt} \in x_{st} )</td>
<td>Intermediate inputs of commodity ( g ) in sector ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( k_{sft} \in k_{st} )</td>
<td>Inputs of factor ( f ) used by sector ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( p_{st} \in p_t )</td>
<td>Price of commodity ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( w_{ft} \in w_t )</td>
<td>Price of factor ( f ) in period ( t ),</td>
</tr>
<tr>
<td>( y_{st} )</td>
<td>Quantity of output from sector ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( P_t(p_t) )</td>
<td>Unit expenditure (expenditure needed to achieve one unit of utility in period ( t )),</td>
</tr>
<tr>
<td>( Y_t )</td>
<td>Aggregate economic activity in period ( t ),</td>
</tr>
<tr>
<td>( d_{st} )</td>
<td>Demand for commodity ( s ) in period ( t ),</td>
</tr>
<tr>
<td>( I_t )</td>
<td>Investments made in period ( t ),</td>
</tr>
<tr>
<td>( K_t )</td>
<td>Capital stock in period ( t ),</td>
</tr>
<tr>
<td>( P^K_t )</td>
<td>Present value price of capital in period ( t ),</td>
</tr>
<tr>
<td>( L_t )</td>
<td>Labor endowment in period ( t ),</td>
</tr>
<tr>
<td>( K_t )</td>
<td>Capital endowment in period ( t ),</td>
</tr>
<tr>
<td>( M )</td>
<td>Finite horizon income,</td>
</tr>
<tr>
<td>( E )</td>
<td>Aggregate expenditures,</td>
</tr>
<tr>
<td>( W )</td>
<td>Consumer welfare,</td>
</tr>
<tr>
<td>( C_t )</td>
<td>Aggregate consumption in period ( t ).</td>
</tr>
</tbody>
</table>
the condition that determines output, or activity levels, for sector $s$. Let $\pi_s(p_t, w_t)$ represent the optimized unit profits as a function of the commodity and factor price vectors. Zero profits are satisfied at

$$\pi_s(p_t, w_t)y_{st} = 0. \quad (2.3)$$

Embedded in $\pi_s(p_t, w_t)$ is the usual price = marginal cost condition for optimal firm behavior. This equation is associated with the variable $y_{st}$, meaning that the level of output adjusts to maintain this equality.

Demand for inputs, $x_{sgt}$ and $k_{ft}$, are given by applying Hotelling’s lemma to the profit function (2.3):

$$x_{sgt} = -y_{st} \frac{\partial \pi_s}{\partial p_{gt}} \quad (2.4)$$

and

$$k_{sft} = -y_{st} \frac{\partial \pi_s}{\partial w_{ft}} \quad (2.5)$$

### 2.2.2 Household Behavior and Income Balance

The representative household solves another optimization problem, that of maximizing utility subject to a budget. The household receives income by supplying factors of production, and allocates this income to purchases. Within a given time period household behavior is specified by a unit expenditure function:

$$P_t = P_t(p_t) \quad (2.6)$$

The unit expenditure function is the minimized cost of generating a unit of within-period utility. The arguments of the function are the elements of the commodity price vector. Denoting within-period $t$ aggregate economic activity $Y_t$, we recover
commodity demand by Shephard’s lemma:

\[ d_{st} = Y_t \frac{\partial P_t}{\partial p_{st}}. \]  

(2.7)

Households also optimize across time. Forgone current consumption generates new investment \((I_t)\), and the capital stock evolves according to the following:

\[ K_t = (1 - \delta)K_{t-1} + I_{t-3}, \]  

(2.8)

where \(\delta\) is the fixed depreciation rate. We assume that new investments in capital are available for production after a three year investment lag. Households optimally invest up to the point that the present-value price of capital in the maturation year (three years in the future) equals the marginal cost in terms of forgone consumption:

\[ P^K_{t+3} = P_t \]  

(2.9)

where \(P^K_t\) is the price of a unit of capital. Consistent with (2.8), the present-value price of a unit of capital equals the present value of its future earnings as a factor of production. The gross of depreciation rental price of a unit of capital is \(w_Kt\) so the price of that unit is given by the following:

\[ P^K_t = w_Kt + (1 - \delta)P^K_{t+1}. \]  

(2.10)

The representative household has an intertemporal budget constraint that defines the economy’s resources. Present-value income over the infinite horizon is given by the return to labor plus value of the initial capital endowment. Consistent with neo-classical growth, the labor endowment includes a constant productivity and pop-
ulation growth augmentation such that $L_{t+1} = (1 + g)L_t$, where $g$ is the economic growth rate. We only compute the dynamic equilibrium over a finite horizon (2005 to 2060), so we must adopt an approximation strategy. As outlined by Lau et al. (2002) the key to adopting an accurate approximation strategy is to generate the appropriate demand for the “post-terminal capital stock.” We endogenously adjust the terminal-capital demand by imposing equivalent growth rates for consumption and investment across the final two periods (as suggested by Lau et al. (2002)). This termination strategy is preferred over extending the model horizon because it allows for more complexity in each solution period. Finite horizon income, $M$, includes a payment for terminal-capital demand:

$$M = \sum_{t} w_{Lt} \bar{L}_t + P_0^K \bar{K}_0 - P_{T+1}^K \bar{K}_{T+1} \tag{2.11}$$

Equation 2.11 is the income balance condition used in the computational model. We need, however, to relate intertemporal income to consumption. Utility across time periods is aggregated according to a constant elasticity of intertemporal substitution, $\sigma$, and a fixed discount rate, $\rho$. The constant elasticity of intertemporal substitution utility function is given by

$$W = \sum_{t=0}^{T} \left( \frac{1}{1 + \rho} \right)^t \frac{C^{1-1/\sigma}_t - 1}{1 - 1/\sigma}, \tag{2.12}$$

which is a monotonic transformation of a conventional CES function.

In dual form we have minimized intertemporal expenditures as a function of the vector of prices and the level of welfare (and the preference parameters):

$$E = E(P_1, P_2, ..., P_T, W, \rho, \sigma) \tag{2.13}$$
In equilibrium $E = M$ and demand for the consumption aggregate in each period is given by Shephard’s lemma:

$$C_t = \frac{\partial E}{\partial P_t}.$$  \hspace{1cm} (2.14)

### 2.2.3 Market Clearance Conditions

The final set of equilibrium conditions are zero excess demand conditions for each commodity and factor of production. The associated variable with each equation is the commodity price or factor price, which adjusts to bring supply and demand into balance. For commodities priced at $p_{st}$ we have

$$y_{st} = d_{st} + \sum_g x_{sgt};$$  \hspace{1cm} (2.15)

for factors priced at $w_{ft}$ we have

$$\bar{L}_t = \sum_s k_{sLt},$$

$$K_t = \sum_s k_{sKt};$$  \hspace{1cm} (2.16)

and for the macroeconomic aggregate priced at the index $P_t$ we have

$$Y_t = C_t + I_t.$$  \hspace{1cm} (2.17)

### 2.2.4 Equilibrium

In equilibrium, the vector of prices satisfies market clearance and the optimality conditions embedded in the profit and expenditure functions. The profit and expenditure functions are calibrated to a base year data set, consisting of a balanced Social Accounting Matrix (SAM) that includes payments between different sectors.
and agents within the economy. The dynamic trajectories are then found to match growth and present-value price assumptions. Once a benchmark equilibrium is found, counterfactual experiments can be run, and their results compared to the benchmark outcome. In this study we specifically examine the CO\textsubscript{2} emissions restrictions for Colorado under the Ritter Plan.

2.3 Model Specifics

The model utilized here is calibrated to a base year of 2005, the year from which proposed emissions reductions are based. It includes nine sectors\textsuperscript{1}, focusing on energy. Table 2.3 gives the sector names. In addition, the model includes one representative agent who is endowed with all factors of production and makes all consumer purchases. The current model makes the simplifying assumption that government activities are subsumed into the behavior of the representative agent. The model horizon runs from 2005 to 2060, with every fifth year being solved (to reduce computational complexity). The model is solved using GAMS 21.1 with MPSGE (Rutherford (1998), Rutherford (1995)). The dynamic formulation and terminal conditions are taken from Lau et al. (2002).

Production technologies and consumer welfare are formulated as nested CES production functions, emphasizing the complexity of energy substitution opportunities. See Figures 2.2 and 2.3 for a graphical representation of the nesting structure, including elasticities. A more thorough description is found in Appendix A. These functions include a detailed nesting structure for energy inputs. Imported and domestic varieties of each good are considered imperfect substitutes, according to the Armington (1969) assumption. Colorado is modeled as a small open economy, indicating that

\textsuperscript{1}The “Other” includes mining, trade and transportation, and other miscellaneous sectors
Table 2.3. List of model sectors. The “Other” includes mining, trade and transportation, and other miscellaneous sectors.

<table>
<thead>
<tr>
<th><strong>Energy Sectors</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>COL</td>
<td>Coal</td>
</tr>
<tr>
<td>ELE</td>
<td>Electricity</td>
</tr>
<tr>
<td>GAS</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>OIL</td>
<td>Oil</td>
</tr>
<tr>
<td>CRU</td>
<td>Oil and Gas Extraction</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Non-Energy Sectors</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AGR</td>
<td>Agriculture</td>
</tr>
<tr>
<td>MAN</td>
<td>Manufacturing</td>
</tr>
<tr>
<td>SVC</td>
<td>Services</td>
</tr>
<tr>
<td>OTH</td>
<td>Other</td>
</tr>
</tbody>
</table>

Colorado is a price taker in external markets.

Given the importance of electricity generation as a contributor to overall emissions, the production technology is formulated with specific elaborations. Electricity may be produced by conventional means, or by renewable technology. The renewable power sector does not use fossil fuels, but requires more capital to produce a unit of electricity. In this chapter, renewable production of electricity is assumed to meet or exceed 9%, the current level of production, throughout the model period. In Chapter 4, the 20% renewable portfolio standard is considered. Further documentation is given in Appendix A, and model code is given in Appendix B.

### 2.3.1 Dynamics

Because this model is dynamic, outcomes and decisions must be linked across time. Investment provides this link, with investment in one period becoming new capital in future periods. Households are assumed to be forward looking and invest optimally based on the full intertemporal price vector. The assumed time-to-build is three years. New capital is necessary to replace that lost to depreciation and allow
Figure 2.2. Nested CES Production Structure. The arches represent input substitution possibilities in the nested CES production functions according to the given elasticities of substitution. The functions emphasize substitution possibilities between energy sources.
Figure 2.3. Nested CES Consumer Utility Nesting. The arches represent input substitution possibilities in the nested CES welfare function according to the given elasticities of substitution. The function emphasizes consumers’ substitution possibilities between energy sources.
for economic growth. The model includes a partial putty-clay capital structure, in which a fraction of existing capital at the beginning of the period is clay, or fixed in its current use, and new capital is putty, or able to be substituted across sectors and against other inputs. As an example, consider an existing coal-fired power plant that requires a fixed amount of coal to produce a given output of electricity. Compare this plant with a new facility built with more flexibility in anticipation of future emissions control legislation.

The baseline is calibrated to include EIA projections of energy prices and production. This is achieved by the use of a calibrated productivity shift to match the forecasts. The model also includes sector-specific projections, allowing the sectors of the economy to evolve differently over time. Macroeconomic theory suggests that in a developed country, such as the US, the services sector will grow faster than sectors such as agriculture and manufacturing. Forecasts were made from World Bank data on sector shares from 1960 forward. However, these projections differed so little from the baseline case that they have been omitted to allow more computational freedom. For more details on model dynamics, please refer to Section A.8.

2.3.2 Emissions Permits

In the benchmark, the consumer is endowed with a sufficient number of permits to cover projected emissions. This results in a zero-price for permits, as permits are not scarce. In counterfactual experiments, reducing the endowment of permits reduces the allowable emissions. This reduction in the supply of permits causes permits to have a positive price, and reduces the emissions by an equivalent percentage (because permits are required in proportion to the carbon content of each fuel input).

Figure 2.4 displays a representation of the market for emissions permits before
Figure 2.4. Supply and Demand for Emissions Permits. At \((P_1, Q_1)\) permits are not scarce and therefore have a price of zero. By restricting the supply of permits to Supply\(_2\), the equilibrium price rises to \(P_2\).

and after the reduction in supply. The consumer is initially endowed with \(Q_1\) permits. This fixed supply is shown as Supply\(_1\) in the figure, which intersects the demand curve at a price of zero. By reducing the number of available permits to \(Q_2\), the supply curve shifts to Supply\(_2\), and price rises to \(P_2\).

We assume that permits are not scarce until the time period in which the reduction is mandated, for instance, the 20% reduction in 2020 is undertaken entirely in that period, with an excess supply of permits in previous periods. Because there is only one representative agent in the model, the allocation of permits would not affect the model outcome, though in reality, permit allocation can affect not only permit prices and the cost of a given reduction in emissions, but also the political feasibility of a permit scheme.
2.4 Data

The SAM used to calibrate the model is 2002 data from IMPLAN.\textsuperscript{2} 2005 is a logical choice for the starting year because current proposals base emissions reductions off of 2005 levels. To reach the starting date of 2005, the data is scaled up by the assumed growth rate for three years. The 509 sector IMPLAN data is aggregated into the nine sectors discussed in the previous section. The nine income levels from IMPLAN are aggregated into the one representative agent.

Projections of CO\textsubscript{2} emissions are taken from the Energy Information Agency (EIA) (United States Energy Information Agency (2008b)). These projections run from 2005 to 2030 at the national level. To get projections for the state of Colorado, these projections are scaled by the share of total emissions produced by Colorado in the base year. The projections are also extended to 2060 using a linear forecast. Compared to estimates given in Ritter (2007), these projections are conservative.

The EIA's projections are given for three fuel types: coal, petroleum, and gas; and five different sectors: Commercial, Industrial, Residential, Transport, and Electric Power Generation. All emissions from the residential sector are assigned to the households in the model. An adjustment is then made to assign some of the transport emissions to households, based on the percentage of total transport demand made by households from United States Census Bureau (2005) data. The total of the remaining transport emissions and the emissions from the rest of the sectors is assigned to the productive sectors based on the share of each fuel that they purchased in the base year, as given by the IMPLAN data. The calculated 2005 Colorado emissions by fuel and sector are given in Table 2.4.

Elasticities for the production and utility functions have been taken from Bal-

\textsuperscript{2}Minnesota Implan Group. www.implan.com
Table 2.4. 2005 Emissions by Fuel and Sector (in tons). Emissions produced from using fuels coal, oil, and natural gas in each model sector in 2005. The United States Energy Information Agency (2008b) sectors (Residential, Transportation, Industrial, Commercial and Electricity Generation) have been mapped to the model sectors.

<table>
<thead>
<tr>
<th>Sector</th>
<th>COL</th>
<th>OIL</th>
<th>GAS</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGR</td>
<td>41,701</td>
<td>2,242,110</td>
<td>108,795</td>
<td>2,392,605</td>
</tr>
<tr>
<td>COL</td>
<td>6,069,677</td>
<td>236,091</td>
<td>611</td>
<td>6,306,380</td>
</tr>
<tr>
<td>CRU</td>
<td>0</td>
<td>594,732</td>
<td>41,479</td>
<td>636,210</td>
</tr>
<tr>
<td>ELE</td>
<td>25,547,455</td>
<td>505,469</td>
<td>14</td>
<td>26,052,938</td>
</tr>
<tr>
<td>GAS</td>
<td>1,880,395</td>
<td>83,489</td>
<td>2,917</td>
<td>1,966,802</td>
</tr>
<tr>
<td>MAN</td>
<td>3,300,836</td>
<td>1,415,123</td>
<td>4,525,370</td>
<td>9,241,329</td>
</tr>
<tr>
<td>OIL</td>
<td>5,868</td>
<td>1,853,983</td>
<td>397,006</td>
<td>2,256,857</td>
</tr>
<tr>
<td>OTH</td>
<td>72,664</td>
<td>10,945,392</td>
<td>1,832,840</td>
<td>12,850,897</td>
</tr>
<tr>
<td>SRV</td>
<td>306,636</td>
<td>14,244,168</td>
<td>9,770,547</td>
<td>24,321,547</td>
</tr>
<tr>
<td>Households</td>
<td>76,983,94</td>
<td>895,047</td>
<td>6,582,257</td>
<td>7,554,288</td>
</tr>
<tr>
<td>Total Emissions</td>
<td></td>
<td></td>
<td></td>
<td>93,579,658</td>
</tr>
</tbody>
</table>

istreri and Rutherford (2004). These can be found in Figures 2.2 and 2.3, and are discussed further in Appendix A.

2.5 Results

In order to achieve the suggested emissions reduction of 80% below 2005 levels by 2060, several changes will occur in Colorado’s economy. The CGE model of the state predicts that consumption by residents falls by 4% from the business-as-usual level. Coal mining is eliminated from the state, and conventional electricity production is nearly eliminated, although these results depend on strict model assumptions. Emissions permit prices peak at $167/ton in 2050. This section presents these and other results generated under the “Ritter Plan” scenario.
Table 2.5. Emissions permit prices and equivalent increase in the price of one gallon of gasoline. The permit prices are denominated in the year 2005 price of consumption. The carbon price per gallon of gasoline was computed based on the permit price and the carbon content of gasoline.

<table>
<thead>
<tr>
<th>Year</th>
<th>Permit Price</th>
<th>Equivalent Increase In Gasoline Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>$3.72</td>
<td>$0.04</td>
</tr>
<tr>
<td>2025</td>
<td>$8.13</td>
<td>$0.08</td>
</tr>
<tr>
<td>2030</td>
<td>$12.84</td>
<td>$0.12</td>
</tr>
<tr>
<td>2035</td>
<td>$21.72</td>
<td>$0.21</td>
</tr>
<tr>
<td>2040</td>
<td>$39.78</td>
<td>$0.39</td>
</tr>
<tr>
<td>2045</td>
<td>$79.22</td>
<td>$0.77</td>
</tr>
<tr>
<td>2050</td>
<td>$167.35</td>
<td>$1.62</td>
</tr>
<tr>
<td>2055</td>
<td>$144.35</td>
<td>$1.40</td>
</tr>
<tr>
<td>2060</td>
<td>$122.07</td>
<td>$1.18</td>
</tr>
</tbody>
</table>

2.5.1 Permit Prices

Table 2.5 presents the projected permit prices under the scenario over the model period. As a point of reference, Table 2.5 also shows the corresponding increase in the price of a gallon of gasoline at the permit price for each solution year. In the first year that permits are traded, 2020, the permit price is $3.72, reflecting that the initial 20% reduction can be achieved cheaply. Permit prices rise to $167.35 in 2050, when the last emissions reduction is achieved. From 2050 to 2060, the permit price falls to $122.07, as producers continue to adapt to the emissions cap and production shifts into less polluting activities.

For comparison, Balistreri and Rutherford (2004) estimate that the state of Colorado would see a 2010 price of $54.27 per ton of CO$_2$ to achieve a 7% reduction from 1990 levels. This estimate rises to $63.00 per ton if a national system is considered, and falls to $10.10 with international trade in permits. If Colorado acts alone, its permit price is lower than under a national system since production can move
to other states. However, international trade in permits reduces the price because a wider trading area allows for greater efficiency in emissions reduction activities. More recently, the EIA has published estimates of the impact of the Lieberman-Warner Climate Security Act for the US economy. This 63% reduction from 2005 levels in 2050 would result in permit price estimates ranging from $60 to $156 in the year 2030, depending on the availability of international offsets.3

2.5.2 Macroeconomic Indicators

Figure 2.5 shows the percentage changes in Investment, Capital Stock, and Consumption compared to the baseline scenario. By the end of the model period in 2060, Investment has fallen by 11%, the Capital Stock by 11%, and Consumption by 4%, compared to the baseline outcome. The behavior of each of these economic variables is described below.

**Investment** Investment fluctuates the most widely of the three economic indicators given. Leading up to the permit scheme, investment increases slightly, as agents prepare for the coming permit policy. Investments are made while they are relatively cheap and can help shift economic activity into less emitting sectors and more flexible technologies. After the system is introduced, the investment continues while permits are cheap, but in 2050, it declines, relative to the baseline, in order to prevent consumption from declining further. This is the most expensive year for emissions, so investment is sacrificed in favor of consumption, as forward-looking agents know that the years before and after offer more flexibility. Investment is needed to maintain the capital stock and to continue to grow those sectors that produce fewer emissions, and

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3These estimates are available at http://www.eia.doe.gov/olaf/servicerpt/s2191/index.html
its level increases as the level of emissions is held constant and permit prices begin to fall.

**Capital Stock**  The capital stock in a given year depends on the level of investment in prior years (due to the assumed investment lag), and the rate of depreciation. As the level of investment peaks in 2045 and proceeds to fall, the level of the capital stock also begins to decline. (though less steeply than investment). Because of the reduction in investment, the capital stock is reduced by 11% compared to the benchmark case by the end of the model period.

**Consumption**  The level of consumption does not fluctuate as widely as the other economic variables. Consumers can offset reduced production in the state by purchas-
Figure 2.6. Percentage change in the price level, compared with the benchmark case. The real price level is indexed by the 2005 price of consumption.

ing more imported goods. Consumption is reduced slightly, compared to the baseline, as the permit price continues to rise. This is offset in later years by a reduction in the level of investment. Consumption levels off after the last reduction in emissions, settling at a 4% decline from the baseline scenario.

**General Price Level**  Figure 2.6 displays the percentage change in the general price level compared to the benchmark. Prices are indexed by the price of consumption in the base year, 2005. The price level increases over the entire period of emissions restriction. The level of prices in 2060 is 6% higher than in the benchmark case. The high price of permits is offset somewhat by the fact that imports are available, and the assumption that import prices do not depend on the level of imports.
2.5.3 Sectoral Output

As the price of permits rises, we should expect that economic activity will shift from emissions-intensive sectors to those that are less so. The impacts on individual sectors are shown in Figure 2.7. Some sectors decline dramatically, while other sectors, such as services, are relatively unaffected. Notice that the coal mining sector is quickly driven to extinction. The production of electricity from coal is very emissions intensive, and the electricity sector switches to other fuels as it contracts over time. As shown in Table 2.1, Colorado currently produces most of its electricity in coal-fired plants. Residents would import electricity rather than generating emissions within...
Electricity output falls by 90% over the model period compared to the benchmark scenario. However, electricity use in the state falls by less - 26%. The model assumes that Colorado is a small open economy, and can import as much electricity as desired at a fixed external price. This assumption may be unrealistic, depending on transmission capacity and availability of electricity in nearby states. With limited electricity imports, the coal mining sector would likely see a smaller decline in output.

The imports of electricity and other carbon-intensive goods are financed by the sale of exports such as crude oil. As demand for crude oil declines within the state, the relative external price increases, and exports become more profitable. In this way, the production of emissions intensive goods moves out of state; the raw materials are exported, and the final goods are imported. Other sectors that are severely affected include the energy-intensive agriculture sector and the production of fuels. Again, these results are exaggerated by the small open economy assumption.

By exporting more crude in order to purchase electricity and other goods produced elsewhere, Colorado is essentially exporting emissions to meet its target. Greenhouse gases are uniformly mixing pollutants; therefore, relocating the production of emissions is ineffective. The next chapter discusses this effect, known as emissions leakage, and quantifies the amount of leakage resulting from the policy.

2.6 Conclusions

This chapter has described the impacts on the Colorado economy of a carbon emissions reduction policy. It shows that the economy shrinks as a result of the policy, relative to the baseline projection, and some sectors are nearly eliminated. The potential decline of these sectors may make such a policy politically difficult.
The reduction in productive activity within the state is offset by imports of emissions-intensive goods, and this leakage of emissions lessens the effectiveness of the policy.

Clearly, this analysis has some limitations. Firstly, the state is assumed to act unilaterally, a situation that is not likely. If Colorado were to use such a permit system, it would probably do so along with other Western states or under a national policy. A broader system may experience very different outcomes. With a wider trading area, more opportunities exist to reduce emissions cheaply. Imports of goods, such as electricity, would not be as readily available when neighboring states also commit to emissions reductions. Leakage rates may be reduced because of the higher prices of imports. While a larger agreement may be preferable, at present Colorado is not a trading member of the WCI, nor has a federal policy been enacted. Until such an agreement is achieved, the results presented in this chapter give a sense of the difficulties encountered in meeting Colorado’s emissions reduction goals.

Another limitation is that the external prices faced by Colorado consumers are assumed not to increase with the increased demand for imports. This may dampen the impacts of a permit scheme. While this assumption may be unrealistic, the alternative requires individually modeling other state or regional economies, a task beyond the scope of this research. Finally, it is not hard to see that Colorado consumers have a strong incentive to cease emissions intensive activities and import those final goods instead. This lessens the global emissions reduction achieved under the policy. The next chapter will explore the implications of emissions leakage more thoroughly.
Chapter 3

MEASURING THE LEAKAGES FROM A STATE-LEVEL POLICY

ABSTRACT

As many US states attempt to reduce their greenhouse gas emissions, the relocation of these emissions to other areas, known as emissions leakage, must be considered. The state of Colorado is presently designing policies to undertake such a reduction in emissions. This chapter attempts to quantify the emissions leakage expected under the state’s current goal of an 80% reduction in CO$_2$ emissions from 2005 levels by 2050. These estimates are provided for nine sectors, representing energy and non-energy commodities, from a dynamic computable general equilibrium model of the state economy. We find that in the central parameterization, the emissions leakage rate associated with meeting the state’s long-run goals peaks at 7%, with higher rates for the electricity sector. These leakage rates depend on the ability of Colorado consumers to import carbon-intensive goods, and the flexibility to switch between energy inputs.

3.1 Introduction

When evaluating proposals to reduce carbon dioxide (CO$_2$) emissions, the effectiveness of a policy is as important a consideration as the economic impact. For example, emissions reduction policies may result in reduced output of goods and services, employment changes, and a redistribution of income. These economic con-
sequences may be acceptable if a substantial reduction in emissions can be achieved. However, there are aspects of a policy’s design that can reduce the amount by which emissions are reduced globally.

In the state of Colorado, several measures have been introduced to encourage energy efficiency and the use of renewable energy sources. A renewable portfolio standard (RPS) is in place, requiring that 20% of the electricity sold in the state be generated by renewable sources by 2020.\footnote{Many other measures are described in Chapter 1.} Importantly, Governor Bill Ritter has suggested that the state work to reduce its CO$_2$ emissions by 80% from 2005 levels by 2050, with an intermediate reduction of 20% from 2005 levels by 2020 (Ritter (2007)). This emission reduction goal is referred to as the “Ritter Plan” throughout this chapter.

In this chapter, we analyze the reduction in carbon emissions achieved by the state of Colorado through the use of a tradable emissions permit policy. By considering the leakage of emissions to other states, we investigate how effective the state can be in meeting its emissions reduction goals under the “Ritter Plan.” The next section details policy concerns for the state. Section 3.2 reviews the methodology used, and Section 3.3 presents leakage rates for the results from Chapter 2. Results are presented which show the sensitivity of the leakage rate to model parameters in Section 3.4, and Section 3.5 concludes.

### 3.1.1 Concerns for Local Emissions Reduction Policies

When relatively small jurisdictions act unilaterally to control global pollutants such as CO$_2$, the emissions reductions achieved are undermined by leakage and reshuffling effects (Bushnell et al. (2008)). Leakage occurs when polluting activities move...
to other jurisdictions with less stringent regulation. Residents of the heavily regulated area can import the goods, undermining the reduction in global emissions of the pollutant. Reshuffling refers to the ability of residents in a regulated area to import “green” varieties of a good without installing new clean production technology. If these goods are available in unregulated areas, residents can simply import them, and no new capacity is built either inside or outside of the regulated area. Both of these phenomena are relevant to Colorado’s attempts to reduce CO$_2$ emissions.

Emissions reduction policies increase production costs in the affected jurisdiction relative to outside areas. The productive activity, and the associated emissions, relocate from the regulated area, while consumers within the area can import the final goods. The global level of emissions may not be significantly reduced under such a policy. While the relocation of economic activity may protect sensitive areas from local pollutants, it is not as helpful in the case of a global pollutant like CO$_2$.

Emissions leakage is relevant to the policy debate within Colorado. If Colorado were to act unilaterally to meet its emission reduction goals, market forces would push electricity production out of the state, as discussed in Chapter 2. Table 2.1 shows that most electricity generated within Colorado is produced in coal-fired plants, which are emissions intensive. Generators would have incentives to cite new plants and shift generation to plants outside of the state if emissions permits were required.

Even if Colorado were to join the Western Climate Initiative (WCI) as a trading partner, possibilities for emissions leakage exist. Colorado’s goal of a 20% reduction from 2005 levels by 2020 is more restrictive than the WCI’s mandated 15% reduction by 2020. More importantly, the WCI is a voluntary collaboration between states. For instance, the neighboring state of Wyoming, with its valuable coal mining industry, would not, in all likelihood, join such an agreement. Without a national policy to
limit carbon emissions, Colorado policy makers must consider the real possibility of significant emissions leakage.

Reshuffling is another way to circumvent local pollution controls. Many regulations require goods consumed in an area be produced in a clean way. Notably, an RPS requires that a specified percentage of electricity sold in an area is generated by renewable sources. If existing renewable capacity already exists outside the area, demand may be met by importing the renewable electricity without installing new renewable capacity. For instance, consider the case of a hydroelectric facility located in an unregulated state. Residents of a regulated state could purchase electricity from the hydroelectric facility in order to meet their RPS requirement, and reduce traditional generation accordingly. If the unregulated state increases its traditional generation to meet its own demand, the RPS has not caused any new renewable capacity to be built.

Colorado is working to meet an RPS requiring 20% of electricity sold in the state be generated by renewable sources by 2020. In 2008, over nine percent of the state’s electricity was generated by renewable means, primarily hydroelectric, wind, and solar. Several initiatives are underway to meet the RPS goals, including the formation of panels to identify sites for renewable electricity generation facilities, and increased support for the development of renewable technologies (Ritter (2007)). More information about Colorado’s RPS policy can be found in 4.

Reshuffling could be a concern for Colorado’s renewable portfolio standard legislation. However, many states across the US have implemented similar policies, limiting the availability of renewable electricity imports. The RPS legislation also includes incentives for the citing of renewable capacity within the state. For these reasons, we will focus on emissions leakage throughout this chapter as the more important
Emissions leakage can have other causes besides the movement of productive activity to other jurisdictions. Fischer and Morgenstern (2008) suggest that emissions reduction policy reduces the demand for fossil fuels within the jurisdiction. If the regulated area and the emissions reduction are large enough, the price of these fuels may be reduced. The lower price stimulates demand for these fuels in unregulated areas, increasing emissions in these locations and reducing the effectiveness of the emissions reduction policy.

A related effect is apparent in the results presented in Chapter 2. While Colorado is considered a small open economy that cannot affect the global price of fuels, it begins the period of consideration as a net exporter of oil and gas. When the tradable emissions permit policy is introduced, demand for oil and gas decline within the state, resulting in a relatively lower price for these fuels within Colorado. Exports of crude oil actually increase as the relative external price rises and Colorado residents try to finance their imports of emissions intensive goods. When computing emissions leakage for a particular sector we look at the increased carbon content of new imports relative to reduced emissions in Colorado. For crude extraction imports fall and the leakage is caused by increased exports, which induce increased scenario emissions.

As economic activity relocates from a regulated area, there are employment impacts. The loss of jobs can make an emissions reduction policy unpopular and less likely to be enacted, especially if the lost jobs are in the area’s politically sensitive industries. Jensen and Rasmussen (2000) point out that revenues from permit auctioning can be used to subsidize these industries and prevent the loss of employment. Because the industries most at risk under an emissions reduction policy are those that produce emissions intensively, subsidizing these industries reduces leakage by
encouraging them to remain in the jurisdiction.

Alternatively, emissions leakage can be reduced by taxing the carbon content of imports. The theory of the second best suggests that the undesirable result of the emissions reduction policy should be offset by another policy. In this case, an import tariff would raise the effective price of imports and discourage emissions leakage. Tariffs are not considered in this analysis because the area of interest is an American state, making the use of such policies illegal. While the use of tariffs is not available to Colorado, a renewable portfolio standard can be used along with the emissions reduction policy. As Goulder (2007) argues, requiring electric utilities to account for the emissions associated with their sales, regardless of where the electricity was generated, can help reduce emissions leakage.

3.1.2 Leakage Measurement

Measuring emissions leakage resulting from an emissions reduction policy is a challenge for groups who employ this type of legislation. The Regional Greenhouse Gas Initiative (RGGI) reports its concerns for leakage in Farnsworth et al. (2007). Emissions leakage is a concern for this group of states, because their cap on emissions will raise the price of electricity generated by covered plants. In the competitive market for electricity, production will then shift to other plants which are not covered by the emissions cap. The organization suggests monitoring this leakage by tracking the shares of the load within the RGGI region that are produced by participating plants, plants in other regions, and plants too small to be regulated. By examining the attributes of these plants, the organization hopes to estimate emissions leakage. The group is also designing policies to reduce leakage, such as encouraging energy efficiency and using emissions portfolio standards.
Alvarado (2006) presents a way of estimating the generation mix of electricity imports for California. The method is tailored to California’s electricity profile, and the author suggests that electricity purchased through short-run contracts to supplement the baseline level of generation within the state is the most important component of electricity imports. He identifies the resources that are used to meet this demand in different areas of the state to produce estimates of the composition of electricity imports.

The concern for emissions leakage is not unique to US states. Even large international agreements, such as the Kyoto protocol, do not include all nations, and are subject to leakage concerns. Developing nations are not asked to reduce emissions at the expense of economic growth. Other nations, like the US, have declined to participate in the agreement over economic concerns. By not including these nations; possibilities for emissions leakage exist. Paltsev (2002) estimates carbon leakage for the Kyoto Protocol agreement at 10%. Babiker (2005) suggests that emissions reduction policies in the developed world may actually increase global emissions by moving carbon-intensive industries to the developing world where they can expand with fewer restrictions using less efficient technologies.

Geres and Michaelowa (2002) propose a methodology for measuring the leakages associated with Clean Development Mechanism and Joint Implementation projects undertaken through the Kyoto Protocol. Through these programs, participating countries can support emissions abatement and clean energy programs in developing nations in exchange for reduction credit in their home nation (UNFCCC (1997)). This methodology is important, because CDM guidelines require that leakages be considered when designing projects. Kallbekken (2007) predicts that these programs will help to reduce emissions leakage by allowing developing countries to reduce emissions
more cheaply.

3.2 Methodology

In order to understand the emissions leakage associated with a policy, a leakage rate can be used. This rate is defined as the tons of emissions generated outside of the regulated area on behalf of its residents per ton of emissions reduction achieved within the area. Formally, the leakage rate for a sector \( i \) in time \( t \) is defined as:

\[
\text{Leakage rate}_i = \frac{\text{emissions content of new imports}}{\text{emissions reduction}} = \frac{(M^S_{it} - M^B_{it})(E^B_{it})}{E^B_{it} - E^S_{it}}, \tag{3.1}
\]

where

\( i \in \{1, \ldots, 9\} \) indexes sectors,

\( t \in \{1, \ldots, 12\} \) indexes the solution periods,

\( E^B_{it} = \) Benchmark emissions for sector \( i \) in period \( t \),

\( E^S_{it} = \) Scenario emissions for sector \( i \) in period \( t \),

\( M^B_{it} = \) Benchmark imports of good \( i \) in period \( t \),

\( M^S_{it} = \) Scenario imports of good \( i \) in period \( t \),

\( X^B_{it} = \) Benchmark production of good \( i \) in period \( t \),

\( H^B_t = \) Benchmark household emissions in period \( t \), and

\( H^S_t = \) Scenario household emissions in period \( t \).
The leakage rate for sector \( i \) in period \( t \) equals the increase in imports of good \( i \) under the policy compared with the business-as-usual level, times the carbon content of the good, divided by the reduction in emissions for sector \( i \) within the state. Put another way, it is the tons of emissions exported to other areas for each ton of emissions reduction achieved by the policy. To get an overall leakage rate for the state in year \( t \), the sectors can be summed in the following manner:

\[
\text{Overall leakage} = \frac{\sum_{i=1}^{9} [(M_{it}^S - M_{it}^B)(E_{it}^B)]}{\sum_{i=1}^{9} (E_{it}^B - E_{it}^S) + (H_{it}^B - H_{it}^S)}.
\]  

The reduction in emissions generated by households is included in the overall leakage rate so that all emissions reductions are accounted for. Household generation of emissions cannot be exported because we do not consider policy-induced migration.

### 3.2.1 Computable General Equilibrium Model of Colorado

The changes in imports, exports, and emissions needed to calculate the leakage rates for Colorado are generated by the computable general equilibrium (CGE) model detailed in Chapter 2 and Appendix A. This model generates a baseline forecast of the Colorado economy, calibrated to 2005 IMPLAN data and forecasts of emissions, energy production, and energy prices from the US Energy Information Agency. The dynamic model assumes forward-looking agent behavior and links investment to capital accumulation. Nested CES production functions focus on energy substitution for production of goods and consumer welfare. This baseline forecast can be compared to a Ritter Plan scenario in which tradable permits are introduced to meet the state’s emission reduction goals.

The model runs from 2005, the year from which emissions reductions are based, to 2060, ten years beyond reaching the final emissions reduction goal. The model
includes nine sectors. The energy sectors are crude oil and gas production, coal mining, oil, gas, and electricity generation. The non-energy sectors are agriculture, manufacturing, services, and an aggregate of other small sectors. Leakage rates are computed for each of these sectors in each model year.

3.2.2 Impacts of the Ritter Plan

As discussed above, Governor Ritter has proposed that the state reduce its CO$_2$ emissions by 20% from 2005 levels by 2020, and 80% by 2050. In the CGE model, agents are endowed with a sufficient quantity of permits to result in a zero-price of permits until the reduction is undertaken. In 2020, the quantity of permits is reduced by 20% of their 2005 level to force an equivalent reduction in emissions. CO$_2$ emissions are directly linked to fuel inputs, allowing for the possibility of a system that attaches emissions permits to fuels, instead of monitoring the emissions themselves. In the model, every five years the number of permits is reduced by 10%, resulting in a 2050 level that is 80% below the 2005 emissions output. After 2050, the allowable emissions are held constant.

Full results of the Ritter Plan scenario may be found in Chapter 2. The model predicts that the reduction in emissions causes consumption to fall by 4% while the price of consumption rises by 6%, compared to the benchmark case. Permit prices rise from $3.72 to $167.35 as the available quantity of permits is reduced. Some carbon-intensive sectors of the economy are either lost or decline dramatically, such as electricity production and coal mining. These impacts continue beyond the model period due to the reduction in investment in later periods which helps to smooth consumption. This lack of investment reduces the capital stock and therefore economic growth for years beyond 2060.
Table 3.1. Leakage rates (in percent). The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. Several sectors have negative leakage rates because of a decline in imports. The crude oil and gas extraction sector has positive leakage rates because of the increase in its exports. Electricity is a large, emissions intensive sector and therefore has the highest leakage rates.

<table>
<thead>
<tr>
<th>Year</th>
<th>AGR</th>
<th>COL</th>
<th>CRU</th>
<th>OIL</th>
<th>GAS</th>
<th>ELE</th>
<th>OTH</th>
<th>MAN</th>
<th>SRV</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-3.28</td>
<td>-2.33</td>
<td>16.03</td>
<td>-84.95</td>
<td>0.82</td>
<td>15.20</td>
<td>-17.69</td>
<td>0.36</td>
<td>-1.72</td>
<td>2.76</td>
</tr>
<tr>
<td>2025</td>
<td>-1.93</td>
<td>-6.31</td>
<td>17.84</td>
<td>-54.96</td>
<td>0.83</td>
<td>18.36</td>
<td>-11.63</td>
<td>0.17</td>
<td>-1.82</td>
<td>4.67</td>
</tr>
<tr>
<td>2030</td>
<td>-1.31</td>
<td>-6.96</td>
<td>17.85</td>
<td>-43.60</td>
<td>1.17</td>
<td>21.03</td>
<td>-8.71</td>
<td>0.27</td>
<td>-1.28</td>
<td>6.40</td>
</tr>
<tr>
<td>2035</td>
<td>-0.87</td>
<td>-7.57</td>
<td>17.77</td>
<td>-32.96</td>
<td>0.48</td>
<td>21.54</td>
<td>-6.20</td>
<td>0.30</td>
<td>-1.15</td>
<td>7.00</td>
</tr>
<tr>
<td>2040</td>
<td>-0.56</td>
<td>-7.57</td>
<td>23.12</td>
<td>-23.93</td>
<td>0.24</td>
<td>20.49</td>
<td>-4.02</td>
<td>0.42</td>
<td>-0.96</td>
<td>6.53</td>
</tr>
<tr>
<td>2045</td>
<td>-0.58</td>
<td>-6.40</td>
<td>42.97</td>
<td>-18.67</td>
<td>-0.14</td>
<td>15.19</td>
<td>-2.77</td>
<td>0.44</td>
<td>-0.84</td>
<td>4.36</td>
</tr>
<tr>
<td>2050</td>
<td>-0.57</td>
<td>-5.01</td>
<td>-4.36</td>
<td>-13.87</td>
<td>0.17</td>
<td>9.27</td>
<td>-1.49</td>
<td>-0.38</td>
<td>-1.35</td>
<td>2.15</td>
</tr>
<tr>
<td>2055</td>
<td>-0.58</td>
<td>-3.94</td>
<td>-2.14</td>
<td>-10.33</td>
<td>0.62</td>
<td>7.36</td>
<td>-1.05</td>
<td>-0.03</td>
<td>-0.62</td>
<td>1.82</td>
</tr>
<tr>
<td>2060</td>
<td>-0.45</td>
<td>-3.07</td>
<td>-1.64</td>
<td>-8.16</td>
<td>0.51</td>
<td>5.74</td>
<td>-0.81</td>
<td>-0.03</td>
<td>-0.48</td>
<td>1.44</td>
</tr>
</tbody>
</table>

Because Colorado is assumed to act unilaterally in this scenario, the emissions intensive goods that are no longer produced in state can be imported. Importing these goods reduces the welfare impacts of the policy, but results in emissions leakage. The next section presents the leakage rates associated with this emissions reduction policy.

3.3 Leakage Rates

Table 3.1 displays leakage rates for the nine sector Colorado economy over the period of emissions reduction. The total leakage rate for the state ranges between 1.4% and 7.0%, representing the additional tons of emissions produced out of state for each ton avoided in Colorado. The total emissions leakage rate increases once the period of emissions reduction begins, and then declines as consumption falls and the economy adapts to the policy shock. Rates for the individual sectors vary due to differences in energy intensity and elasticities governing the demand (both final and
intermediate) for the good.

The increase in exports of crude oil results in high leakage rates for that sector. The energy intensive electricity sector experiences high rates of leakage; natural gas and manufacturing exhibit positive rates of leakage (in most years). The service sector sees negative leakage rates over the model period because this sector expands slightly in comparison to the baseline forecast. Services are not carbon intensive, so factors of production move into the sector, while the overall economy contracts. On the other hand, agriculture sees negative leakage rates because the decrease in consumption of agricultural products is not completely offset by an increase in imports.

3.3.1 Fuel Sectors

Sectors COL, OIL, and GAS produce fuels which are used as inputs to other productive sectors. When the emissions reduction policy is implemented, less of these fuels are demanded by producers of other goods and by consumers. Producers of goods reduce their demand for fuels both by substituting away from fuels into other inputs and by reducing output. Consumer demand for all goods falls, reducing demand for fuels directly and indirectly. The reduced demand for fuels leads to fewer net imports of fuels. The process of producing these fuels is also carbon intensive; further reducing the instate production of these fuels.

For the COL and OIL sectors, the leakage rate is negative due to the reduction in imports. Because natural gas has a lower carbon content than coal and oil, consumers of fuels switch to gas. The increase in demand causes GAS to have a positive leakage rate. This rate is small because Colorado is a net exporter of gas in the baseline forecast, and these exports are redirected to meet in state demand, reducing the demand for imports.
3.3.2 Crude Oil

The crude oil and gas extractive sector, CRU, experiences a much higher leakage rate than the fuel goods. This sector experiences an increase in output and a reduction in net imports. Domestic demand for CRU falls as the domestic fuel sectors (OIL and GAS) shrink. External prices of CRU are stable, however, so CRU sales outside of Colorado become an important surplus in the balance of payments. Colorado uses the exports of crude to finance its purchases of other goods. Consistent with this, imports of CRU fall. In the calculation of leakage, both the numerator and denominator are then negative, and leakage can be thought of as moving in the opposite direction. Through the trade equilibrium, the policy induces increased production and emissions from the CRU sector in Colorado. To be consistent across sectors the increased emissions associated with the increase in CRU output must be taken into account as leakage. Leakage rates for CRU rise and then fall dramatically as the level of production for export decreases, as shown in Figure 2.7.

3.3.3 Electricity

The electricity sector experiences a larger rate of leakage than the economy as a whole. This sector is carbon intensive, so output declines within the state by nearly 65% in 2035 (compared to the baseline level), when leakage peaks. Electricity is an important input to all of the other sectors of the economy, and is needed by consumers as well. The limited ability to substitute away from electricity requires that electricity be imported. Again, the leakage computation used here assumes that the increased electricity production in other states to meet Colorado's new imports has the same emissions intensity as current generation in Colorado. Differences in the generation profile may change the actual number of tons of emissions shifted to other states.
3.3.4 Non-Energy Sectors

The four non-energy sectors, agriculture, manufacturing, services, and a composite of other small sectors, experience different leakage rate patterns. Agriculture is energy intensive, and experiences a dramatic decline in output. The negative leakage rate occurs because imports of agricultural goods also fall. It may seem unlikely that agricultural imports would fall while production also declines within the state. However, agricultural products are the largest input to the agriculture sector, representing almost half of the total inputs. Under the emissions reduction scenario, agricultural production falls by more than 80%, relative to the benchmark projection, dramatically reducing the demand for imports of other agricultural products such as seed crops and animal feed.

Manufacturing experiences a small, positive leakage rate for most of the duration of the emissions reduction program. The reduction in output within the state is offset by the reduction in consumption. As the level of consumption continues to fall and imports of manufactured goods decrease, leakage rates become negative. The miscellaneous sector, OTH, also experiences negative leakage rates because of the reduced demand for imports of mining and transportation services.

The services sector, denoted SRV, experiences small, negative rates of leakage. This sector is the least energy intensive, and consequently, is affected the least by the emissions reduction policy. Output increases slightly, reducing the demand for imports of service goods. Imports are also reduced by the general reduction in consumption. Emissions may be slightly reduced by switching to other fuels, but not dramatically because the sector already uses comparably few energy inputs.

Why aren’t the leakage rates across all sectors higher? Production by some sectors, such as coal, is virtually eliminated, while the overall level of consumption
for Colorado residents only falls by four percent. Changes in domestic absorption range from a 13% drop in manufactured goods to a 98% drop in the use of coal.

Firstly, exports of goods decline. Coal, oil, gas, and electricity virtually cease to be exported; agriculture and manufacturing sectors see their exports fall by more than 50%. So even though domestic production of these items is reduced, more of this production is consumed in state. Secondly, emissions generated by households cannot be exported, because migration is not considered in the model. The use of fuels for personal transportation and household needs fall when emissions permits are introduced. For instance, if a consumer buys a unit of gasoline, they must purchase a permit to go along with it, whether the gasoline was produced in Colorado or not. The higher cost of energy causes households to reduce their consumption of energy goods, thereby reducing emissions.

Finally, the ability to export emissions is limited by several model parameters, specifically the Armington elasticity and the elasticity of substitution between fuels and electricity. This substitution elasticity used to generate these results is set at a low level, reflecting the technological differences in these methods for consuming energy. The next section investigates the model outcome’s sensitivity to these parameters.

### 3.4 Sensitivity Analysis

The leakage rates discussed in the previous section are generated under a few key model assumptions. As mentioned in the previous section, production technologies are assumed to be identical in and outside of Colorado. In reality, leakage rates may be higher or lower depending on the technologies used, although this is difficult to measure. Colorado is also assumed to be a small, open economy that can import or export goods at fixed external prices. Relaxing this assumption would reduce leakage
rates, as importing energy intensive goods would become more expensive.

Several parameters may affect the estimates of leakage generated by the model. These parameters govern the ability of consumers to substitute between domestic production and imports, as well as between energy and non-energy inputs. In this section we discuss the sensitivity of leakage rates to two of these parameters: the Armington elasticity, \( \sigma_a \), and the elasticity of substitution between electricity and other fuels, \( \sigma_e \). Results are presented for the overall leakage rate and the leakage rate for the electricity sector. The results presented up to now use a value of 10 for \( \sigma_a \) and 0.2 for \( \sigma_e \).

### 3.4.1 Armington Elasticity

A key assumption about the ability of Colorado residents to import carbon intensive goods is taken from Armington (1969). The Armington assumption considers domestically produced and imported varieties of the same good as imperfect substitutes. This explains the observation that the same good can be imported and exported by a region, known as “cross-hauling.” If imports and domestic production were considered perfect substitutes, there would be no reason to expect that one good would be both imported and exported. Assuming a finite elasticity of substitution between these varieties limits the amount of trade activity response that occurs in the model outcome.

In order to implement this assumption in the CGE model, an Armington activity is utilized. This activity takes imported and domestic varieties of the same good and aggregates them together according to an assumed \( \sigma_a \). This elasticity parameter may be given different values for different sectors of the economy, allowing, for instance, energy sectors to have a higher elasticity than non-energy sectors. By increasing \( \sigma_a \),
Table 3.2. Total leakage rates (in percent) for various Armington elasticities. The Armington elasticity controls the substitution between domestic and imported varieties of the same good. Higher Armington elasticities allow for higher leakage rates in early years, due to increased flexibility to import emissions intensive goods, and lower leakage rates in later years, due to the increased flexibility to switch back to cleaner production in Colorado.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_a = 0$</th>
<th>$\sigma_a = 6$</th>
<th>$\sigma_a = 10$</th>
<th>$\sigma_a = 30$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>-1.59</td>
<td>1.44</td>
<td>2.76</td>
<td>7.33</td>
</tr>
<tr>
<td>2025</td>
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<td>2.43</td>
<td>4.67</td>
<td>10.97</td>
</tr>
<tr>
<td>2030</td>
<td>-1.86</td>
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<td>6.40</td>
<td>11.98</td>
</tr>
<tr>
<td>2035</td>
<td>-1.53</td>
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<td>7.00</td>
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</tr>
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<td>6.63</td>
</tr>
<tr>
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<td>4.62</td>
<td>4.36</td>
<td>4.15</td>
</tr>
<tr>
<td>2050</td>
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<td>2.15</td>
<td>1.99</td>
</tr>
<tr>
<td>2055</td>
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<td>1.93</td>
<td>1.82</td>
<td>1.68</td>
</tr>
<tr>
<td>2060</td>
<td>-0.84</td>
<td>1.53</td>
<td>1.44</td>
<td>1.33</td>
</tr>
</tbody>
</table>

model agents have more flexibility to import goods, increasing the leakage rates. In this section, sensitivity of leakage rates to the Armington elasticity parameter are investigated.

For the results presented here, the elasticity for the non-energy sectors is fixed at a level of 10.0. This level allows the flexibility to switch to imports of non-energy goods, but by keeping the level constant, the results of the sensitivity experiment are driven by energy intensive sectors.

Tables 3.2 and 3.3 show leakage rates under several Armington elasticities. With a low elasticity, emissions leakage is small (or even negative) in early periods and increases as the emissions reduction policy becomes more restrictive. We would expect smaller leakage rates with the lower elasticity, as consumers of energy intensive goods have less ability to switch to imported varieties. Compared to a higher elasticity, the decline in leakage rates in later years is smaller, because consumers have less flexibility to switch back into domestic varieties as the economy adjusts to the policy.
Table 3.3. Electricity sector leakage rates (in percent) for various Armington elasticities. The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. The Armington elasticity controls the substitution between domestic and imported varieties of the same good. Higher Armington elasticities allow for higher leakage rates in early years, due to increased flexibility to import emissions intensive goods, and lower leakage rates in later years, due to the increased flexibility to switch back to cleaner production in Colorado.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_a = 0$</th>
<th>$\sigma_a = 6$</th>
<th>$\sigma_a = 10$</th>
<th>$\sigma_a = 30$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>15.20</td>
<td>31.66</td>
</tr>
<tr>
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<td>6.06</td>
<td>5.74</td>
<td>5.50</td>
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</tbody>
</table>

With a higher Armington elasticity, emissions leakage is much larger in early periods. However, in later periods, leakage is smaller than with a low elasticity. Instate consumers then have more flexibility to purchase goods that are now produced in a cleaner way within the state. Model outcomes are not stable with Armington elasticities between one and five. Computationally, a substantial amount of flexibility between imports and domestic varieties is needed to solve for the counterfactual outcome, given the dramatic emissions reductions.

3.4.2 Elasticity of Substitution Between Electricity and Fuels

As discussed in section 3.3.3, electricity represents a large source of emissions leakage from Colorado under the Ritter Plan. The amount of electricity generation that moves out of state is partially governed by the ability to substitute electricity for other fuels. The relationship between this elasticity, $\sigma_e$, and the leakage rate is
Table 3.4. Total leakage rates (in percent) for various elasticities of substitution between electricity and fuels. The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. Higher values of $\sigma_e$ result in less emissions leakage in early years, due to the flexibility to switch into cleaner energy, and more leakage in later years, due to the ability to switch into imported electricity.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_e = 0$</th>
<th>$\sigma_e = 0.2$</th>
<th>$\sigma_e = 1$</th>
<th>$\sigma_e = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>2.82</td>
<td>2.76</td>
<td>2.39</td>
<td>0.09</td>
</tr>
<tr>
<td>2025</td>
<td>4.70</td>
<td>4.67</td>
<td>4.15</td>
<td>1.59</td>
</tr>
<tr>
<td>2030</td>
<td>6.55</td>
<td>6.40</td>
<td>5.66</td>
<td>2.63</td>
</tr>
<tr>
<td>2035</td>
<td>7.12</td>
<td>7.00</td>
<td>6.20</td>
<td>2.78</td>
</tr>
<tr>
<td>2040</td>
<td>6.31</td>
<td>6.53</td>
<td>6.47</td>
<td>2.84</td>
</tr>
<tr>
<td>2045</td>
<td>3.70</td>
<td>4.36</td>
<td>6.05</td>
<td>2.93</td>
</tr>
<tr>
<td>2050</td>
<td>1.53</td>
<td>2.15</td>
<td>4.64</td>
<td>2.77</td>
</tr>
<tr>
<td>2055</td>
<td>1.35</td>
<td>1.82</td>
<td>3.73</td>
<td>2.24</td>
</tr>
<tr>
<td>2060</td>
<td>1.07</td>
<td>1.44</td>
<td>2.96</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Reducing the elasticity of substitution between electricity and fuels $\sigma_e$ decreases the flexibility of firms to switch from fuels to electricity in order to reduce their demand for emissions permits. This effect acts to decrease the demand for imported electricity and therefore leakage. However, by lowering this elasticity, firms have less ability to switch out of electricity if the prices of fuels fall due to decreased demand, increasing the possibility of emissions leakage.

The relationship between the economy-wide leakage rate and $\sigma_e$ is complex. These leakage rates are displayed in Table 3.4. Allowing no substitution between electricity and fuels forces firms to purchase a set level of electricity per unit of output produced. Compared to the basic case of $\sigma_e = 0.2$, the associated leakage rates are higher in early years, and lower in later years when the policy becomes more restrictive and imported electricity becomes more attractive. Increasing $\sigma_e$ beyond the level in the central case actually reduces the amount of emissions leakage. The
Table 3.5. Electricity sector emissions leakage rates (in percent) for various elasticities of substitution between electricity and fuels. The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. More emissions leakage is experienced with higher elasticities because of the increased demand for imported electricity.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_e = 0$</th>
<th>$\sigma_e = 0.2$</th>
<th>$\sigma_e = 1$</th>
<th>$\sigma_e = 5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>14.90</td>
<td>15.20</td>
<td>16.15</td>
<td>23.32</td>
</tr>
<tr>
<td>2025</td>
<td>18.00</td>
<td>18.36</td>
<td>18.83</td>
<td>19.10</td>
</tr>
<tr>
<td>2030</td>
<td>21.00</td>
<td>21.03</td>
<td>20.88</td>
<td>18.46</td>
</tr>
<tr>
<td>2035</td>
<td>21.50</td>
<td>21.54</td>
<td>20.99</td>
<td>16.00</td>
</tr>
<tr>
<td>2040</td>
<td>19.48</td>
<td>20.49</td>
<td>21.25</td>
<td>14.08</td>
</tr>
<tr>
<td>2045</td>
<td>13.33</td>
<td>15.19</td>
<td>20.02</td>
<td>12.41</td>
</tr>
<tr>
<td>2050</td>
<td>7.33</td>
<td>9.27</td>
<td>17.12</td>
<td>10.98</td>
</tr>
<tr>
<td>2055</td>
<td>5.90</td>
<td>7.36</td>
<td>13.45</td>
<td>8.67</td>
</tr>
<tr>
<td>2060</td>
<td>4.60</td>
<td>5.74</td>
<td>10.54</td>
<td>6.75</td>
</tr>
</tbody>
</table>

Limited availability of imported electricity dictated by the Armington elasticity (fixed at 10.0) encourages switching not only into electricity, but also into lower carbon fuels and other inputs.

Some of the unexpected results of the sensitivity analysis may be partly due to the way in which the model is constructed. In order to calibrate the model to projections of energy prices and outputs, a productivity adjustment is used. More details of this process are available in Appendix A. Unfortunately, these adjustments are calibrated subject to the elasticities provided to the model. By changing the elasticities, the productivity adjustment is affected, acting to counteract the sensitivity experiments. This modeling artefact may account for some of the behavior in the sensitivity experiments, however, incorporating the projections improves the baseline forecast for the state economy.

The leakage rate of the electricity sector behaves differently. As shown in Table 3.5 increasing the elasticity increases emissions leakage, to a point. Increasing the
Table 3.6. Total leakage rates (in percent) for various Armington elasticities and elasticities of substitution between electricity and fuels. The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. The Armington elasticity controls the substitution between domestic and imported varieties of the same good.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_a = 0.2$</th>
<th>$\sigma_a = 0$</th>
<th>$\sigma_e = 0$</th>
<th>$\sigma_e = 5$</th>
<th>$\sigma_e = 6$</th>
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<td>$\sigma_a = 30$</td>
<td>$\sigma_a = 0$</td>
<td>$\sigma_a = 30$</td>
<td>$\sigma_a = 6$</td>
</tr>
<tr>
<td>2020</td>
<td>2.76</td>
<td>7.78</td>
<td>-1.70</td>
<td>0.11</td>
<td>1.41</td>
</tr>
<tr>
<td>2025</td>
<td>4.67</td>
<td>11.44</td>
<td>-1.94</td>
<td>2.70</td>
<td>2.34</td>
</tr>
<tr>
<td>2030</td>
<td>6.40</td>
<td>12.41</td>
<td>-1.98</td>
<td>4.66</td>
<td>3.54</td>
</tr>
<tr>
<td>2035</td>
<td>7.00</td>
<td>9.35</td>
<td>-1.62</td>
<td>4.81</td>
<td>4.05</td>
</tr>
<tr>
<td>2040</td>
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<td>6.10</td>
<td>-1.36</td>
<td>4.44</td>
<td>4.59</td>
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<tr>
<td>2045</td>
<td>4.36</td>
<td>3.54</td>
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<td>4.78</td>
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<td>-1.07</td>
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<tr>
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<td>1.44</td>
<td>0.97</td>
<td>-0.85</td>
<td>2.50</td>
<td>3.04</td>
</tr>
</tbody>
</table>

elasticity further increases the leakage in the first period, but leakage rates quickly decline. As the Armington elasticity limits the imports of electricity, firms have the flexibility to switch into fuels as instate electricity generation declines and electricity prices rise. Keep in mind that the relatively low-carbon fuel natural gas is available, and some flexibility exists to substitute capital and labor for energy.

3.4.3 Interaction Effects

Tables 3.6 and 3.7 show leakage rates for the entire economy and the electricity sector under a variety of combinations of elasticities. The highest leakage rates are generated by high $\sigma_a$ and low $\sigma_e$. In this case, imports of electricity are readily available while there is no flexibility to switch out of electricity. With no flexibility, leakage rates are negative. Leakage rates are low when both elasticities are high. Energy consumers have little flexibility to switch into imports, but they can choose to switch into fuels as electricity becomes relatively more expensive.
Table 3.7. Electricity sector leakage rates (in percent) for various Armington elasticities and elasticities of substitution between electricity and fuels. The leakage rate is the ratio of the emissions content of increased imports to the emissions reduction achieved, relative to the baseline. The Armington elasticity controls the substitution between domestic and imported varieties of the same good.

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sigma_e = 0.2$</th>
<th>$\sigma_e = 0$</th>
<th>$\sigma_e = 5$</th>
<th>$\sigma_e = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\sigma_a = 10$</td>
<td>$\sigma_a = 30$</td>
<td>$\sigma_a = 0$</td>
<td>$\sigma_a = 30$</td>
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<tr>
<td>2020</td>
<td>15.20</td>
<td>31.58</td>
<td>-8.52</td>
<td>34.10</td>
</tr>
<tr>
<td>2025</td>
<td>18.36</td>
<td>32.97</td>
<td>-5.53</td>
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</tr>
<tr>
<td>2030</td>
<td>21.03</td>
<td>31.68</td>
<td>-4.81</td>
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</tr>
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<td>25.40</td>
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</tr>
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<td>2055</td>
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<td>5.64</td>
<td>-0.17</td>
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</tr>
<tr>
<td>2060</td>
<td>5.74</td>
<td>4.40</td>
<td>-0.11</td>
<td>9.58</td>
</tr>
</tbody>
</table>

3.4.4 Renewable Technology

One other model assumption that affects leakage rates is the availability of renewable technology. In this chapter, the portion of electricity generated from renewable sources is held constant at 9%, the state’s current level. In the next chapter, this percentage is changed to match the state’s RPS goals. Increasing the availability of renewable, and less polluting, electricity generation may act to reduce the rates of leakage predicted by the model.

3.5 Conclusions

This chapter has shown that a unilateral policy on the part of Colorado may not be as effective at lowering global atmospheric CO₂ levels as residents would like to believe. The leakage of emissions to other locations is a consequence of such legislation. While the import of carbon intensive goods by Colorado consumers helps
to reduce the economic impacts of an emissions reduction policy, it also reduces the
effectiveness of the policy. The leakage rates presented here show that for each ton
of reduction achieved within Colorado, as much as 7% of that ton may be exported
to other areas, amounting to as many as 3.64 million tons of CO₂ per year.

However, the amount of emissions leakage produced by the policy is limited by
a number of factors. Productive activities may not need to shift to other locations if
exports can be redirected to meet in state demand. Emissions produced directly by
Colorado households (as opposed to firms) cannot be exported without the migration
of residents. Migration may occur with the reduction in size of many industries, but
this is reduced by the increase in demand for labor as firms try to switch out of fuel
inputs and the service sector expands.

Not all sectors experience emissions leakage. For some sectors, the negative
leakage rates are driven by the decline in income and therefore consumption and
imports. The service sector, however, increases in size under the emissions reduction
policy because it produces few emissions per unit of output. Policies that increase
the size of low-carbon, domestic industries, such as subsidies or employee training
programs, can reduce the possibilities of both emissions leakage and unemployment.

Other sectors, as well as households, can reduce leakage by reducing their demand
for carbon emissions. Lower carbon permit prices mean less discrepancy between
production costs in and outside of the state, reducing the incentives to import goods.
Policies that increase energy efficiency may do just that. Aiding firms in developing
and installing technology that allows them to use lower carbon fuels can decrease
emissions leakage.

The amount of emissions leakage also depends on the flexibility of Colorado
consumers to switch to lower carbon energy sources and imports of emissions intensive
goods. This flexibility must be considered when designing an emissions reduction policy. Leakage rates rise when there is a lack of ability to substitute between fuels and electricity. In this case, the goods must be imported because they cannot be produced in a less polluting way. Policies that encourage firms to switch into cleaner fuels like natural gas can reduce emissions without pushing production out of state. Leakage rates are higher when imports of goods are more available, suggesting that an RPS policy that applies the same restrictions to imports as domestic electricity may reduce emissions leakage.

In the next chapter the renewable portfolio standard is investigated more thoroughly as a way to reduce emissions leakage. By requiring a specified portion of electricity be generated by renewable sources, leakage can be avoided by encouraging investments in technology that is less carbon intensive. The interaction between the RPS and the Ritter Plan policy is investigated, and the effects on leakage rates are presented.
Chapter 4

INTERACTIONS BETWEEN STATE-LEVEL EMISSIONS REDUCTION POLICIES

ABSTRACT

Renewable portfolio standards (RPS) have been implemented in many US states as a mechanism to reduce greenhouse gas (GHG) emissions and become more energy independent. One of these states, Colorado, has enacted an RPS requiring 20% of electricity sold within the state come from renewable sources by 2020. In this chapter we present results of a dynamic computable general equilibrium model of the state economy to demonstrate the economic impacts of the RPS. Results are presented for the RPS alone and with the state’s specific emissions reduction goals. We find that compared to the emissions permit scheme alone, leakage rates and permit prices are reduced in early years, but this benefit is lost as the program becomes more restrictive.

4.1 Introduction

Across the US, state legislatures are rapidly enacting renewable portfolio standard (RPS) legislation. These policies are popular because of their perceived benefits of reducing GHG emissions, increasing energy independence, and promoting investments in cleaner energy production. RPS policies mandate that a specified percentage of electricity sold in a region must be generated by renewable means. Subsidies and other incentives may be used alongside an RPS to meet the goal. Allowable
sources may vary, and some technologies may be favored by the legislation, but all RPS policies attempt to reduce emissions by increasing the share of renewable energy production.

In this chapter we use the computable general equilibrium model from previous chapters to investigate the impacts of such a policy on the Colorado economy. We measure these impacts, and compare them to the cases from previous chapters. The interactions between the RPS legislation and a market-based mechanism to meet the state’s long-term emissions reduction goals are discussed. These interactions are shown to decrease permit prices in early years, but the prices converge to the case of permits alone as the program becomes more restrictive. Leakage is reduced until the RPS ceases to be binding in 2035, leading to a reduction in the cumulative emissions generated over the period. Consumer welfare is further lowered compared to the case of permits alone, as capital is allocated inefficiently in early years to meet the RPS. However, by reducing leakage, the RPS increases the net emissions reduction achieved.

The rest of this section describes RPS policies in more detail, and provides information on Colorado’s renewable energy policies. The next section details the modeling of the renewable electricity generation sector. Section 4.3 presents outcomes for the Colorado economy under the RPS with and without an emissions permit scheme used to meet the state’s long term emissions reduction goals. The final section offers conclusions about the costs and benefits of using an RPS to reduce carbon dioxide emissions within the state.
4.1.1 Characteristics of Renewable Portfolio Standards

Renewable portfolio standards are favored at the moment because of a few key features. First, as shown in Chapter 2, restrictions on electricity generation that raise production costs may encourage generators to relocate from the regulated area. The associated loss of employment and/or tax revenue makes such measures politically difficult. However, an RPS policy regulates electricity sold in an area regardless of its origin, thus reducing the incentives for generation to shift to other areas.

Secondly, for a small jurisdiction, such as an individual state, an RPS may be more effective at reducing emissions than other policies. The amount of reshuffling under this policy is limited by the existing capacity and demand from other states. More renewable capacity must be installed to meet these regulations. Emissions leakage should also be small, because electricity sold in the state is regulated regardless of where it was generated. Retailers cannot import dirtier electricity from across state lines in order to meet the standard for a smaller number of instate facilities.

Finally, an RPS does not mandate that any one specific technology be used to reduce emissions. The flexibility to choose from a range of alternative energy sources exists, allowing generators to invest in the cheapest, most efficient sources for their particular operation. Colorado’s policy includes the ability for generators to buy renewable credits from other generators who exceed their requirements, including small generators that are not covered at all or face lighter regulation under the law. This flexibility should limit the costliness of lowering emissions through a technology requirement.

While a standard may be a useful tool for reducing emissions in small jurisdictions, there are some drawbacks to such a policy. Most importantly, the RPS only focuses on electricity generation, when opportunities for emissions reduction are exist
throughout the economy. An RPS does not require a specific technology, but mandates an increase in more expensive forms of generation. In most cases, emissions abatement, such as fuel switching or direct carbon sequestration at the stack, is not counted towards the standard, even though this technology may be cheaper at reducing emissions. By restricting the means of achieving emissions reductions, these reductions may not be made in the least-cost manner. Furthermore, the exact emissions reduction achieved is not known, and depends on the specific technologies used in electricity generation, electricity demand, economic growth, and other factors.

4.1.2 Interactions with Permit Policies

In many cases, RPS policies are one tool used to meet a larger emissions reduction goal. Throughout this document, Colorado is assumed to meet its emissions reductions goals with the use of a permit scheme, but the RPS is a complementary policy. Such is the case for the Regional Greenhouse Gas Initiative in the US Northeast (RGGI), which is using an RPS to reduce emissions leakage resulting from its tradable emissions permit scheme. The US Congress is currently considering both of these policies.

The interaction of these policies may have positive and negative effects. These effects are investigated by Stavins (1998), who asks the question of how the pre-existing regulatory environment can affect the operation of a permit scheme, and by Bushnell et al. (2008), who state that the flexibility that is the "key advantage of market-based mechanisms" is reduced when combined with other regulation. This interaction is particularly relevant for the highly regulated electricity industry. By limiting flexibility, adding an RPS to a permit scheme may raise the cost of achieving a desired reduction in emissions. This is due to the additional constraints added to
the manner in which emissions are reduced. Without the RPS emissions are reduced where it is least expensive to do so. However, with a 20% RPS, much of the emissions reduction is undertaken through the installation of renewable electricity generation technology, which may be more expensive than other abatement methods, such as reducing output, switching fuel inputs, or retrofitting emissions scrubbers.

On the other hand, efficiency standards may offset some of the negative side-effects from permit schemes, such as emissions leakage. When permits are used alone, increased production costs push industries out of the regulated area, and residents import final goods. Using an RPS with a permit policy may prevent this relocation because the good must be produced in a particular manner, regardless of its origin. Not only does this act to reduce leakage, it also reduces the loss of employment caused by the policy. In fact RPS policies are often enacted in hopes of drawing new investment and employment in renewable technology to the area. Reducing the demand for carbon-based fuels in the electricity sector may also reduce the price of permits.

4.1.3 Colorado’s RPS Policy

In 2007, the state of Colorado became the first in the US to pass an RPS by voter initiative. Amendment 37 originally required 10% of electricity be generated by renewable sources by 2010. The legislature then increased this requirement to 20% from renewables by 2020. The renewable sources allowed by this amendment include wind, solar, geothermal, biomass, hydroelectric, and hydrogen fuel cells; nuclear power is absent.¹ Table 2.1 displays the November 2008 electricity generation profile for Colorado. Hydroelectric makes up 2% of generation, with another 7% generated from

¹The full text of this amendment is available at http://www.dsireusa.org/documents/Incentives/CO26R.htm
other renewable sources, mostly wind and solar (United States Energy Information Agency (2009)).

The motivation provided for this amendment declares that Colorado’s renewable resources are underutilized, and that by developing these resources, growing energy demand can be met at a lower cost. At the same time, the regulation will help to improve environmental quality and reduce the electricity sector’s demand for scarce water resources (used in cooling traditional power plants). Finally, the measure is hoped to bring jobs to the state in the renewable technology industry and grow the economies of rural areas where these facilities can be cited. The state predicts that this measure will add $1.9 billion to the state GDP between 2008 and 2020.

The amendment that sets the RPS includes a few other restrictions on its implementation. Utility customers are entitled to a $2.00 per megawatt rebate for solar generation. The price increase that utilities can pass on to residential consumers is limited to 50 cents per month per household. Utilities cannot claim eminent domain over land to cite facilities. Finally, tradable renewable credits are established, allowing small, uncovered facilities to sell their renewable capacity to larger companies.

House bill 1281,\(^2\) enacted March 27, 2007, increased the percentage of renewables required by the RPS to 20% by 2020. Of the renewables required in each year, four percent must come from solar, and half of this amount should come from household solar units. Shortfalls may be met though renewable energy credits or efficiency and conservation projects. Cooperatives, which were not covered by the original legislation, are included in this bill, and they are required to meet a goal of 10% renewable generation by 2020.

The bill includes additional incentives for new facilities to be cited within Colorado, in an effort to meet the goals of stimulating employment and rural economic activity. Large generators may count 1.25 KW for each KW of renewable production within Colorado, co-ops may count 1.5 KW for each KW produced in state, and each KW of solar may be counted as 3 KW until 2015. While this lessens the amount of renewable generation required under the legislation, it reduces the reshuffling caused by the policy.

In addition to the RPS policy in Colorado, several other initiatives are in place to promote renewable energy use within the state. The Colorado Climate Fund allows individuals and businesses to purchase carbon offsets at $20 per ton.\(^3\) Proceeds of the fund are to be used for in-state projects in the areas of anaerobic digestion, solar water heater installation, biogas, energy efficiency, and transportation.

The Governor’s Energy Office provides high efficiency light bulbs, appliances, and insulation to low-income families. The office has also set goals for water use, paper use, and waste reductions for state offices.\(^4\) Rebates are available for the installation and maintenance of solar cells. Programs are in place to support the development of small hydroelectric and wind facilities, biomass, and biogas projects. Heating facilities using woody biomass are also being installed. This fuel includes wood chips from the routine thinning of forests as well as trees killed by pine beetle infestation.

The ability of states to meet their RPS requirements through imports is limited by the demand for renewables from other states with similar policies. Currently, 33 US states have some sort of renewable electricity goal. These goals range from Iowa’s 105 megawatts from renewable sources, which has been in effect since 1983, to California’s 20% renewable power by 2010. Ohio requires a 25% “alternative” energy standard by

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\(^3\)Please see http://www.coloradocarbonfund.org/ for more information.

\(^4\)Please see http://www.colorado.gov/energy/ for more information on the various programs.
2025, with at least 12.5% from renewables, and the rest to include third-generation nuclear plants, fuel cell production, clean coal technologies, and increased efficiency in generation. Minnesota’s goal is a 25% overall share of renewables by 2025, with Xcel energy, which provides over 50% of the state’s electricity, meeting a restriction of 30% by 2020. In addition to Colorado, five other states (Delaware, Maryland, Nevada, New Jersey, Pennsylvania) require a set level of the renewable standard be met by solar production (Pew Center for Global Climate Change (2009)).

4.2 Renewable Technology

Under House Bill 1281, electricity used in Colorado must be composed of 10% from renewables by 2010, 15% by 2015, and 20% from 2020 on. Currently, 9% of electricity is generated by renewable sources, as shown in Table 2.1. In previous chapters, renewable production was assumed to meet this level, but adding the RPS policy requires that this fraction be adjusted. This adjustment is made in the renewable electricity sector in the CGE model.5

Within the model of the Colorado state economy, electricity can be generated by conventional or renewable technology. The renewable sector uses no fuel inputs, but requires an additional amount of capital. Inputs are used in fixed proportions, to prevent substitution away from this capital, which is specific to the renewable sector. The household is initially endowed with a level of renewable capital chosen to meet the observed level of renewable generation. This amount is determined by a constraint that requires the specified fraction of electricity use, or imports plus production, that must be exceeded by the renewable sector. An assumption is made that the same

5See Chapter 2 and Appendix A for more description. Appendix A also presents a more technical description of the renewable sector.
9% of production comes from renewables in the generation of imported electricity. Capital for renewable generation, above the benchmark, comes at an increasing cost, relative to generic capital. We assume a constant elasticity of supply, so renewable penetration comes at ever increasing costs.\footnote{In the central case we assume an elasticity of supply of two.}

Given the current state of renewable technology, it is reasonable to assume that in the near future, more expensive technologies will be needed to meet the RPS requirements. The share of renewables must increase over the next five to ten years, and considering the time needed to design and receive approval for new installations, many of the required projects are well underway. Over time, however, technological progress may drive down the cost of renewable technology. In fact, a major argument for RPS policies is that they will encourage innovation in renewable electricity generation. Rather than modeling this behavior explicitly, we capture this innovation implicitly by including the EIA forecasted prices and quantities of energy commodities. These forecasts include current and pending renewable policies across the country, energy efficiency gains, and technological improvement (United States Energy Information Agency Office of Integrated Analysis and Forecasting (2009)).

The constraint that governs the level of renewable electricity production ensures that the RPS must be met or exceeded. This allows for the growth of the renewable sector in the case of no policy, which is consistent with the forecasted increases in prices of energy commodities. Also, in the case of both the permit policy and the RPS, we expect that the RPS may not be binding as traditional electricity production declines. Not only are investments made in renewable energy technologies, but as traditional generation declines, the fraction of electricity produced through renewable means increases.
4.3 Policy Impacts

Introducing a renewable electricity generation sector into the model allows a comparison of policy scenarios. These include the RPS alone, the permit scheme alone (presented in previous chapters) and the RPS and permits used simultaneously. The RPS policy causes a reduction in emissions, net of leakage, from the productive sectors within Colorado of 0.6 million tons of CO$_2$. This emissions reduction is achieved at the expense of a 0.12% loss in consumer welfare over the model period. Total in-state production of electricity declines by 0.13% by 2060, with conventional generation declining by a larger amount as renewable production increases. Electricity price increases peak at 0.09% above the baseline level in 2040.

More interesting is the comparison between the permit scenario cases, with and without the addition of the RPS policy. CO$_2$ emissions under different policy scenarios are shown in Figure 4.1. Some interactions between these policies are desirable; for instance, permit prices and emissions leakage are reduced in early years. Several economic indicators are compared here under these policy scenarios.

4.3.1 Permit Prices

Figure 4.2 gives permit prices with and without the RPS policy with a plot of the difference between them. When the RPS is added, emissions permit prices fall in the early years of the program. As the energy intensive electricity sector demands fewer emissions permits, prices are reduced. However, in the later years of the program, emissions permits prices are nearly the same as in the case of permits alone. The large size of the emissions reduction required, and the sub-optimal investments made as a result of the RPS policy cause there to be no significant reduction in permit prices for these years.
Figure 4.1. CO₂ emissions in million tons under policy scenarios. The “baseline” emissions figures differ from those presented in Chapter 2 because of the availability of renewable electricity technology.

Figure 4.2. Permit prices with and without the RPS ($/ton CO₂). The RPS raises permit prices slightly until 2035 while it is binding.
4.3.2 Energy Prices

Figure 4.3 displays prices for fuels COL, OIL, and GAS as well as electricity for the baseline case (allowing for renewable production) and with both the RPS and permit policies. The prices shown are the Armington aggregate prices for fuels, indexed to 2005 levels. With the emissions reduction policies in place, prices of fuels rise compared to the baseline level. This occurs because instate production of these fuels is reduced dramatically. While demand for fuels is also reduced, the production of fuels is carbon intensive, so local production of coal, oil, and gas are drastically reduced. The price of imports does not change, so the decline in local supply is experienced as a slight price increase within Colorado. Electricity prices increase as fuels become more expensive, permits are required, and demand increases. Again, the price increase is limited because import prices are unchanged, but possible because imports and domestic production are not considered perfect substitutes.

4.3.3 Sectoral Output

As Figure 4.4 shows, the RPS policy does not dramatically change the output of commodities, with the exception of coal. Production of COL declines by up to 9% in 2025, as less coal is demanded by the traditional electricity sector. Output patterns under the permit system alone are discussed in detail in Chapter 2. By adding the RPS to the permit policy, few additional changes are observed in sectoral output. With the RPS, coal production drops off faster than with the permits alone. The magnitude of the emissions reduction overwhelms the RPS policy, particularly in later periods. The ELE production in Figures 4.4, 4.5, and 4.6 represents electricity.

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7The baseline values do not exactly match the forecasts because these values are computed allowing for renewable capacity to expand as fuel prices rise. The additional renewable capacity causes a reduction in demand for fuels and reduce their prices.
Figure 4.3. Normalized energy prices under policy scenarios. Adding the emissions constraint and the RPS causes energy prices to rise relative to the baseline case.
Figure 4.4. Changes in sectoral output from baseline under the RPS policy alone. The coal mining sector suffers the largest contraction relative to the baseline when the 20% RPS is achieved in 2020.
Figure 4.5. Changes in sectoral output from baseline under the permit policy alone. Coal output declines, as it is a carbon-intensive sector and the electricity sector reduces its demand for coal. By the end of the period, all electricity produced in Colorado is generated by renewables. The low-carbon services sector increases compared with the baseline. Increased exports of crude oil help to finance the increase in imports of other goods.
Figure 4.6. Changes in sectoral output from baseline under both the RPS and permit policies. Compared to the case with no RPS, the coal mining sector begins its contraction earlier.
produced by both traditional and renewable means. The share of electricity produced by these technologies differs under the policy scenarios.

The shares of renewable electricity produced and used in Colorado differ depending on the amount of imports. Tables 4.1 and 4.2 give the proportion of renewable electricity used and produced within the state of Colorado. In the baseline case (with no policy), renewable production increases over time as fuel inputs become more expensive, according to their projections. However, the proportion of renewable use remains lower than the level required by the RPS. When the RPS policy is added, it is therefore binding. If permits alone are used to reduce emissions, the proportion of renewables used increases dramatically, as traditional production and consumption of electricity are reduced. When the RPS and permits are used together, the RPS is binding until 2030, after which the increasing emissions reduction forces the RPS to be exceeded. Renewable use matches that under the permit system alone, and renewable production is driven to 100% of the total electricity use.

4.3.4 Consumption and Welfare

Percentage changes in macroeconomic indicators (from the baseline) are displayed in Figures 4.7, 4.8, and 4.9. For the RPS alone, investment, and therefore the capital stock increases, compared to the baseline. New capital is needed to facilitate an increase the production of renewable electricity, and because this capital is sector specific, investments in mobile capital also increase to maintain the mobile capital stock. The percentage change in consumption is insignificant. Using the permit and RPS policies together only changes the outcome of the permit system in the early years of the program, when the emissions reductions are small and the RPS is binding. In these years, investment and the capital stock are larger than in the case
Table 4.1. Share of renewable electricity use under policy scenarios (in percent). Renewable use increases in the baseline due to increasing energy prices (according to EIA projections). The RPS is binding in all years when used alone, and in early years when used with the emissions permit system.

<table>
<thead>
<tr>
<th>Year</th>
<th>No policy</th>
<th>RPS</th>
<th>Permits</th>
<th>Permits and RPS</th>
<th>RPS requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>N/A</td>
</tr>
<tr>
<td>2010</td>
<td>9.23</td>
<td>10.00</td>
<td>9.22</td>
<td>10.00</td>
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</tr>
<tr>
<td>2015</td>
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<td>15.00</td>
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<td>20.00</td>
<td>10.49</td>
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<td>20.00</td>
</tr>
<tr>
<td>2025</td>
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<td>20.00</td>
<td>12.26</td>
<td>20.00</td>
<td>20.00</td>
</tr>
<tr>
<td>2030</td>
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<td>20.00</td>
<td>15.57</td>
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</tr>
<tr>
<td>2035</td>
<td>10.33</td>
<td>20.00</td>
<td>21.82</td>
<td>21.81</td>
<td>20.00</td>
</tr>
<tr>
<td>2040</td>
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<td>20.00</td>
</tr>
<tr>
<td>2060</td>
<td>10.41</td>
<td>20.00</td>
<td>64.09</td>
<td>64.10</td>
<td>20.00</td>
</tr>
</tbody>
</table>

Table 4.2. Share of renewable electricity production under policy scenarios (in percent). Renewable production increases in the baseline due to increasing energy prices (according to EIA projections). In the permit cases, traditional electricity generation is eliminated by 2045.

<table>
<thead>
<tr>
<th>Year</th>
<th>No policy</th>
<th>RPS</th>
<th>Permits</th>
<th>Permits and RPS</th>
<th>RPS requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>9.00</td>
<td>N/A</td>
</tr>
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<td>9.25</td>
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<td>9.25</td>
<td>10.11</td>
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</tr>
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<td>21.23</td>
<td>10.72</td>
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</tr>
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<td>13.01</td>
<td>22.36</td>
<td>20.00</td>
</tr>
<tr>
<td>2030</td>
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<td>21.21</td>
<td>18.09</td>
<td>24.03</td>
<td>20.00</td>
</tr>
<tr>
<td>2035</td>
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<td>21.94</td>
<td>30.28</td>
<td>30.22</td>
<td>20.00</td>
</tr>
<tr>
<td>2040</td>
<td>10.43</td>
<td>20.73</td>
<td>76.21</td>
<td>76.21</td>
<td>20.00</td>
</tr>
<tr>
<td>2045</td>
<td>10.45</td>
<td>20.57</td>
<td>100.00</td>
<td>100.00</td>
<td>20.00</td>
</tr>
<tr>
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<td>10.45</td>
<td>20.45</td>
<td>100.00</td>
<td>100.00</td>
<td>20.00</td>
</tr>
<tr>
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<td>20.35</td>
<td>100.00</td>
<td>100.00</td>
<td>20.00</td>
</tr>
<tr>
<td>2060</td>
<td>10.44</td>
<td>20.27</td>
<td>100.00</td>
<td>100.00</td>
<td>20.00</td>
</tr>
</tbody>
</table>
Figure 4.7. Changes in economic indicators from benchmark under the RPS policy alone (in percent). An increase in investment is needed to build the renewable capital stock.
Figure 4.8. Changes in economic indicators from benchmark under the permit policy alone. Investment falls (relative to the baseline) in 2050 to allow for consumption smoothing.
Figure 4.9. Changes in economic indicators from benchmark under both the RPS and permit policies. An increase in investment is needed in early years to build the renewable capital stock. Investment falls (relative to the baseline) in 2050 to allow for consumption smoothing.
with permits alone.

Consumer welfare changes under the policy scenarios are given in Table 4.3. These percentages represent the percent equivalent variation, or percent of present value of consumption that consumers would pay to avoid the policy, over the period 2005-2060. Further reductions in welfare may be experienced beyond 2060, compared to the baseline, due to the decreased capital stock at the end of the model period. Using the RPS policy decreases consumer welfare slightly, as capital is allocated in a less efficient way than in the benchmark case. Using a permit scheme results in a larger decrease in welfare as the magnitude of the policy shock is much larger. Using both policies further decreases consumer welfare, because the RPS is binding in early years, causing sub-optimal capital investment.

This measure of welfare does not account for the benefits of the policy. While the emissions reduction achieved by Colorado is too small to affect atmospheric concentration of GHG's, other localized pollutants may be reduced by switching, for instance, out of coal-fired electricity generation. Colorado residents may also receive some benefit from the sense of accomplishment gained by reducing emissions. These benefits are not captured in the utility function. Furthermore, as shown in Table 4.3, adding the RPS leads to an additional net reduction in emissions due to the reduction in emissions leakage.

4.3.5 Leakage Rates

Table 4.4 presents emissions leakage rates for the electricity sector and the overall economy under the two permit policy scenarios. These are generated under the central model assumptions and parameter values discussed in Chapter 3. RPS policies are touted as a way to reduce emissions without simply exporting these emissions to other
Table 4.3. Changes in consumer welfare (in percent equivalent variation (EV)) over the period 2005 - 2060. The percent EV is the percent of the present value of consumption the consumer would pay to avoid the policy. For comparison, the cumulative emissions, net of emissions leakage, generated by Colorado over the model period is presented. By reducing emissions leakage, the addition of the RPS produces a small reduction in emissions, with or without the emissions constraint.

<table>
<thead>
<tr>
<th>Policy scenario</th>
<th>Change in welfare from benchmark</th>
<th>Cumulative emissions 2005-2060, MMT CO₂ (net of leakage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPS alone</td>
<td>-0.12</td>
<td>1286</td>
</tr>
<tr>
<td>Permits alone</td>
<td>-0.62</td>
<td>672</td>
</tr>
<tr>
<td>RPS and permits</td>
<td>-0.68</td>
<td>672</td>
</tr>
<tr>
<td>Additional emissions reduction from RPS alone</td>
<td>0.6 MMT CO₂</td>
<td></td>
</tr>
<tr>
<td>Additional emissions reduction from RPS with permits</td>
<td>0.8 MMT CO₂</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4. Leakage rates (in percent) under different policy scenarios. Adding the RPS reduces the emissions leakage in the years when it is binding.

<table>
<thead>
<tr>
<th>Year</th>
<th>Electricity</th>
<th>Economy-wide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permits alone</td>
<td>Permits and RPS</td>
</tr>
<tr>
<td>2020</td>
<td>15.2</td>
<td>9.0</td>
</tr>
<tr>
<td>2025</td>
<td>18.4</td>
<td>15.4</td>
</tr>
<tr>
<td>2030</td>
<td>21.0</td>
<td>19.9</td>
</tr>
<tr>
<td>2035</td>
<td>21.6</td>
<td>21.5</td>
</tr>
<tr>
<td>2040</td>
<td>20.5</td>
<td>20.5</td>
</tr>
<tr>
<td>2045</td>
<td>15.2</td>
<td>15.2</td>
</tr>
<tr>
<td>2050</td>
<td>9.3</td>
<td>9.3</td>
</tr>
<tr>
<td>2055</td>
<td>7.4</td>
<td>7.4</td>
</tr>
<tr>
<td>2060</td>
<td>5.7</td>
<td>5.7</td>
</tr>
</tbody>
</table>
jurisdictions. This benefit should be seen as a decrease in leakage rates when this policy is used as part of a scheme to reduce emissions. In this case, emissions leakage is reduced in those years when the RPS is binding. The RPS requires investment in renewable electricity generation occur earlier in the period. This additional renewable electricity replaces some of the imports that would be required with the permit system alone.

We assume that the renewable capacity required to meet the RPS will be built within Colorado. This assumption is reasonable because imports of renewable power are limited, and new capacity must be built in order to meet the state’s demand.\textsuperscript{8} Also, the legislation provides incentives for this new capacity to be built within Colorado, specifically allowing each KWh produced in Colorado to be counted as more than one KWh. These incentives ensure that Colorado meets its requirements for renewables within the state.

As a result of the decrease in leakage for the electricity sector, leakage rates decrease for the overall economy when the RPS is added. Other sectors still experience positive leakage rates as electricity and fuels become more expensive within Colorado (as shown in Figure 4.3). While the RPS cannot be met solely by reducing electricity production, it can be met by reducing use accordingly. The incentive remains for emissions-intensive industries to relocate.

4.4 Conclusions

Colorado’s RPS policy is designed to reduce CO$_2$ emissions while encouraging growth in the renewable sector, all without increasing the leakage of emissions to

\textsuperscript{8}As discussed in section 4.1.3, many states have similar legislation, limiting the availability of renewable imports
other states. This policy is part of a larger goal to reduce emissions by 80% of 2005 levels by 2050. The effectiveness of the RPS at limiting the economic impacts of the overall reduction goal depend on the size of the reduction goal being undertaken. In early years when the reduction goals are small, the RPS is binding, and emissions permit prices are reduced. However, as the emissions reductions goals become larger, the RPS is no longer binding. Traditional generation, mostly using carbon-intensive coal, is drastically reduced, and all of this power is imported. Leakage rates are no longer lower than without the RPS policy.

The renewable portfolio standard alone cannot meet Colorado's emissions reduction goal, nor is it able to completely solve the problems associated with a state level tradable permit policy. Because the overall goal is extremely restrictive, leakage rates are only reduced in the first years of the program. Permit prices are reduced when the policies are of comparable size, but once the RPS is no longer binding it has no effect.

A few noteworthy assumptions govern the accuracy of these estimates. The energy price and output forecasts, and the emissions forecasts, generated by the EIA include some amount of substitution into renewable production that is not included in the model. This may lead the results presented here to overestimate the impacts of emissions reduction policy. On the other hand, the small open economy assumption allows Colorado residents to import unlimited electricity from other states. In reality, there are limits to transmission capacity and availability of supply. These limits will cause an overestimate of leakage rates, and an underestimate of electricity prices and coal production. Advances in technology not captured by this model can also help to meet the state's emissions goal. Finally, with national policy seemingly on the horizon, emissions leakage concerns become less significant for small jurisdictions,
except where these areas choose more stringent targets.

The RPS scenario enlightens the problematic aspects of the state’s emissions reduction goal: the ability to import traditional electricity, the added expense of implementing more energy efficient technology, and the incentives for productive activity to relocate to unregulated regions. RPS policies aim to alleviate these problems by limiting electricity imports, encouraging otherwise uneconomical technology, and replacing emissions intensive production with the burgeoning clean energy industry. However, for a large emissions reduction goal, renewable technology becomes economical on its own. Adding the RPS restriction makes the program more effective in early years, but makes the system more costly for consumers over the policy horizon.
Chapter 5

CONCLUSIONS

5.1 Summary

Throughout this document, we have discussed the economic impacts resulting from carbon emissions reduction policy within the state of Colorado. Global climate change is expected to have several negative impacts for the state, as discussed in Chapter 1. These impacts include changes in precipitation patterns and therefore water supply; changes in temperature that may affect tourism, agriculture, and human health; and other ecosystem damage, such as a loss of biodiversity.

Two proposed CO$_2$ emissions reductions policies for the state of Colorado have been evaluated: a tradable permit scheme and a renewable portfolio standard. These policies have been suggested to meet the state’s goal of an 80% reduction from 2005 levels of CO$_2$ emissions by 2050. The RPS would require 20% of electricity be generated by renewable means by 2020. The impacts on the state economy of these two policies when used together and separately have been presented. These impacts include reductions in consumption and consumer welfare, changes in output of commodities, changes in the way electricity is generated, and the movement of polluting activities across state lines.

Summary of impacts of the Ritter Plan with 20% RPS:

- Emissions permit prices range from $4 to $167 over the model period
• Consumer Welfare declines by 0.68% over the period 2005 - 2060, relative to the baseline.

• Consumption declines by 4% by 2060, relative to the baseline.

• The capital stock declines by 11% by 2060, relative to the baseline.

• Other sectors, such as agriculture and fuels, see dramatic declines in output.

• A leakage rate of 7.5% in 2040 implies 4.2 million tons of emissions per year are produced outside of Colorado on behalf of Colorado residents.

• Leakage rates depend on the flexibility to switch into cleaner fuels and import electricity, and are reduced by the RPS policy.

• Adding the RPS may exacerbate economic impacts and increase permit prices because of sub-optimal investments made in early years.

5.2 Implications

These results have shown that a large, unilateral emissions reduction policy on the part of the state of Colorado would be painful for its economy. Such a measure is not likely to be enacted if the large reductions in output of energy and agricultural goods are anticipated. The achieved emissions reduction would be undermined by leakage to other jurisdictions, and voters should weigh the actual possible reduction in emissions against the reduction in consumption, relative to the baseline case.

Chapter 3 showed that the amount of emissions leakage depends on the flexibility to import goods and to switch between electricity and fuels. Leakage rates are lowest when consumers have less flexibility to switch into imports, and firms have more flexibility to switch into electricity. Policies like the RPS that limit imports of
dirtier versions of a good should reduce emissions leakage, while making the economic impacts of the policy more severe. In this case, the RPS reduces leakage only in those years when it is binding. The RPS policy does help to decrease permit prices in early years when the overall reduction is of manageable size. This policy could help to achieve a smaller emissions target with less emissions leakage.

Opportunities to improve the effectiveness of the policy do exist. Some sectors are not greatly affected by the policies. In the scenarios, the services sector experiences negative leakage rates as the sector expands and the demand for imports is reduced. This sector is able to grow, compared to the benchmark level, because of its low carbon intensity. Aiding the transition to such industries, through subsidies or training programs, may help to minimize economic impacts. By keeping production activities in these sectors within the state, and attracting other low-carbon industries, emissions leakage can be reduced.

5.3 Benefits

When comparing the policy scenario results to the “business-as-usual” case, it is important to remember that there are costs of inaction not captured in the baseline. These costs are difficult to quantify because of the large amount of uncertainty in climate predictions, however, several changes are predicted to occur with high probability, or are already being observed. Costs associated with higher temperatures may include health care expenditures and lost labor productivity due to mortality and morbidity caused by heat stress, ozone pollution and airborne particulates produced by forest fires. Reduced agricultural yields may result from extreme heat events or drought. Tourism may decline as snowfall becomes less reliable and wildlife habitat is lost (National Science and Technology Council (2008)).
Including these types of impacts into a CGE setting is difficult because of uncertainty in the magnitude of the effects as well as a lack of data (Kuik et al. (2008)). Variables like water quality, snowfall, or agricultural yield are determined by complex natural systems. Values for the non-market services that ecosystems provide are difficult to determine. Relationships, like that between temperature and tourist flows, have been sparsely studied.

Leaving aside the costs of inaction, legislation aimed at avoiding GHG emissions also reduces the emissions of other pollutants. This is especially true for the electricity generation sector. By encouraging the shift from coal to other energy inputs, emissions of mercury and particulates are reduced. Reducing these pollutants may reduce incidence of respiratory symptoms. Again, these impacts are not straightforward to incorporate into the modeling framework used in this study, but should not go unmentioned.

5.4 Model Assumptions

Some model assumptions will lead to over or understatement of the program impacts. The most basic of these, that Colorado acts alone, demonstrates the major impacts of a small jurisdiction taking on such a large emissions reduction goal. In all likelihood, federal legislation will be passed before Colorado resorts to these measures. The state would also be eligible to join the WCI trading program set to begin next year. A larger trading area allows for more flexibility in reducing emissions, which may lead to smaller impacts and lower permit prices. Those states currently acting to reduce emissions foresee benefits to acting early to limit their emissions. These states may be more prepared if and when a national policy is enacted. Colorado hopes that its RPS policy will draw technology firms to the state that will prosper under larger
scale GHG regulation.

Secondly, we assume that Colorado is a small open economy that can import goods at fixed external prices. In the policy scenarios, Colorado residents import increasing amounts of electricity. In reality, this electricity may not be available due to capacity or transmission limits, and what is available would most likely increase in price as demand increases. If electricity imports were limited or more expensive, sectoral changes may not be as dramatic, though consumers may suffer. The availability of other goods at fixed prices will lead to underestimates of economic impacts and overestimates of emissions leakage. Modeling interstate trade, either by modeling other regions of the US or estimating import supply elasticities is beyond the scope of this research.

Third, migration is not considered in the model. If Colorado residents could move to other states, the economic impacts would be different. Leakage estimates would need to account for pollution generated by residents who relocate. Labor supply changes would affect productive sectors, and per capita income and consumption would have to be compared.

The data sources used to project energy prices, production, and emissions in the baseline case include some trends in renewable generation, fuel efficiency, and energy policy. If, for example, the EIA emissions projection includes growth in renewable electricity use nationwide, using it to forecast the results of an RPS policy will tend to overestimate the impact of the policy.

Throughout this document, we have shown the costs to the state economy the proposed emissions reduction scheme. While these costs are significant, there are benefits associated with reducing emissions not captured here. While Colorado’s total emissions reduction may be small compared to the global total, other local pollu-
tants are reduced when the burning of fossil fuels is reduced. For instance, mercury, arsenic and other toxins are released into the atmosphere when coal is burned, and currently coal is the largest input to electricity generation in the state. Cleaner air generally leads to a healthier, more productive population. Cost estimates may be improved by incorporating the impacts of demographic changes on health care costs and government expenditures.
REFERENCES


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Western Climate Initiative (2008a) ‘Draft design recommendations on elements of the cap-and-trade program’

. (2008b) ‘General Q and A’

The model of the Colorado state economy presented in this dissertation was written in GAMS 21.3 utilizing the MPSGE package. This appendix provides documentation of the model formulation, and the following appendix include the actual computer code. The GAMS/MPSGE environment provides an efficient means of formulating an Arrow-Debreu general equilibrium directly from the social accounting matrix. Computationally the model is formulated as a non-linear Mixed Complementarity Problem (MCP).

A.1 Overview of the MCP Formulation

In a standard representation of an Arrow-Debreu MCP there are three types of non-negative variables associated with three types of inequality conditions. First, there are linearly-homogeneous transformation activity levels associated with optimality conditions. Denote the activity level \( y_j \), where \( j \in J \) and the set \( J \) includes all transformations. The zero-profit equilibrium conditions (\( \forall j \)) can be represented as follows:

\[
-\pi(p) \geq 0 \perp y_j \geq 0, \quad (A.1)
\]

where \( \pi(p) \) is a proper unit-profit function from duality theory (which represents technologies). Firm optimality is embedded in the profit function. The \( \perp \) symbol indicates a complementary-slack relationship between the equilibrium condition and
the associated variable. If the price vector indicates negative optimal profits then the activity level is zero. If the activity is being used \((y_j > 0)\) then the activity level adjusts such that economic profits are zero.

The second set variables in the model are prices \(p_i\) \((i \in I)\) which are associated with \(I\) market clearance conditions. Denote a household’s endowments of commodities \(\omega_{hi}\) and household Marshallian demands \(d_{hi}(p, m_h)\), where \(m_h\) is nominal income and \(h \in H\) is the index on the household type. Market clearance (\(\forall i\)) is thus given by

\[
\sum_j y_j \frac{\partial \Pi_j(p)}{\partial p_i} + \sum_h [\omega_{hi} - d_{hi}(p, m_h)] \geq 0 \perp p_i \geq 0
\]  
(A.2)

The first term is simply an application of Hotelling’s lemma, which indicates the net-put of commodity \(i\) from each activity. The \(\perp\) symbol, again, indicates a complementary-slack relationship: supply equals demand for commodities with positive prices, and if supply exceeds demand the price must be zero.

The final set of variables are household income levels, \(m_h\). These variables are associated with income balance. As any non-trivial household will have a positive income level the condition is usually simply represented as an equality between the value of endowments and the value of final demand (\(\forall h\)):

\[
\sum_i p_i d_{hi}(p, m_h) = \sum_i p_i \omega_{hi} \perp m_h > 0.
\]  
(A.3)

The Arrow-Debreu equilibrium is complete and can be solved computationally for relative prices, activity levels, and nominal incomes.\(^1\)

One of the key advantages of GAMS/MPSGE as a programing environment is

\(^1\)The general equilibrium is homogeneous degree zero in prices. To compute a unique solution one commodity is selected as numeraire. The value of this price is fixed, and the associated market-clearance condition is satisfied by Walras Law.
that it largely automatically formulates the $J+I+H$ dimensional general equilibrium represented by conditions (A.1), (A.2), and (A.3). The user must provide the social accounts and arrange them such that the unit profit functions and preferences are properly calibrated, but the functions are checked for consistency and market clearance conditions are generated automatically. In GAMS/MPSGE there is little room for programing errors, and the neo-classical general equilibrium must be closed (all value is allocated to a household).

As the goal of policy studies is often a welfare analysis for households. It is convenient, therefore, to explicitly include an activity which represents the utility of a given household. Let $u_h = y_h$ denote the utility level and $p_h$ the true-cost-of-living price index for household $h$, then the equilibrium condition for maximized utility is given by

$$e_h(p) - p_h > 0 \land u_h \geq 0,$$  

(A.4)

where $e_h(p)$ is the unit expenditure function (representing preferences). So, for the activity which represents the level of utility we have $-\pi(p) = e_h(p) - p_h$. In this case the only commodity consumed by the household is composite *utils* which have a unit cost of $p_h$. The market clearance and income balance condition are thus modified to the following:

$$u_h - d_{hh}(m_h) = 0;$$  

(A.5)

$$p_h d_{hh}(m_h) = \sum_i p_i \omega_{hi}.$$  

(A.6)

Given that preferences are linearly homogeneous, we can simply calculate percentage changes in Hicksian *equivalent variation* by measuring the percent changes in the activity level $u_h$.

In application to the analysis of climate-change policy for Colorado the standard
Arrow-Debreu representation includes specific features that deserve special attention and discussion. For example, the model is dynamic so the activity and commodity dimensions are expanded to include a time index. That is, \( J = \tilde{J} \cup T \) and \( I = \tilde{I} \cup T \), where \( T \) is the set of time periods and \( \tilde{J} \) and \( \tilde{I} \) are the sets of sectors and commodities. Households are intertemporal maximizers and the activities will include the capital stock and optimal investment behavior. In addition, for a given sector there may be multiple calibrated activities representing fossil-fuel versus renewables production. The following provides an explanation of the specific extensions and structural formulations used in the Colorado model.

A.2 Production Structure

The production of goods is modeled using nested, constant elasticity of substitution (CES) functions, with a focus on energy substitution. At the highest level, intermediate goods enter in fixed proportions with other inputs. In the next level of nesting, energy inputs can be substituted with a composite of capital and labor with the elasticity \( \sigma_{va} \). Capital and labor are substituted according to \( \sigma_{al} \). Within the energy nest, electricity is substituted with fuels according to \( \sigma_{el} \), oil is substituted with coal and gas according to \( \sigma_{fa} \), and coal and gas can be substituted with elasticity \( \sigma_{cg} \). All elasticities can be found in Table A.1. Figure 2.2 gives a graphical representation.

A.3 Consumer Welfare

The representative consumer selects the basket of goods to purchase according to the utility function. This nested CES function allows consumers to substitute between energy and non-energy consumption with the elasticity of substitution \( \sigma_{zs} \).
Within the energy nest, consumers can substitute electricity for fuels with elasticity $\sigma_{ze}e$, and the fuels coal, oil, and gas can be substituted according to $\sigma_{zen}$. These elasticities are also found in Table A.1, and a graphical representation is found in Figure 2.3.

### A.4 Armington Aggregation

Imported and domestic varieties of a good can be considered imperfect substitutes according to Armington (1969). An Armington sector aggregates the imports of a good with the domestically-produced version, according to a selected elasticity of substitution. These resulting Armington aggregate goods are purchased by consumers and enter into production functions. The Armington elasticity, represented by $\sigma_a$ is given in table A.1. The value can be changed by sector, in the central case, the elasticity for energy and non-energy commodities is the same. In the sensitivity experiment presented in section 3.4.1, leakage rates are presented for a variety of Armington elasticities for energy goods.

### A.5 Emissions Permits

Emissions permits are required to be purchased with fuels. They enter into the production functions for all goods and consumer welfare. These functions are described in section A.2. Emissions from each fuel for each sector are read into the model. In the benchmark, the production functions are calibrated to use this amount as an input, with permits purchased in fixed proportions. In the scenario, the total number of permits is reduced by the percentage desired for emissions reduction. Because the permits are used in fixed proportions, this will result in the correct emissions reduction. In the benchmark, the consumer is endowed with the same
number of permits as are needed for production. Because permits are not scarce, they have a zero price. When the number of permits is reduced, they will have a positive price.

A.6 Renewable Technology

Electricity can be generated through traditional or renewable means. Traditional electricity is generated by the $y$ and $xy$ sectors, while renewable electricity is produced by the $y_r$ sector. This sector uses sector specific renewable capital, $r k_r$, which is used in fixed proportions with the other inputs. This renewable capital replaces the fuel inputs used in the other forms of ELE production. A specified percentage, $\mu_{st}$, of goods, in this case ELE, is produced by this sector. The endowment of $r k_r$ is adjusted to

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_a$</td>
<td>$= 10$</td>
<td>Armington elasticity</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$= 0.5$</td>
<td>Elasticity of supply of exports</td>
</tr>
<tr>
<td>$\sigma_s$</td>
<td>$= 0$</td>
<td>Elasticity of substitution between materials and other inputs</td>
</tr>
<tr>
<td>$\sigma_vac$</td>
<td>$= 0.5$</td>
<td>Elasticity of substitution between capital-labor composite and energy inputs</td>
</tr>
<tr>
<td>$\sigma_{va}$</td>
<td>$= 1$</td>
<td>Elasticity of substitution between capital and labor</td>
</tr>
<tr>
<td>$\sigma_{el}$</td>
<td>$= 0.2$</td>
<td>Elasticity of substitution between electricity and fuels</td>
</tr>
<tr>
<td>$\sigma_{ful}$</td>
<td>$= 0.1$</td>
<td>Elasticity of substitution between oil and the coal-gas composite</td>
</tr>
<tr>
<td>$\sigma_{cg}$</td>
<td>$= 2$</td>
<td>Elasticity of substitution between coal and gas</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$= 1$</td>
<td>Intertemporal elasticity of substitution</td>
</tr>
<tr>
<td>$\sigma_{zs}$</td>
<td>$= 0.5$</td>
<td>Household elasticity of substitution between energy and non-energy goods</td>
</tr>
<tr>
<td>$\sigma_{zne}$</td>
<td>$= 1$</td>
<td>Household elasticity of substitution between electricity and fuels</td>
</tr>
<tr>
<td>$\sigma_{zen}$</td>
<td>$= 0.5$</td>
<td>Household elasticity of substitution between fuels</td>
</tr>
</tbody>
</table>
produce the correct level of renewable production.

The input \( r_k \) is taken from the endowment of non-specific, putty capital. However, renewable production exists from the beginning of the model period, and the level of renewable production should represent the correct percentage of the total ELE production, not just that from the \( y \) sector. An adjustment is made so that the \( y \) sector produces an amount of renewable ELE equal to \( \mu_{st} \) percent of the ELE produced by \( y \) and \( xy \). The new parameter \( \mu_{st}^{\text{ref}} \), defined

\[
\mu_{st}^{\text{ref}} = \frac{\mu_{st}}{1 - x_k},
\]

represents the correct reference trajectory for renewables. In the benchmark case, \( \mu \) is held constant at 9%, the current level of renewable production. In the RPS scenarios, \( \mu_{st} \) and \( \mu_{st}^{\text{ref}} \) are updated and the model resolved.

### A.7 Baseline Calibration

The model is calibrated to projections of energy production and prices from the EIA by the use of a calibrated productivity shift. For each of the energy goods, a "phantom subsidy" is calculated that would result in the correct level of output. The value of the subsidy is taken away from the consumer's income. As this subsidy is distortionary, a productivity coefficient, \( \phi_{st} \), is then computed to match the effect of the subsidy, and the subsidy is removed.

### A.8 Dynamics

A dynamic computable general equilibrium model must link the equilibrium in one period with the outcome in the next (Lau et al. (2002)). In a Ramsey model, this
is accomplished by the investment of consumer savings to produce capital in future periods. The new capital is needed to replace capital lost to depreciation and to allow for economic growth. In the social accounting matrix used to calibrate the model, we can observe the capital demand from each sector and the capital supply provided by households, which must be balanced, as well as investment (savings) made by households. The rate of growth of the economy, $g$, and the rate of depreciation, $\delta$, are assumed. The initial capital stock, $K_0$, can be calculated using the following relationship:

$$I_0 = K_0(1 + g) - K_0(1 - \delta).$$  \hspace{1cm} (A.8)

This relationship states that investment in the benchmark, $I_0$, must cover the capital lost to depreciation as well as the new capital needed to allow the economy to grow at the assumed rate. Solving for the capital stock,

$$K_0 = I_0/(g + \delta)$$  \hspace{1cm} (A.9)

The capital supply given in the SAM along with the assumed rates of growth and depreciation will determine the interest rate in the economy. These interest rates tend to be high relative to observed rates, and there are several ways to deal with this discrepancy. One option is to compute the level of investment consistent with the desired interest rate, and adjust the benchmark levels of investment and consumption accordingly. Another option is to implement a tax on capital, and calibrate the tax rate to give the correct capital demand.

Taking the latter approach and assuming an interest rate $r$,

$$rk_0 = r + \delta;$$ \hspace{1cm} (A.10)
that is, the gross rate of return to capital must equal the interest rate plus the rate of depreciation. The flow of rental payments to capital is given by

\[ K S'_0 = K_0 r k_0 \]  \hspace{1cm} (A.11)

This is reconciled across sectors by computing the required tax on capital payments.

\[ tk = \frac{K S_0}{(K_0 r k_0)} - 1 \]  \hspace{1cm} (A.12)

The revenue from this tax, representing the difference in the value of the observed capital supply and the value calibrated to the desired interest rate, is allocated to households. Now that the initial value of the capital stock is matched to the equilibrium interest rate, the level of capital evolves with the level of investment in previous periods. The capital sector in the model takes the current period’s investment and transforms it into next period’s capital and returns to capital. This continues until the last period, when, instead of producing capital, an output called “post-terminal capital” is produced\(^2\). The post-terminal capital represents the amount of capital that must be left over at the end of the model period. The level of post-terminal capital demand is determined by the following constraint.

\[ \frac{I_T}{Z_{T-1}} - \frac{I_{T-1}}{Z_T} = 0 \]  \hspace{1cm} (A.13)

In this constraint, \( T \) represents the end period of the model, \( I_T \) is the investment at time \( T \), and \( Z_T \) is an aggregate of consumption at time \( T \). The equality ensures that the percent changes in investment and consumption must be equal in the last

\(^2\)This termination strategy is taken from Lau et al. (2002)
time period, and the level of post-terminal capital demand will adjust to make sure this holds. With a post-terminal capital demand, agents do not reduce investment as the problem terminates, which gives us an infinite-horizon approximation.

To limit the mobility of capital between sectors, and more realistically slow the adoption of cleaner technologies, a putty-clay capital structure is used. To begin the model period, 80% of capital is fixed in its current usage, and the other 20% is mobile between the sectors. New capital produced in later years remains flexible, reflecting that investments made within the context of the emissions reduction policy will need to be used in the least carbon-intensive way.

To implement this structure, an additional production technology is used. This technology uses the extant, fixed capital in fixed proportions with other inputs. It produces a fraction of output equal to the fraction of clay capital for all of the commodities in the model, with the exception of renewable electricity. All capital used in the generation of renewable power sector is flexible, by assumption.
APPENDIX B

MODEL CODE

$title MPSGE Model for Colorado Carbon Policy based on IMPLAN data

*Lauren M. Davis (ldavis@mymail.mines.edu) and
*Edward J. Balistreri (ebalistr@mines.edu)
*June 2009.

*9 sectors:

* 

COL AGR

* 

CRU MAN

* 

OIL SRV

* 

GAS OTH

* 

ELE

$if not setglobal lastyear $setglobal lastyear 2010
$if not set ds $set ds ceri3

SET r(*) Regions (counties),

s(*) Sectors and goods;

$gdxin data\%ds%

$load r s

set ff(s) Fuel Types /COL,OIL,GAS/;

set en(s) Energy Types /COL,OIL,GAS,ELE/;

set el(s) Electricity /ELE/;

set sh(s) Share sectors /AGR,MAN,SRV/;

alias (s,g);

SET yr Years /2000*2100/,

t(\year) Model solution years /2005,2010,2015,2020,

2025,2030,2035,2040,

2045,2050,2055,2060/,

t0(t) Initial period of the model

tt(t) Terminal period of the model;

\t0(t) = yes$(ord(t) eq 1);

\tt(t) = yes$(ord(t) eq card(t));
SET trd  Trade partners in the IMPLAN data/
FTRD "Foreign Trade (25001)"
DTRD "Domestic Trade (28001)"

hh  Private (household) institutions /
HHL "Households LT5k  (10001)"
HH5 "Households 5-10k  (10002)"
HH10 "Households 10-15k  (10003)"
HH15 "Households 15-20k  (10004)"
HH20 "Households 20-30k  (10005)"
HH30 "Households 30-40k  (10006)"
HH40 "Households 40-50k  (10007)"
HH50 "Households 50-70k  (10008)"
HH70 "Households 70k+  (10009)"

pub  Public (government) institutions /
FND "Federal Government NonDefense (11001)"
FD  "Federal Government Defense (11002)"
FIN "Federal Government Investment (11003)"
SLN "State Local Govt NonEducation (12001)"
SLE "State Local Govt Education (12002)"
SIN "State Local Govt Investment (12003)"

alias (h,hh);

SCALARS gamma Benchmark growth rate /0.015/,
delta Annual capital depreciation rate /0.07/,
rho Benchmark net interest rate /0.05/,
sigma Intertemporal elasticity of sub /1/;

parameter
x0(r,s,trd) Exports by market
m0(r,g,trd) Imports from domestic and foreign sources
id0(r,g,s) Intermediate demand
kd0(r,s) Capital return
ld0(r,s) Labor demand
bt0(r,s) Busines taxes
fica(r) Labor tax rate (social security)
i0(r,g) Investment demand by commodity
g0(r,g,pub) Public demand by commodity
le0(r,hh) Labor endowment
ke0(r,hh) Capital endowment
cd0(r,g,hh) Consumer demand
invd0(r,hh) Investment;

$load x0 m0 id0 kd0 ld0 bt0 fica i0 g0 le0 ke0 cd0 invd0

* IMPLAN data in millions of dollars
* scale up 2002 IMPLAN data to 2005 and rescale to billions of dollars

\[ x_{0}(r,s,\text{trd}) = (x_{0}(r,s,\text{trd}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ m_{0}(r,g,\text{trd}) = (m_{0}(r,g,\text{trd}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ i_{d0}(r,g,s) = (i_{d0}(r,g,s) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ k_{d0}(r,s) = (k_{d0}(r,s) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ b_{t0}(r,s) = (b_{t0}(r,s) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ f_{ica}(r) = (f_{ica}(r) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ i_{0}(r,g) = (i_{0}(r,g) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ g_{0}(r,g,\text{pub}) = (g_{0}(r,g,\text{pub}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ l_{e0}(r,\text{hh}) = (l_{e0}(r,\text{hh}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ k_{e0}(r,\text{hh}) = (k_{e0}(r,\text{hh}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ c_{d0}(r,g,\text{hh}) = (c_{d0}(r,g,\text{hh}) \times 10^{-3}) \times (1+\gamma)^{3} \]

\[ i_{vd0}(r,\text{hh}) = (i_{vd0}(r,\text{hh}) \times 10^{-3}) \times (1+\gamma)^{3} \]

*---------read in energy data from spreadsheets---------*

* purchases of fuel by sector in base year

\[ \text{CALL GDXXRW.exe EIAPredictions.xls par=sectoruse rng=B69:K72} \]

\[ \text{LOAD sectoruse} \]

\[ \text{LOAD sectoruse} \]

* national projections by sector in million metric tons

\[ \text{CALL GDXXRW.exe EIAPredictions.xls par=projff rng=A62:BE65} \]

\[ \text{LOAD projff} \]

* distribute emissions to sectors

\[ \text{LOAD projff} \]

* household national projections in million tons

\[ \text{CALL GDXXRW.exe EIAPredictions.xls par=hproj rng=A82:BE85} \]

* energy price projections

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]

\[ \text{LOAD hproj} \]
* energy price projections

SCALL GDXXRW.exe energy.xls par=yeproj rng=A13:BE17
parameter yeproj(en, yr);
$GDXIN energy.gdx
$LOAD yeproj
$GDXIN

* energy price projections
SCALL GDXXRW.exe energy.xls par=ysproj rng=A21:M24
parameter ysproj(sh, yr);
$GDXIN energy.gdx
$LOAD ysproj
$GDXIN

* scale by Colorado's share of 2004 emissions from eia
parameter
total Total US emissions in 04 (in million tons co2)
coemit Colorado emissions in 04
coshare Colorado share of emissions;

coemit = 93.1;
total = 5953.7;
coshare = coemit/total;
display coshare;

* rescale to billion tons and get Colorado's share of national total
eproj(s, ff, t) = eproj(s, ff, t)*coshare*1e-3;
hproj(ff, t) = hproj(ff, t)*coshare*1e-3;

parameter
carblim(t) Colorado carbon cap;

carblim(t) = sum((ff, s), eproj(s, ff, t)) + sum(ff, hproj(ff, t));
display carblim;

parameter
sx0(s, trd) Exports by market
sm0(g, trd) Imports from domestic and foreign sources
sid0(g, s) Intermediate demand
skd0(s) Capital return
sld0(s) Labor demand
sbt0(s) Business taxes
sfica Labor tax rate (social security)
si0(g) Investment demand by commodity
sg0(g, pub) Public demand by commodity
sle0(hh) Labor endowment
ske0(hh) Capital endowment
scd0(g, hh) Consumer demand
sinvd0(hh) Investment
\begin{align*}
\text{(1)} & \quad \text{n0}(g) \quad \text{ntra-national trade}; \\
\text{(2)} & \quad \text{sx0}(s, \text{trd}) = \sum(r, x0(r, s, \text{trd})); \\
\text{(3)} & \quad \text{skd0}(s) = \sum(r, kd0(r, s)); \\
\text{(4)} & \quad \text{skd0}(s) = \sum(r, 1d0(r, s)); \\
\text{(5)} & \quad \text{sid0}(g, s) = \sum(r, id0(r, g, s)); \\
\text{(6)} & \quad \text{skd0}(s) = \sum(r, kd0(r, s)); \\
\text{(7)} & \quad \text{skd0}(s) = \sum(r, 1d0(r, s)); \\
\text{(8)} & \quad \text{sbto}(s) = \sum(r, bt0(r, s)); \\
\text{(9)} & \quad \text{mfica} = \sum(r, fica(r)); \\
\text{(10)} & \quad \text{si0}(g) = \sum(r, 10(r, g)); \\
\text{(11)} & \quad \text{sg0}(g, \text{pub}) = \sum(r, g0(r, g, \text{pub})); \\
\text{(12)} & \quad \text{sle0}(hh) = \sum(r, le0(r, hh)); \\
\text{(13)} & \quad \text{ske0}(hh) = \sum(r, ke0(r, hh)); \\
\text{(14)} & \quad \text{scd0}(g, hh) = \sum(r, cd0(r, g, hh)); \\
\text{(15)} & \quad \text{sinv0}(hh) = \sum(r, invd0(r, hh)); \\
\text{(16)} & \quad \text{d0}(s) = \text{round}(\text{sbto}(s) + \text{skd0}(s) + \text{sld0}(s) + \sum(g, \text{sid0}(g, s)) - \\
\text{(17)} & \quad \sum(\text{trd}, \text{sx0}(s, \text{trd})), 6); \\
\text{(18)} & \quad \text{y0}(s) = \text{d0}(s) + \sum(\text{trd}, \text{sx0}(s, \text{trd})); \\
\text{(19)} & \quad \text{a0}(s) = \sum(\text{trd}, \text{sm0}(s, \text{trd})) + \text{d0}(s); \\
\text{(20)} & \quad \text{gov0}(\text{pub}) = \sum(g, \text{sg0}(g, \text{pub})); \\
\text{(21)} & \quad \text{inv0} = \sum(g, \text{si0}(g)); \\
\text{(22)} & \quad \text{incadj}(hh) = \sum(g, \text{scd0}(g, hh)) + \text{sinv0}(hh) - \text{ske0}(hh) - \text{sle0}(hh); \\
\text{(23)} & \quad \text{m0}(g) = \text{sx0}(g, "dtrd"); \\
\end{align*}

---

**Parameter**

\begin{align*}
\text{(24)} & \quad \text{d0}(s) \quad \text{Domestic consumption of domestically produced } s \\
\text{(25)} & \quad \text{y0}(s) \quad \text{Domestic production of } s \\
\text{(26)} & \quad \text{a0}(s) \quad \text{Domestic consumption of } s \\
\text{(27)} & \quad \text{gov0}(\text{pub}) \quad \text{Government} \\
\text{(28)} & \quad \text{inv0} \quad \text{Investment} \\
\text{(29)} & \quad \text{incadj}(hh) \quad \text{Household saving\textbackslash borrowing}; \\
\text{(30)} & \quad \text{d0}(s) = \text{round} (\text{sbto}(s) + \text{skd0}(s) + \text{sld0}(s) + \sum(g, \text{sid0}(g, s)) - \\
\text{(31)} & \quad \sum(\text{trd}, \text{sx0}(s, \text{trd})), 6); \\
\text{(32)} & \quad \text{y0}(s) = \text{d0}(s) + \sum(\text{trd}, \text{sx0}(s, \text{trd})); \\
\text{(33)} & \quad \text{a0}(s) = \sum(\text{trd}, \text{sm0}(s, \text{trd})) + \text{d0}(s); \\
\text{(34)} & \quad \text{gov0}(\text{pub}) = \sum(g, \text{sg0}(g, \text{pub})); \\
\text{(35)} & \quad \text{inv0} = \sum(g, \text{si0}(g)); \\
\text{(36)} & \quad \text{incadj}(hh) = \sum(g, \text{scd0}(g, hh)) + \text{sinv0}(hh) - \text{ske0}(hh) - \text{sle0}(hh); \\
\text{(37)} & \quad \text{m0}(g) = \text{sx0}(g, "dtrd"); \\
\end{align*}

---

**Parameter**

\begin{align*}
\text{(38)} & \quad \text{qref}(t) \quad \text{Reference quantity path (steady state)} \\
\text{(39)} & \quad \text{qproj}(s, t) \quad \text{Sector specific quantity projection} \\
\text{(40)} & \quad \text{qref_em}(s, t) \quad \text{BAU qref to correct carbon coefficients} \\
\text{(41)} & \quad \text{ssproj}(s) \quad \text{Logical switch for sector specific projections} \\
\text{(42)} & \quad \text{ppproj}(s, t) \quad \text{Commodity-specific price projection} \\
\text{(43)} & \quad \text{psproj}(s) \quad \text{Logical switch to turn on price projections} \\
\text{(44)} & \quad \text{phi}(s, t) \quad \text{Sector specific TFP shock} \\
\text{(45)} & \quad \text{p PHI}(g, t) \quad \text{Commodity specific TFP shock on Armington for prices} \\
\text{(46)} & \quad \text{pref}(t) \quad \text{Reference path of present value prices} \\
\text{(47)} & \quad \text{year}(yr) \quad \text{Year represented as an integer} \\
\text{(48)} & \quad \text{k0} \quad \text{Base year capital stock} \\
\text{(49)} & \quad \text{tk} \quad \text{Calibrated capital earnings tax} \\
\text{(50)} & \quad \text{tkrev} \quad \text{Revenue from tk}
\end{align*}
pkd0(s) Reference price on capital demand
theta Weight on post terminal consumption
inlag Investment lag in years /2/
clay0 Initial share of clay /0.6/
xk(t) Fraction of K that is clay in t
srvshr Single period survival share
alpha Next period maturation share
kfirst Capital stock in t0
rk0 Benchmark returns to k
pk0 Net price of a unit of k at t0;

year(yr) = 2000 + (ord(yr)-1);
qref(t) = (1 + gamma)**(year(t) - 2005);
qref_em(s,t)=qref(t);
qproj(s,t) = no;
ssproj(s) = no;
pproj(s,t) =no;
psproj(s) =no;
phi(s,t) = 1;
p_phi(g,t)=1;
pref(t) = (1/(1 + rho))**(year(t)-2005);
theta = sum(t$tt(t),((1 + gamma)/(1 + rho))**(card(t) + 1));
srvshr = (1 - delta)**5;
alpha = inlag/5;

*----------------------------------------------------------*

display theta,qref,pref;

*----------------renewable electricity-------------------*

parameter mu(s) share of industry that is non-fossil
mu_ref(s,t) reference trajectory for non-fossil
RPS(t) trajectory of RPS minimum renewables;
mu(s)=0;
mu("ele")=0.09;
rps(t)=mu("ele");

xk(t)=clay0*(1-delta)**((5*(ord(t)-1));
mu_ref(s,t) = mu(s)*qref(t)/(qref(t)-xk(t));

*----------------------------------------------------------*

* Capital stock equals investment divided by (growth + depreciation)*
k0 = inv0/
     ((1/5)*((1+gamma)**5 - srvshr)/
     (alpha + (1-alpha)*(1+gamma)**5));

kfirst = k0*(qref(t0)-xk(t0))
\[-5(1-\alpha)\text{inv0}\text{qref(t0)};\]

\[\text{net price of k at t0}\]
\[pk0 = (1/5) / (1/(1 + \rho))^{**5} \cdot \alpha + (1-\alpha);\]

\[\text{Implied marginal tax on capital earnings}\]
\[tk = (\text{sum(hh,ske0(hh))})/(k0*\text{rk0})-1;\]

\[pkd0(s) = (1+tk);\]
\[tkrev = tk*\text{sum(s,(skd0(s)/pkd0(s))));}\]

\[\text{display tk};\]

\[\text{Implied marginal tax on capital earnings}\]
\[\text{display tk};\]

\[\text{parameter}\]
\[\text{pbar(t)} \quad \text{exogenous price of carbon (CO2 tax),}\]
\[\text{us_p(s,t)} \quad \text{US mkt price,}\]
\[\text{w_p(s,t)} \quad \text{World market price};\]

\[\text{Parameter arm(g)} \quad \text{armington elasticity}\]
\[\text{tau(g)} \quad \text{export elasticity};\]

\[\text{Parameter arm(g)} = 10;\]
\[\text{tau(s)} = 0.5;\]

\[\text{parameter eledist};\]
\[\text{eledist("imports")}=\text{sm0("ele","dtrd")};\]
\[\text{eledist("production")}=(\text{d0("ele")}+\text{sum(trd, sx0("ele",trd))});\]
\[\text{eledist("absorption")}=a0("ele");\]

\[\text{display eledist;}\]

\[\$ontext\]
\[\$model:soe\]

\[\$SEPS:1e-10\]

\[\$sectors: w\]

\[y(s,t)$y0(s) \quad ! \text{Household utility}\]

\[y_r(s,t)$y0(s) \quad \text{and mu(s)} \quad ! \text{Sectoral production renewables}\]

\[xy(s,t)$y0(s) \quad \text{! Sectoral production Extant}\]

\[cet(s,t)$y0(s) \quad \text{! CET activity}\]
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\texttt{a}(s,t) \texttt{a}(s) \quad \texttt{! Armington aggregation}

\texttt{z}(t) \quad \texttt{! Macroeconomic Aggregation}

\texttt{k}(t) \quad \texttt{! Index on the k stock}

\texttt{i}(t) \quad \texttt{! Investment index}

\texttt{\$commodities:}

\texttt{pw} \quad \texttt{! Intertemporal price index}

\texttt{p}(s,t) \texttt{d}(s) \quad \texttt{! Sectoral output prices domestic}

\texttt{py}(s,t) \texttt{y}(s) \quad \texttt{! Sectoral output prices}

\texttt{pa}(s,t) \texttt{a}(s) \quad \texttt{! Armington aggregate prices}

\texttt{pc}(t) \quad \texttt{! Price of Macro Good}

\texttt{pl}(t) \quad \texttt{! Wage rate}

\texttt{rk}(t) \quad \texttt{! Return to capital}

\texttt{rk_r}(t,el) \quad \texttt{! Renewable sector capital}

\texttt{pk}(t) \quad \texttt{! Price index on a unit of K}

\texttt{xrk}(s,t) \quad \texttt{! Return to extant capital}

\texttt{ptk} \quad \texttt{! Price of post terminal k}

\texttt{pfx} \quad \texttt{! Foreign exchange}

\texttt{ptax}(t) \quad \texttt{! Business taxes}

\texttt{pcarb}(t) \quad \texttt{! Price of permits}

\texttt{\$consumers:}

\texttt{rh} \quad \texttt{! Institutions}

\texttt{\$Auxiliary:}

\texttt{kt} \quad \texttt{! Terminal k stock}

\texttt{PHAT}(s,t) \texttt{y}(s) \texttt{ssproj}(s) \quad \texttt{! Endogenous Phantom subsidy}

\texttt{M_adj}(s,t) \texttt{y}(s) \texttt{ssproj}(s) \quad \texttt{! Income adjustment}

\texttt{P_PHAT}(g,t) \texttt{a}(g) \texttt{psproj}(g) \quad \texttt{! Endogenous Phantom subsidy to hit prices}

\texttt{P_M_adj}(g,t) \texttt{a}(g) \texttt{psproj}(g) \quad \texttt{! Income adjustment on p_phat}

\texttt{mu_adj}(t) \quad \texttt{! Endogenous adjustment to non-fossil trajectory based on RPS}

\texttt{rkadj}(t) \quad \texttt{! Adjustment for renewable capital}

\texttt{\$prod: cet}(s,t) \texttt{y}(s) \texttt{t:tau}(s)

\texttt{op}(s,t) \texttt{q:do}(s) \quad \texttt{p:pref(t)}

\texttt{op:px} \texttt{q:sum(trd,pref(t)*sx0(s,trd))}

\texttt{ip:py}(s,t) \texttt{q:sum(trd,sx0(s,trd))}

\texttt{\$prod: y}(s,t) \texttt{y}(s) \texttt{s:0}

\texttt{va:0.5} \quad \texttt{va(vae):1} \quad \texttt{el(vae):0.2}

\texttt{+ ful(el):0.1 cg(ful):2 oil(ful):0}

\texttt{+ gas(cg):0 col(cg):0}

\texttt{op:py}(s,t) \texttt{ssproj}(s) \texttt{q:phi(s,t)*do(s)*sx0(s,trd))}

\texttt{A:rh N:PHAT(s,t) M:-1}

\texttt{op:py}(s,t) \texttt{not ssproj}(s) \texttt{q:do(s)*sx0(s,trd))}

\texttt{i:pa}(g,t) \texttt{not en(g)} \texttt{q:sid0(g,s) p:pref(t)}

\texttt{i:pa("ele",t) q:sid0("ele",s) p:pref(t) el:}

\texttt{i:pa(ff,t) q:sid0(ff,s)*(1+mu_ref(s,t)/(1-mu_ref(s,t)));

\texttt{i:pcarb}(t) \texttt{(ff) q:eproj(ff,s,t)/qref_em(s,t) p:pref(t)*1e-8)

\texttt{i:pl(t) q:sld0(s) p:pref(t) va:}

\texttt{i:rk(t) q:(skd0(s)*/sum(s,ff,(mu_ref(s,t)/(1-mu_ref(s,t)))*sid0(ff,s))))/pkd0(s))}
\[
p: (pkdO(s) * pref(t)) + p: pref(t) va: a: rh t: tk
i: ptx(t) q: sbtO(s) p: pref(t)
\]

\[
$prod: y_r(s, t)$(yO(s) and \mu(s)) s: 0
o: py(s, t) ssproj(s) q: (\phi(s, t) * (dO(s) + sum(trd, sxO(s, trd)))) A: rh \ N: PHAT(s, t) M: -1
o: py(s, t) not ssproj(s) q: (dO(s) + sum(trd, sxO(s, trd)))
\]

\[
i: pa(g, t)$(not en(g)) q: sidO(g, s) p: pref(t)
i: pa("ele", t) q: sidO("ele", s) p: pref(t)
i: pa(ff, t) q: sidO(ff, s) p: pref(t)
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pc(\Sigma) q: (\text{eproj}(s, ff, t) / qref_em(s, t)) p: (pref(t) * 1e-8)
i: pl(ff) q: (us_p(g, t) * pref(t) * smO(g, "dtrd")) p: (1 / us_p(g, t)) m:
i: pk(t) q: (k0)

$\prod_{i=0}^{j} i(t)$

$O: ptk\#(tt(t)) q: (inv0*5*alpha)

$O: pk(t+1) q: (inv0*5*alpha)$

$O: pk(t) q: (inv0*5*(1 - alpha))$

$i: pc(t) q: inv0$

$d: pc(t)$

$e: pk(t0) q: kfirst$

$e: xrk(s,t) q: (skd0(s)/pkd0(s)*xk(t))$

$e: r_k_r(t, "ele")$

$q: ((mu_ref("ele",t))\*qref(t)-xk(t))\*((skd0("ele")\+sum(ff, sid0(ff,"ele")))\./pkd0("ele"))$

+r: mu_adj(t)

$e: rk(t)$

$q: (-mu_ref("ele",t))\*qref(t)-xk(t))\*((skd0("ele")\+sum(ff, sid0(ff,"ele")))\./pkd0("ele"))$

+r: r_kadj(t)

$e: pl(t) q: (qref(t)\*sum((s,hh),(sle0(hh)*sld0(s)/sum(g,sld0(g)))))$

$e: pfx q: (sum(t, pref(t)\*qref(t)\*sum(hh, incadj(hh))))$

$e: pfx q: (sum((t, pub), (qref(t)\*pref(t)\*gov0(pub))))$

$e: pl(t) q: (qref(t)\*sum(s,sfica*sld0(s)/sum(g,sld0(g))))$

$e: ptax(t) q: (qref(t)\*sum(s,sbt0(s)))$

$e: pfx q: (-sum(t, pref(t)\*qref(t)\*sum(s,sbt0(s))\+sum(s,sfica*sld0(s)/sum(g,sld0(g))))))$

$e: pcarb(t) q: carblim(t)$

$e: ptk\#(tt(t)) q: (-1) r: kt$

$e: py(s,t) q: (y0(s) and ssproj(s)) q: 1 r: m_adj(s,t)$

$e: pa(g,t) q: (a0(g) and psproj(g)) q: 1 r: p_m_adj(g,t)$

$constraint: P_PHAT(g,t) q: (a0(g) and psproj(g))$

$pfx*pproj(g,t)*pref(t) - pa(g,t))\*(ord(t) le 6)$

$+p_phat(g,t)\*(1-0.1*(ord(t) le 9)) - p_phat(g,t-1))\*(ord(t) gt 6)$

= 0;

$constraint: P_M_adj(g,t) q: (a0(g) and psproj(g))$

$P_M_adj(g,t)$

$a0(g)\*a(g,t)\*P_phat(g,t);$

$constraint: kt$

$sum(tt(t), i(t)\*z(t-1) - i(t-1)\*z(t))$

= 0;

$constraint: r_kadj(t)$

$r_k(t)\*rkadj(t)$

= $r_k_r(t, "ele")\*mu_adj(t)\*2;$

$constraint: mu_adj(t)$

$y_r("ele", t)\*(d0("ele")\+sum(trd,sx0("ele", trd))) +$
0.09*(w_p("ele",t)*pref(t)*sm0("ele","ftrd") )*A("ele",t)*
(PA("ele",t)*p_phi("ele",t)*1/((w_p("ele",t)/PFX*pref(t)))*arm("ele")+
0.09*(us_p("ele",t)*pref(t)*sm0("ele","dtrd") )*A("ele",t)*
(PA("ele",t)*p_phi("ele",t)*(1/us_p("ele",t)))/(PFX*pref(t)))*arm("ele")

= rps(t)*((y_r("ele",t)+xyC("ele",t)+y("ele",t))*((dO("ele")+
sum(trd,sxO("ele",trd))))+
(w_p("ele",t)*pref(t)*sm0("ele","ftrd") )*A("ele",t)*(p_phi("ele",t)*
PA("ele",t)*1/((w_p("ele",t)/PFX*pref(t)))*arm("ele")+
(us_p("ele",t)*pref(t)*sm0("ele","dtrd") )*A("ele",t)*(p_phi("ele",t)*
PA("ele",t)*(1/us_p("ele",t)))/(PFX*pref(t)))*arm("ele")

);
\[ p_{l}(t) = \text{pref}(t); \]
\[ r_{k}(t) = \text{pref}(t); \]
\[ x_{rk}(s,t) = \text{pref}(t); \]
\[ p_{k}(t) = p_{k0}\times\text{pref}(t); \]
\[ p_{tax}(t) = \text{pref}(t); \]
\[ p_{carb}(t) = 1e^{-8}\times\text{pref}(t); \]
\[ \text{PHAT.fx(s,t)} = 0; \]
\[ m_{adj.fx}(s,t) = 0; \]
\[ p_{PHAT.fx}(g,t) = 0; \]
\[ p_{m_{adj}.fx}(g,t) = 0; \]
\[ r_{k_{r}}(t,s) = \text{pref}(t); \]
\[ r_{kadj}(t) = 1; \]
\[ \mu_{adj}(t) = 1; \]
\[ l_{0}(t,t) = \frac{1}{(1+\rho)^{5}}\times p_{k}(tt); \]
\[ k_{t}(t) = 5\times\alpha\times\text{inv0}\times q_{ref}(tt) + \text{srvshr}k_{0}\times(q_{ref}(tt) - x_{k}(tt)); \]
\[ \text{numeraire is pfx} \]
\[ \text{pfx.fx} = 1; \]
\[ \text{---------------Solve steady-state-------------------} \]
\[ \text{soe.iterlim} = 0; \]
\[ \text{solve soe using mcp}; \]
\[ \text{Abort$(\text{soe.objval} > 1e^{-3})$ "steady-state is not balanced";} \]
\[ \text{--------------------------} \]
\[ \text{* Insert the sector specific trajectories for energy quantities} \]
\[ \text{ssproj(en)} = \text{yes}; \]
\[ \text{qproj(en,t)} = \text{yeproj(en,t)}; \]
\[ \text{ssproj("cru") = yes}; \]
\[ \text{qproj("cru",t)} = \text{yeproj("oil",t)}; \]
\[ \text{*free the bounds on the endogenous tax} \]
\[ \text{p_{hat}.lo(en,t)} = -0.95; \]
\[ \text{p_{hat}.up(en,t)} = +\text{inf}; \]
\[ \text{m_{adj}.lo(en,t)} = -\text{inf}; \]
\[ \text{m_{adj}.up(en,t)} = +\text{inf}; \]
\[ \text{p_{hat}.lo("cru",t)} = -0.95; \]
\[ \text{p_{hat}.up("cru",t)} = +\text{inf}; \]
\[ \text{m_{adj}.lo("cru",t)} = -\text{inf}; \]
m_adj.up("cru",t) = +inf;

*free up the carblim to ensure no carbon price

carblim(t) = 2*carblim(t);

soe.iterlim = 10000;

solve soe using mcp;

Abort$(soe.solvestat<>1) "Benchmark quantity projections did not solve";

*Insert the commodity price projections
display peproj;

psproj(en) = yes;
pproj(en,t) = peproj(en,t);

*free the bounds on the endogenous tax
p_phat.lo(en,t) = -0.95;
p_phat.up(en,t) = +inf;
p_m_adj.lo(en,t) = -inf;
p_m_adj.up(en,t) = +inf;

soe.iterlim = 10000;
solve soe using mcp;

Abort$(soe.solvestat<>1) "Benchmark price projections did not solve";

*Set the qref_em for all sectors
to get the emissions coefficients correct
qref_em(s,t) = y.l(s,t) + y_r.l(s,t) + xy.l(s,t);

*Reset the carblim to exactly the benchmark emissions level

carblim(t) = sum((ff,s), eproj(s,ff,t)) + sum(ff, hproj(ff,t));

Set the TFP adjustment
and remove the phantom taxes and income adjustments

phi(s,t) = 1 + phat.l(s,t);

p_phat.fx(s,t) = 0;

m_adj.fx(s,t) = 0;
p_phi(g,t) = 1 + p_phat.l(g,t);
p_phat.fx(s,t) = 0;
p_m_adj.fx(s,t) = 0;

soe.iterlim = 0;

*Check the non-steady-state benchmark

soe.iterlim = 0;

solve soe using mcp;
Abort$(soe.objval > 1e-3) "Benchmark projection check did not balance";

parameter  
nonen(t,*) non energy trajectories  
entraj(t,*) energy trajectories  
enprc(t,*) energy price traj;

nonen(t,s)$(not en(s)) = (y.l(s,t)+y.r.l(s,t)+xy.l(s,t))/qref(t);  
nonen(t,"qref") = 1;  
entraj(t,s)$(en(s)) = (y.l(s,t)+y.r.l(s,t)+xy.l(s,t))/qref(t);  
entraj(t,"qref") = 1;  
enprc(t,s)$(en(s)) = pa.l(s,t)/pref(t);  
enprc(t,"cru") = pa.l("cru",t)/pref(t);  
enprc(t,"pref") = 1;

*$libinclude plot nonen  
*$libinclude plot entraj  
*$libinclude plot enprc

*----------compute electricity sector info---------*

parameter  
tradele(s,t)  
renewele(s,t)  
totaleleprod(s,t)  
eleimp(s,t)  
eleuse(s,t)  
renewuse(s,t)

impchk(t);

tradele("ele",t) = (d0("ele")+sum(trd,sx0("ele",trd)))*(y.l("ele",t)+xy.l("ele",t));  
renewele("ele",t) = (d0("ele")+sum(trd,sx0("ele",trd)))*y.r.l("ele",t);  
totaleleprod("ele",t) = tradele("ele",t) + renewele("ele",t);  
eleimp("ele",t) = imp.l("ele",t);  
eleuse("ele",t) = imp.l("ele",t)-

  exp.l("ele",t)+

  (d0("ele")+

sum(trd,sx0("ele",trd)))*

  (y.r.l("ele",t)+y.l("ele",t)+xy.l("ele",t))
)

renewuse("ele",t) = (renewele("ele",t)+(0.09*(eleimp("ele",t))))/eleuse("ele",t);  
impchk(t) =

(w_p("ele",t)*pref(t)*sm0("ele","ftrd") )*A.l("ele",t)*

(PA.l("ele",t)*p_phi("ele",t)*(1/w_p("ele",t))/(PFX.l*pref(t)))**arm("ele")+

us_p("ele",t)*pref(t)*sm0("ele","dtrd")*A.l("ele",t)*

(PA.l("ele",t)*p_phi("ele",t)*(1/us_p("ele",t))/(PFX.l*pref(t)))**arm("ele")

imp.l("ele",t)

display impchk, renewuse;
*--------unload electricity results for benchmark--------*
Execute_Unload "eleb.gdx", S,T, tradele, renewele, totaleleprod, eleimp, eleuse;
Execute 'GDXXRW.exe eleb.gdx par=tradele rng=A2';
Execute 'GDXXRW.exe eleb.gdx par=renewele rng=A12';
Execute 'GDXXRW.exe eleb.gdx par=totaleleprod rng=A22';
Execute 'GDXXRW.exe eleb.gdx par=eleimp rng=A32';
Execute 'GDXXRW.exe eleb.gdx par=eleuse rng=A42';
$offtext