# A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS OF CURRENT CLIMATE CHANGE POLICY IN THE UNITED STATES

by

Jodie L. Capling
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# APPROVAL

**Name:** **Jodie L. Capling**

**Degree:** **Master of Resource Management**

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**Project No.:** **491**

**Examining Committee:**

**Chair:** **Caroline Lee**
Master of Resource Management Candidate

______________________________________

**Mark Jaccard**
Senior Supervisor
Professor,
School of Resource and Environmental Management
Simon Fraser University

______________________________________

**Nic Rivers**
Supervisor
Ph.D. Candidate,
School of Resource and Environmental Management
Simon Fraser University

**Date Defended/Approved:** ______________________________________

## ABSTRACT

In this research I develop a static computable general equilibrium model of the global economy and apply the model to analyze greenhouse gas emission reduction policy. The model is comprised of two regions, the US and ROW (Rest of World), and I use it to simulate policy from 2010 to 2050 in 10 year intervals. I focus on analyzing cap-and-trade systems currently relevant in the US. I found that reducing emissions with a cap-and-trade system would have moderate costs and small negative impacts on the US GDP and consumer welfare. I also found that output-based allocation of revenue to industry could slightly increase the price of emission permits and that linking a US cap-and-trade system to international systems could reduce the price of emission permits in the US. In my analysis carbon capture and storage has an important role in emissions mitigation.



**Keywords:** Climate change policy; Computable general equilibrium model; Energy-economy modelling; US cap-and-trade systems

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## GLOSSARY

| | |
|---|---|
| AEEI | Autonomous Energy Efficiency Index |
| BAU | Business-as-Usual |
| CCS | Carbon Capture and Storage |
| CES | Constant Elasticity of Substitution |
| CGE model | Computable General Equilibrium model |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide Equivalents |
| EIA | Energy Information Administration |
| ESUB | Elasticity of Substitution |
| EV | Equivalent Variation |
| GAMS | General Algebraic Modelling System |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| Gj | Gigajoule ($10^9$ joules) |
| GTAP | Global Trade Analysis Project |
| IPCC | Intergovernmental Panel on Climate Change |
| MAC | Marginal Abatement Cost |
| MPSGE | Mathematical Programming System for General Equilibrium |
| Mt | Megatonne ($10^6$ tonnes) |

| | |
|---|---|
| ppm | parts per million |
| ROW | Rest of World |
| RPP | Refined Petroleum Product |
| SAM | Social Accounting Matrix |
| UNFCCC | United Nations Framework Convention on Climate Change |
| US | United States |
| VERITAS | E**V**aluation of **E**mission **R**eduction for **I**n**T**ernational **A**batement **S**cenarios |

# 1: INTRODUCTION

Climate change is one of the largest challenges that humanity faces today and it is a challenge of our own making. The Intergovernmental Panel on Climate Change (IPCC) has found that global atmospheric concentrations of greenhouse gasses (GHG) have increased since 1750 as a result of human activities and that levels of GHG now far exceed pre-industrial values (IPCC, 2007a). The IPCC has also found with *very high confidence* that the global average net effect of human activities since 1750 has been one of warming.[1]

Carbon dioxide ($CO_2$) is the most important anthropogenic GHG and the atmospheric concentration of $CO_2$ has increased from 280 parts per million (ppm) in pre-industrial times, to 385 ppm in 2008 (IPCC, 2007a; Keeling et al., 2009). The current atmospheric concentration of $CO_2$ exceeds the natural range of 180 to 300 ppm seen over the last 650,000 years, as determined from ice cores (IPCC, 2007a). The main source of increasing $CO_2$ concentrations in the atmosphere is the combustion of fossil fuels in our energy systems; land use changes are also important but make a much smaller contribution (IPCC, 2007a; Karl and Trenberth, 2003).

In this chapter, I briefly describe the international response to anthropogenic climate change and introduce where the United States is in their

[1] The IPCC uses the convention that *very high confidence* means a 9 out of 10 chance of being correct.

response to this problem. Next, I discuss different types of energy-economy models and how they contribute to understanding the challenge of addressing climate change and our options for doing so. I then provide a description and justification of the type of energy-economy model I use in this research. Following this, I present my research objectives and questions. An outline of the rest of this report concludes this chapter.

## 1.1 International Response to Climate Change

The international response to anthropogenic climate change has been centred around the United Nations Framework Convention on Climate Change (UNFCCC). In 1992, many counties joined the UNFCCC, which is an international treaty that focuses on dealing with the problem of climate change. The ultimate goal of UNFCCC, as stated in Article 2, is stabilizing greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system (United Nations, 1992).

The goal of UNFCCC brings into question what dangerous anthropogenic interference actually is and what the target should be for stabilizing GHG concentrations. The fourth IPCC assessment report provides ranges of temperature increases above pre-industrial values and the corresponding level of atmospheric carbon dioxide equivalents ($CO_2e$) that might be necessary to stay within them. $CO_2e$ are one way to measure the amount of GHGs in the atmosphere, taking into account $CO_2$ and GHGs other than $CO_2$. The most widely supported temperature-limiting goal is to keep global temperature increase below 2 degrees Celsius from pre-industrial values. Reaching this temperature target is likely to require stabilization at about 450 ppm $CO_2$e (IPCC, 2007a). However, to have an 80% probability that temperature change will be limited to 2$^{o}$C, the IPCC estimates that $CO_2$e would need to be stabilized at 378 ppm (IPCC, 2007b). Some groups, particularly small island states, have proposed that measures should be taken to limit temperature change to less than 1.5$^{o}$C, which would require even lower levels of stabilized GHG concentrations. While the IPCC provides a summary of the current scientific information about climate change, international agreements are shaped by political constraints and interests of many nations, as well as scientific consensus on climate change.

The Kyoto Protocol is an international treaty that was negotiated under the UNFCCC. Adopted in December 1997 and entered into force in February 2005, it sets binding goals for reducing GHG emissions for 37 industrialized countries. The average targets are to reduce emissions to 5% below 1990 levels for the period of 2008 to 2012. The Kyoto Protocol acknowledges that industrialized countries have historically contributed more to the problem of climate change and that they have a higher financial capacity to pay for mitigation; therefore it puts a heavier burden on developed nations. One large obstacle that the Protocol faced was that the United States did not ratify. This means that the two largest emitters in the world, the US and China, do not have emission reduction targets under the Kyoto Protocol.

While the Kyoto Protocol is an important step in reaching international agreements to deal with the issue of climate change, much of the international focus is now on negotiating a post-Kyoto agreement. There is potential for the

US to be a positive influence in these negotiations, since the Obama administration has made it clear that climate change is a priority. The latest United Nations climate negotiations resulted in the Copenhagen Accord, which has recently been finalized. However, the Copenhagen Accord is not legally binding and essentially summarizes the targets that countries had before the negotiations began. Whether the targets are met will depend on the domestic emission reduction policy that individual countries enact.

## 1.2 Situation in the United States

When it comes to the types of policies that could be used to meet GHG emission reduction targets, cap-and-trade systems are likely, especially in the US. In the absence of federal policy, various states and some Canadian provinces have started designing and implementing cap-and-trade systems to reduce GHG emissions. Examples include the Western Climate Initiative, which is working on an international cap-and-trade system in the US and Canada, the Regional Greenhouse Gas Initiative, which has begun implementing a cap-and-trade system for power generators in the eastern US, and the Midwestern Greenhouse Gas Accord, which is working on developing proposals for a cap-and-trade system in the central US. The European Union also has a cap-and-trade system in place to reduce GHG emissions. The European Union Emissions Trading Scheme has been running since 2005 and sets a precedent for the use of cap-and-trade systems in other regions.

Currently there are two bills that propose cap-and-trade systems for GHGs before the US Senate. In May of 2009, Representatives Waxman and Markey introduced the American Clean Energy and Security Act of 2009, which is also known as the Waxman-Markey bill. This bill is a national climate and energy act that would establish a cap-and-trade system for GHGs and other measures to address climate change and transition to a low-carbon economy. The House of Representatives passed the bill on June 26, 2009 and it was received in the Senate in July 2009. The second bill, the Clean Energy Jobs and American Power Act, is sponsored by Senators Kerry and Boxer and is also known as the Kerry-Boxer bill. The focus of this bill is to create clean energy jobs, promote energy independence, reduce global warming pollution and transition to a clean energy economy. It was introduced to the US Senate in September of 2009. Given the elements of both bills, it seems likely that if the US Congress passes climate change legislation, a key portion will be a cap-and-trade system for greenhouse gasses.

The timing of policies that influence energy use and energy systems is central to dealing with climate change. Every year of delay increases the likelihood that global warming will exceed $2^{o}$C above pre-industrial values. To keep the warming below this level, global emissions need to peak between 2015 and 2020 and then decline rapidly (Allison et al., 2009; IPCC, 2007b). In short, expedient action and well-crafted policies are necessary to meet the challenge of reducing GHG emissions and minimizing climate change.

## 1.3 Energy-Economy Modelling

Energy-economy models are useful in modelling the interactions between the economy, energy systems and the environment and how technologies affect these interactions (van der Zwaan et al., 2002). These models can be helpful to policy makers when they are designing policies to meet environmental, social and economic objectives. In the context of climate change, these models are often used to estimate how various policies could impact the economy and the environment, specifically through the amounts of GHGs emitted into our atmosphere. These models cannot precisely predict the future, but they show possible trends and scenarios that could occur based on our current situation and possible choices of policies.

There are traditionally two main approaches to energy-economy modelling, referred to as bottom-up and top-down. However, the effort to bridge these two methods is evident in the emergence of hybrid models, which attempt to capture the best aspects of each and avoid some of their limitations.

### Bottom-up Models

Traditional bottom-up models are generally based on rich technological detail. They estimate how energy use and corresponding environmental impacts could be affected by changes in energy efficiency, fuel use, emission control equipment and infrastructure (Bataille et al., 2006). Bottom-up models assume that a new technology, which provides the same type of service as an existing, conventional technology, can be substituted directly, only differing in the lower anticipated financial cost or reduced emissions of the new technology (Jaccard, 2005). This assumption ignores possible intangible costs associated with a new technology, including: risk of the new technology failing, different quality of service, and risks associated with long payback investments. It also fails to reflect how consumers or firms behave when faced with decisions about new technologies. By excluding these costs and behaviours, bottom-up approaches often underestimate the true cost of low-emission or more efficient technologies, and thus tend also to underestimate the cost of reducing GHG emissions (Jaccard, 2005). Bottom-up models also often lack the macro-economic feedbacks that link changes induced by policies to the structure of the economy and to the rate or distribution of economic growth (Hourcade et al., 2006).

### Top-down Models

Traditional top-down models are based on aggregate representations of the economy and often use abstract production functions to describe relationships between sectors, inputs and outputs. They are generally based on an equilibrium framework that can capture indirect effects from one sector of the economy to others. The top-down models that are based on full equilibrium are usually referred to as computable general equilibrium (CGE) models (Löschel, 2002). In these models, technologies are usually represented by aggregate production functions for each sector of the economy (McFarland et al., 2004) The lack of technological detail makes top-down models unsuited for analyzing policies that specifically target technological change, such as subsidies for specific technologies or standards that mandate minimum market shares of low emission technologies. The top-down approach is also challenged in portraying future technological change due to the use of historical data as a basis for many model parameters (Hourcade et al., 2006).

One of the strengths of top-down models is their ability to capture macroeconomic feedbacks and the changes in the structure of the economy because of policies. Top-down models are used to analyze market-based policies, where they use parameters estimated from historic economic data to simulate the response of the economy to a financial signal. For example, a tax on GHG emissions is a financial signal, which increases the cost of technologies or energy forms that produce emissions. The size of the signal needed to attain an emissions target indicates the implicit challenge of reaching the target, including intangible costs, such as risk related to new technology and investing in technologies that may require a long payback period. Thus, top-down cost estimates of policies are usually higher than bottom-up estimates because they include the transitional and long run costs of technological change (Jaccard, 2005).

### Hybrid Models

In recent years, there has been a trend towards hybrid energy-economy models, which seek to bridge the gap between top-down and bottom-up. This has involved bottom-up modellers adding more macro-economic feedbacks and behavioural realism to their models and top-down modellers adding more technological explicitness to their models (Hourcade et al., 2006). One example is the MIT-EPPA model which is a CGE that includes multiple electricity-producing technologies (Paltsev et al., 2005). Another example of a hybrid model is CIMS, which is developed by the Energy and Material Research Group of Simon Fraser University. CIMS is technologically explicit like many bottom-up models, but also captures some of the behavioural and macroeconomic feedbacks of top-down models. For a description of CIMS see Bataille et al. (2006) or Murphy et al. (2007).

In this research, I continue along the path of model hybridization, by using the CIMS model to inform a CGE model. The value of this combination is that it utilizes the best characteristics of both model types. The CGE model is useful for tracking the macro-economic impacts and feedbacks that climate change policies could induce on the economy and the CIMS model is technology-rich and includes aspects of behavioural realism. By using the CIMS model to inform the way a CGE model represents technology, it improves the CGE model, but still allows the modeller to investigate the macro-economic impacts of a policy.

This type of model is especially critical for analyzing climate change policy in the US because of the key role that this country has in this global issue. As the second largest GHG emitter on the planet and the largest emitter among the developed nations, the US must be involved in the solution if we are to successfully deal with anthropogenic climate change. A model that provides robust analysis of climate change policy options can help US leaders and decision makers choose the best policies to meet the challenge of climate change, while also addressing important economic and social considerations.

## 1.4 VERITAS-US a CGE Informed by CIMS

My research is based on building a global CGE model to analyze GHG emission reduction policy with a focus on cap-and-trade policy in the United

States. The CGE model that I developed, in conjunction with Caroline Lee, is called VERITAS (E**V**aluation of **E**mission **R**eduction for **I**n**T**ernational **A**batement **S**cenarios).[2] In my research, I focus on evaluation of GHG emission reduction policy in the US and use a US focused version of the model called VERITAS-US.

One of the strengths of VERITAS-US is that it includes parameters that are informed by the CIMS model. Thus, it has the macro-economic feedbacks and behavioural realism of a CGE, combined with aspects of the behavioural realism and technological detail of CIMS. The parameters that I calculate from CIMS help address some of the uncertainty in the way a typical CGE model represents technologies. This combination removes some of the CGE's dependence on historical technology data because CIMS details the technology options that are currently available and those that will potentially be available in the next few decades. The parameters calculated from CIMS also provide VERITAS-US with some sector and regionally specific parameters. This combination is a potential improvement over other CGE models as they often have the same parameters for all regions and sectors, which are based on expert opinion or historical data.

## 1.5 Research Objectives and Questions

Because of the US position as a large GHG emitter and their political power, their participation in addressing climate change is critical. The Obama administration has made action on climate change a priority and there are two

[2] Also the Roman Goddess of Truth

climate change bills before the Senate that would use cap-and-trade systems with emission permits to reduce GHG emission. Robust analyses of these climate change policies are important to make sure that they will meet environmental, economic and social objectives. In designing and passing a climate change bill there are many important issues. One such issue is that of international emissions permit trading and how a US GHG emission reduction policy could be linked to emission reduction efforts internationally. Another important issue is how emission permits or revenue from auctioning of the permits might be allocated and how this could impact the US. The objectives and questions for this research project are a response to these important issues in the current situation and the necessity for analyses of climate change policy options for the US.

**Objectives:**

- To build a global energy-economy model able to analyze climate change policy, with a focus on the United States (using a CGE framework enhanced with information from CIMS),
- To use the model to analyze climate change policy that is currently relevant to American and international situations.

**Questions:**

- What are the potential economic and environmental impacts of currently proposed US climate policy?

- What are the potential effects of trading carbon permits internationally versus the option of the US acting alone without international permit trading?
- What are the potential impacts of revenue recycling or permit allocation within the US?
- How robust is the model to different values for elasticities of substitution and the assumptions made regarding carbon capture and storage costs and capacity?

## 1.6 Report Outline

Chapter 2 describes the methods I use, including the modelling system for building VERITAS-US, the model structure and the policy cases to answer my research questions. Chapter 3 contains results from the runs of the model and the policy simulations. Chapter 4 provides a discussion of the results and a comparison of my results to those from other models that are used for similar types of policy analysis. Conclusions arising from this project and some recommendations for future research are presented in Chapter 5.

# 2: METHODS

In this chapter, Sections 2.1 and 2.2 describe CGE models in general and the modelling systems I used for the project. An overview and details on the VERITAS-US model are provided in Section 2.3. In Section 2.4, I describe the data sources and treatment that I used in building the model. Section 2.5 contains a description of the policy scenarios that I analyze in this project.

## 2.1 Computable General Equilibrium Models

VERITAS-US is a computable general equilibrium (CGE) model of the global economy. In this context, computable indicates that a solution for the model is calculated and general equilibrium denotes that all markets in the economy are in equilibrium when a solution is found.

CGE models are based on the idea of a circular flow of commodities (goods and services) and factors (labour and capital) between agents (firms and households) in the economy. Figure 2.1 shows a very basic economy where consumers rent their time, as labour, and their investments, as capital, to firms in exchange for income and firms in turn, sell goods and services to consumers. In some CGE models, there is also a government, which transfers wealth by collecting taxes and providing services or giving subsidies to households and firms (Paltsev et al., 2005; Sue Wing, 2004).

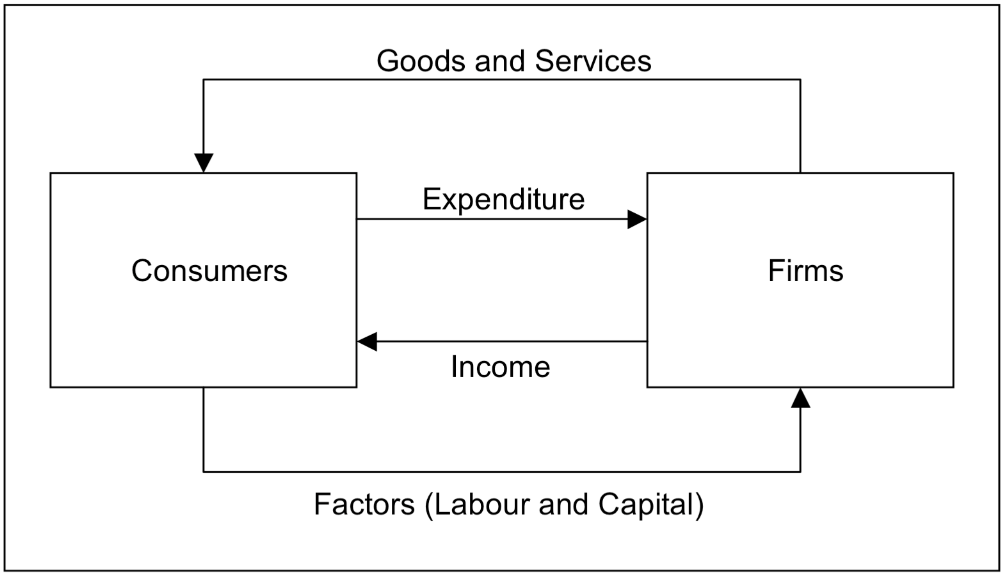



**Figure 2.1 Schematic of a Basic Economy**

Relationships that connect firms, households and the flows of commodities and factors in CGE models are driven by the behaviour of firms and households, which can be described by production and utility functions. The production function portrays how a representative producer or firm uses factors like capital and labour and intermediate inputs like energy, goods and services to produce outputs in each sector. The firm's actions are usually motivated by the goal of minimizing the input costs for a given level of production. The utility function describes how a representative consumer or household maximizes their utility, an economic measure of satisfaction, by consuming various goods and services (Sue Wing, 2004). In some CGE models the consumer is also able to choose leisure time or investing their income as options for maximizing their utility.

The ability to make tradeoffs between inputs in production and utility functions is described by elasticities of substitution (ESUBs). These parameters are very important in CGE models because they regulate how the technologies and preferences of firms and consumers may change, resulting in a different mix of inputs. For example, if a policy that increases the cost of natural gas is imposed, the ESUBs determine how easily a firm or consumer can shift away from natural gas use towards the use of a less expensive fuel. Therefore, these ESUB values have a large impact on how costly a policy is projected to be (Paltsev et al., 2005).

In this project, I use nested constant elasticity of substitution (CES) functions to represent the activities of production and consumption by firms and households. Nested refers to the hierarchical structure that relates the different inputs and their associated ESUBs. I give examples of the nested structures in Section 2.3. Constant refers to the fact that the ESUB values remain constant even if the proportions of inputs in a function change.

For a CGE model of a closed economy to be in equilibrium there are three conditions that must be observed: market clearance, income balance and zero profit (Sue Wing, 2004). Market clearance requires that goods produced must equal goods demanded. To meet the condition of income balance, the value of payments households receive from firms for the use of their labour and capital factors must equal the value of commodity purchases by households. In other words, the consumer must expend all income, although some models allow consumers to save or invest part of their income. The final condition of zero profit is met when the total value of outputs produced is equal to the sum of the value of factors and intermediate inputs used by producers.

Social accounting matrices (SAMs) are central in CGE modelling as they provide data and partially determine model structure. SAMs are created from multiple data sources, including national and product accounting data and input-output tables. They show a static picture of economic transactions in a country or region for a given time period (Pyatt and Round, 1985). The level of aggregation of the data in the SAMs determines part of the CGE's structure. For example, consider a CGE model based on a SAM that is aggregated so the economy is represented by firms and households only and the firms are lumped into two sectors: industry and services. This CGE would have only two sectors, industry and services, and households would be the only final consumer.

An important parameter in energy-focused CGE models is the autonomous energy efficiency index (AEEI). This parameter represents the decoupling of energy use and economic growth from energy price changes; a larger AEEI parameter indicates that the economy is becoming more efficient at using energy relatively rapidly (Bataille et al., 2006; Löschel, 2002). This parameter is a function of both capital stock turnover and technology improvements, independent of energy price changes.

In the field of CGE modelling, there are two sub-types called static and dynamic models. Static models are more simplistic and represent a snapshot of a single time period. Dynamic models have a time component and therefore run over multiple time periods. In a dynamic model, the previous time periods can affect the future ones through multiple factors like prior energy prices, prior time periods' investment levels and capital stock built in prior time periods. VERITAS-US is a static CGE model.

## 2.2 Modelling System

To build VERITAS-US, I used the General Algebraic Modelling System (GAMS) in conjunction with the Mathematical Programming System for General Equilibrium (MPSGE). Developed by Meeraus et al. (1988), GAMS has a variety of routines that can be used to solve linear, non-linear and mixed integer mathematical models and programming problems. A feature of GAMS is that one can build a model without reference to a specific data set, so the same model can be used with multiple data sets of the same format.

While GAMS can be used for a variety of problems, MPSGE, developed by Rutherford (1987, 1997), is specifically designed for economic equilibrium models. MPSGE provides a shorthand way to represent the complicated mathematics that general equilibrium models are based on. It uses nested constant elasticity of substitution production and utility functions. Versions of GAMS with MPSGE embedded have been available since 1993.

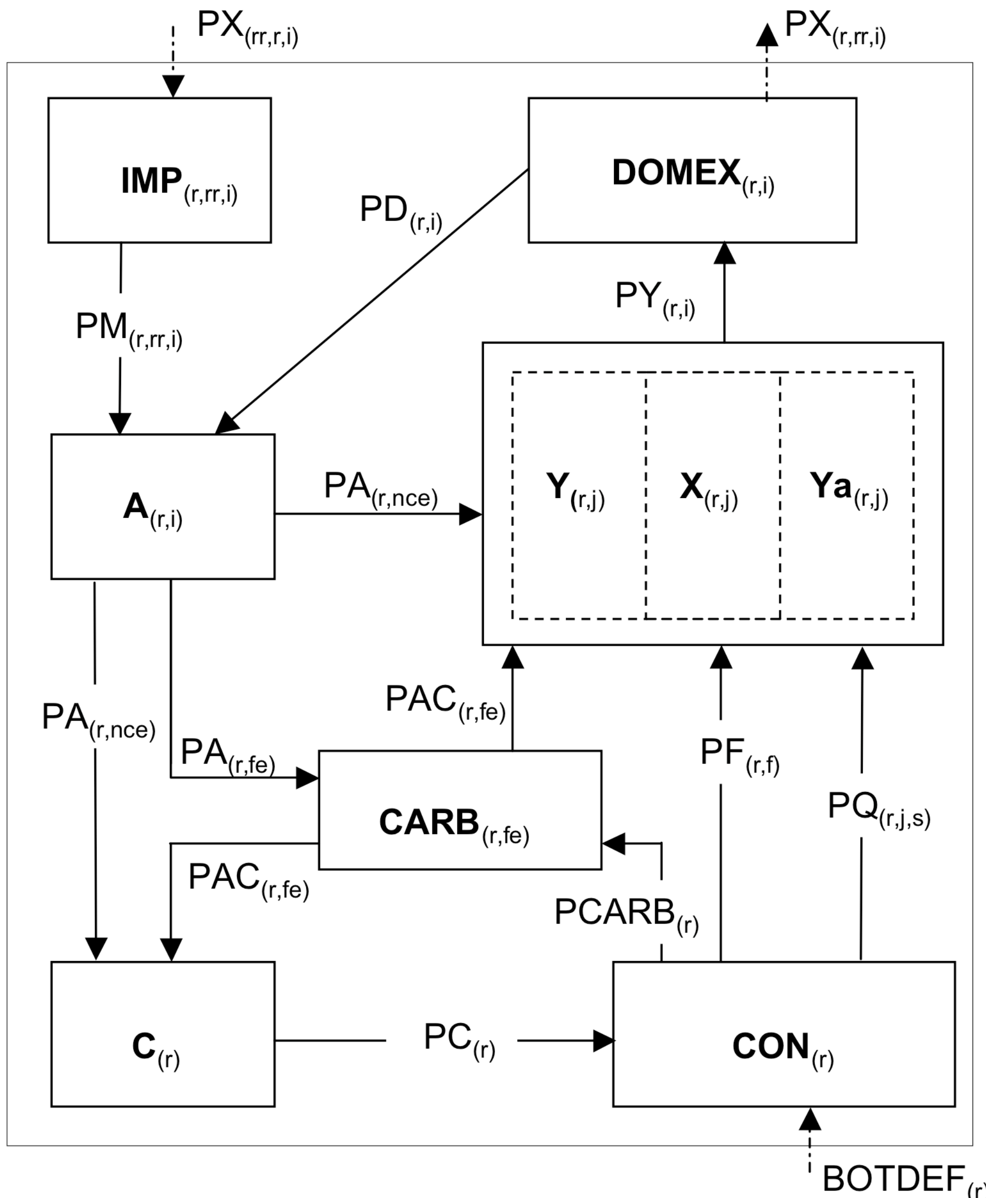
## 2.3 VERITAS-US Model

VERITAS-US is a multi-region, static CGE model, which is comprised of two regions, the United States and Rest Of World (ROW). As a static model, each run of VERITAS-US corresponds to only one time period, so to simulate polices out to 2050, I run the model separately for 2004, 2010, 2020, 2030, 2040 and 2050. The model is a representation of the economy of each region, where factors (capital, labour, land and natural resources) are endowed to households and firms use intermediate inputs and factors to produce goods and services, which are in turn demanded by the final consumer. This final consumer represents both households and government functions. The model also includes exports and imports and tracks bilateral trade. VERITAS-US is able to account for $CO_2$ emissions based on the combustion of fossil fuels. While I could use the model to analyze carbon tax policies, I have chosen to focus on policies that use a cap-and-trade system with emission permits.

The way the model works is driven by two key assumptions about how firms, or producers, and consumers act. There are two parts to the assumption regarding firms. First, they produce with constant-returns-to-scale, i.e. if total inputs increase or decrease, the output changes proportionally. Second, the firms choose inputs to minimize costs for a given level of production. The assumption regarding the actions of consumers is that they maximize their utility, or satisfaction, by maximizing their consumption for a given amount of income. Equilibrium is reached in the model when the three equilibrium constraints (market clearance, income balance and zero profit) are obeyed and both the firms and consumers have achieved their respective cost-minimizing and utility-maximizing goals.

To use VERITAS-US to simulate a policy, I first have the model perform a business-as-usual run. Next, the model is pushed out of equilibrium by applying a policy for reducing GHG emissions. The policies that I simulate put a cap on the amount of carbon emissions allowed in a region and use emission permits to allow individuals or firms to produce emissions, which essentially adds a cost to emitting carbon because of the value of the permits. The model must then reach a new equilibrium taking into account the added costs associated with emitting carbon. I compare this new equilibrium state to the original business-as-usual run to determine the potential impacts of the policy.

The schematic of the overall structure of VERITAS-US (Figure 2.2) shows how each regional economy is represented. Each box, called a ‘production block,’ represents a transformation activity, where inputs are transformed into outputs as goods and factors flow through the economy. These boxes also correspond to blocks of code in the MSPGE section of my model. The box containing Y, X and Ya represents the activity of sectoral production and uses factors and intermediate goods to produce domestic commodities, while minimizing the cost of inputs. The DOMEX box is for transformation of these domestic goods into goods for export and goods for domestic consumption. This is based on the assumption that goods for export and goods for domestic consumption are not perfect substitutes. The IMP box, at the top of the figure, imports goods from other regions. The A box is the Armington aggregator, which amalgamates imported and domestic goods into Armington goods for domestic consumption. This is based on the assumption that goods produced in different places are not perfect substitutes. The Armington goods are used by the sectors as intermediate goods and by the consumer for meeting final demand. The CARB production block allocates emission permits to carbon-emitting fuels.




**Commodity and Factor Flows in VERITAS-US**

| | | | |
|---|---|---|---|
| PY(r,i) | Industrial / sectoral output | PX(r,rr,i) | Exports |
| PD(r,i) | Domestically produced commodities for domestic consumption | PA(r,i) | Armington goods (aggregate of imported and domestic goods) for domestic use |
| PM(r,rr,i) | Imports | PCARB(r) | Carbon permits |
| PAC(r,fe) | Armington goods with carbon permit | PC(r) | Aggregate consumption |
| PF(r,f) | Factors | PQ(r,j,s) | Capacity of carbon capture and storage steps |

**Figure 2.2 Regional Structure of VERITAS-US**

The C block, in Figure 2.2, aggregates all the consumable goods and the CON block represents consumer demand and factors endowed to them. The consumer demand is based on the maximization of utility, or satisfaction, for a given level of income. The GAMS/MPSGE code for VERITAS-US is in Appendix A.

In building VERITAS-US, I used sets to organize the data as shown in Figure 2.2 in the bracketed subscripts. I included the subscripts to aid those readers who wish to understand the model code in Appendix A. The sets consist of: regions, r ; commodities, i ; sectors, j ; factors, f ; and steps in the carbon capture and storage option, s. In the figure, the subscripts 'nce' and 'fe' are also used, both of which are subsets of the commodity set i. They refer to non-carbon emitting (nce) commodities and fuels that emit (fe). The subscript rr is an alias for r and is used when multiple regions are defined, for example, with the exports PX(r,rr,i), r refers to the region the exports are coming from and rr refers to the regions that they are going to.

I chose the two regions, US and ROW, so VERITAS-US includes an approximation of the US interacting with the rest of the globe. This allows me to analyze US policy while having the rest of the world enacting policy as well. Having the ROW region is also important when modelling the US because the US is a large open economy; i.e., it is large enough that changes in US consumption can affect the global price of commodities. The two regions allow for more realism in global trade as commodity and energy prices change.

The set of commodities, i, tracked by VERITAS-US is shown in Table 2.1. In this model, each sector only produces one type of commodity, thus there is a sector, j, that corresponds to each of the commodities in the table below. A detailed description of the activities of each sector is in Appendix B.

**Table 2.1 Set i - Commodities in VERITAS-US**

| | | | |
|---|---|---|---|
| **OIL** | Crude Oil | **MET** | Metal Industrial Goods |
| **ELEC** | Electricity | **NMET** | Non-Metal Industrial Goods |
| **GAS** | Natural Gas | **OMAN** | Other Manufactured Goods |
| **COAL** | Coal | **TRAN** | Transportation |
| **RPP** | Refined Petroleum Products | **ROE** | Other Goods and Services in Rest of Economy |

The model has four types of factors: labour, capital, land and natural resources, which are divided into two subsets, sluggish and mobile. Sluggish, or sector-specific, factors include land, natural resources and fixed capital, which are only used by the sectors they are originally assigned to in the business-as-usual data. I made this distinction because, for example, land used for coal mining is not easily transferred to agricultural use. Mobile factors are labour and flexible capital, which can be used in any of the sectors.

In the next four sections, I describe the function of each ‘production block’ in the schematic of VERITAS-US, Figure 2.2.

### 2.3.1 Sectoral Production

Sectoral production of commodities occurs in the three production blocks Y, X and Ya, and for the most part they are modeled with very similar structure. The Y and X production blocks represent conventional sectoral production; the difference being that Y uses flexible capital as an input and X uses only fixed capital. Flexible capital in the Y production block is open to use by any of the sectors and represents investment in new production technologies. The fixed capital in X must stay in the sector it is assigned to, as it corresponds to installed or built capital. For example, a power plant built to produce electricity cannot be used by the manufacturing sector to process beverages. The Ya production block corresponds to the alternative electricity-producing sector with production technologies that use carbon capture and storage (CCS). This alternative electricity sector is optional and is only used when policies make it economically advantageous to acquire CCS technology instead of conventional combustion technologies that require expensive emissions permits. It uses flexible capital as these CCS technologies would not be installed in the business-as-usual run because of the absence of policy that puts a price on emissions.

The proportion of total capital available to the Y, X and Ya production blocks changes for different time periods. The total amount of capital that is either flexible or fixed is based on the annual capital depreciation rate of 4% per year (Center for Global Trade Analysis, 2001). In the first few time periods, most of the capital is fixed and used only in the X block. In later decades, as fixed capital depreciates and is replaced by flexible capital, a higher proportion of the capital available in the model is flexible and can be used in the Y or Ya blocks. This distinction between fixed and flexible capital allows for more structural change of the modeled economy in later decades. Models that have this ability to differentiate between fixed and flexible capital are often referred to as “putty-clay” models.

Firms, which are represented by the Y production block, use the inputs of factors and intermediate goods and services to produce output. Figure 2.3 shows the nesting structure of the constant elasticity of substitution (CES) production function with all the inputs at the ends of branches and the sectoral production output at the top of the figure. The inputs to Y include: factors of land, natural resources, flexible capital and labour; coal, natural gas and refined petroleum products (RPP) with associated carbon permits; and non-carbon emitting goods and services like non-energy commodities and electricity. The output of this block is the sectoral production of the commodity produced by each individual sector, for example, natural gas is the output of the GAS sector.

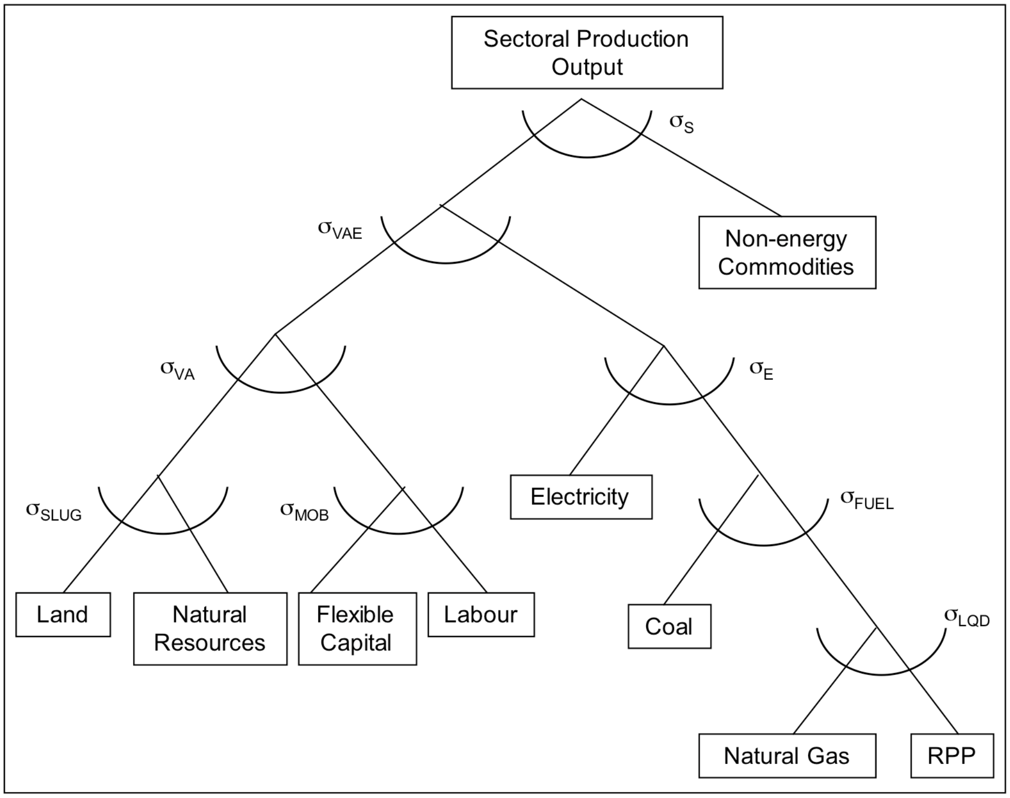



**Figure 2.3 Nesting Structure for Elasticities in Y Production Block**

In Figure 2.3, the elasticities of substitution (ESUBs), which embody the ability of available technologies to use various proportions of inputs, are represented by the symbol, $\sigma$, with subscript labels. Starting at the top of the figure, the ESUB between non-energy commodities and the combined bundle of energy commodities and factors is $\sigma_S$. $\sigma_{VAE}$ is the ESUB between factors and energy commodities. In the left branch of the figure, $\sigma_{VA}$ is the ESUB between sluggish and mobile factors. $\sigma_{SLUG}$ is the ESUB between land and natural resources and $\sigma_{MOB}$ is the ESUB between flexible capital and labour. The right branch of the figure shows the energy inputs, where $\sigma_E$ is the ESUB between electricity and fossil fuels. $\sigma_{FUEL}$ is the ESUB between coal and liquid fossil fuels and $\sigma_{LQD}$ is the ESUB between natural gas and RPP.

The conventional production in the X block is very similar to that in the Y block with a couple of differences. The first is that X uses fixed capital instead of flexible capital as an input. The second difference is that the ESUB values in X are assumed to be zero because the X block represents installed capital, which I assume cannot alter the inputs it requires. The output that the firms represented by the X block produce is the same as the sectoral production output by the firms represented by the Y block.

The alternative electricity production sector, Ya, allows for the optional use of carbon capture and storage (CCS) in the electricity sector. By allowing for CCS in Ya, approximately 85% of carbon emissions from the sector's fuel use are captured and stored and I include this in the model by making the Ya block generate carbon permits for all captured carbon emissions. This alternative electricity sector allows the model to use CCS technologies if a policy makes the cost of emitting high enough that they become economically feasible. This sector represents CCS technologies, which are divided into three steps that have limited amounts of available capacity. The first two steps represent lower and higher cost estimates for CCS technologies that use fossil fuels and the third step represents CCS using biomass as feedstock. As a policy increases the cost of emitting, the model will shift toward the allowed capacity to produce electricity with CCS, starting with the cheapest step and then moving to the more costly steps.

This alternative electricity production block, Ya, generally has the same input and output requirements as conventional electricity production, Y, with a couple of additional requirements. These are PQ(r,j,s), which is the quantity of CCS allowed and land resources, which are required by the biomass step to simulate the land supply constraints of using biomass feedstock. While the alternative electricity sector requires most of the same type of inputs as the conventional electricity sector, it requires more capital and fuel than the conventional sector. The additional output is PCARB(r), which is the carbon permits for the stored emissions and the other output of Ya is electricity, which is the same output as the conventional electricity-producing sector. The alternative electricity sector produces electricity and carbon permits in fixed proportions.

The situation with the ESUBs in the alternative electricity-producing sector is different from the conventional electricity production sectors. The structure of the nested elasticities is similar to that of the conventional Y sectors (Figure 2.3) but most of the ESUBs in Ya are set to zero. The exceptions are fossil fuel related ESUBs which have the same values as in Y. These ESUBs are necessary because Ya represents technology steps involving CCS; however, the first two steps are amalgamations of multiple types of electricity production plants that use coal, natural gas or refined petroleum products to produce electricity with CCS. The initial proportions for the use of each type of fuel are the same as in the business-as-usual data, but as prices change in the policy runs, the ESUBs allow for shifting between fuels used in the technologies in Ya. The ESUBs between energy and factors and between capital and labour are set to zero because I assume the proportions of capital required in the CCS technologies are fixed.

The alternative electricity-producing sector, Ya, requires technical data, such as the required increase in capital and fuel and the amount of required biomass, to represent electricity production using CCS technologies. In the model, the percent increase of capital required by the CCS technologies ranges from 42% to 80% and the percent increase of required fossil fuel ranges from 17% to 30% in the first two CCS steps. These ranges for capital and fuel use mark-ups are based on high and low estimates of CCS technology costs from the IPCC (IPCC, 2005). The mark-up of capital for biomass CCS is based on the estimate that the cost will be double that of conventional CCS (IEA, 2006; Reilly and Paltsev, 2007). I used land as a proxy for biomass feedstock because VERITAS-US does not track biomass. Reilly and Paltsev (2007) estimated that land makes up a proportion of 19% of the total dollar value of inputs required for biomass CCS and I used this estimation in my approximation of biomass CCS technologies.

The amount of emissions that are captured is also an important part of representing the CCS technologies. I assume that 85% of carbon emissions from the fossil fuels combusted are captured (IPCC, 2005). The amount of emissions captured by the biomass CCS step is more complicated as land is used as an approximation for biomass feedstock. The amount of carbon emissions captured by biomass CCS is based on tonnes $CO_2$ stored per dollar of electricity output. I used the value of 0.0007 Mt per dollar of electricity output, which is an estimate from Rhodes and Keith (2005) where they assume that the production, harvest and transport of the biomass feedstock does not produce emissions.

The capacity of the alternative electricity-producing sector is also important. The amount of CCS electricity that the model can produce in 2020 and 2030 is set equal to the business-as-usual (BAU) electricity production, with the capacity equally divided between the three steps. While the capacity is available, the model only uses the CCS steps if they are economically feasible. In 2040 and 2050, the available capacity of the alternative electricity sector, Ya, is set to 120% of the BAU electricity use to allow for fuel switching to electricity in transport, buildings and industry as the planet reduces carbon emissions. These assumptions seem reasonable given the International Energy Agency's estimates for the storage potential for geological sequestration of $CO_2$ (IEA, 2006).

As industry learns more about CCS and the scale of power generation units increases over time, there will likely be a decrease in cost of technologies for electricity production with CCS. To represent this decrease in costs because of learning and economies-of-scale, I reduce the capital and fuel requirements by 40% for the time periods after 2030, which is based on estimates of Al-Juaied and Whitmore (2009).

Representing CCS in a static model is difficult because it does not track capital stock built in previous time periods. The range of mark-ups in capital and fuel use for the first two steps of CCS technologies is meant to represent the increasing costs of CCS as the most ideal sites for CCS are used up. However, in VERITAS-US both steps are available in each time period in which the model is run. It would be more realistic if the most ideal sites were used in the earlier years and then the less ideal sites were used later. This type of tracking of sites could be better represented in a dynamic model because the sites that would be used in early years would not be available in future years.

### 2.3.2 International Trade Blocks

There are three production blocks that involve internationally traded commodities. These blocks, DOMEX, IMP and A, in Figure 2.2 form the links between the regions through imported and exported goods.

The DOMEX production block takes the domestically produced commodities, i.e. the sectoral production from Y, X and Ya if it is used, and splits them into two outputs. One output is commodities for export, PX(r,rr,i), and the other is commodities for domestic consumption, PD(r,i). This block has two distinct outputs as I assume that they are not perfect substitutes and that there is a degree of substitutability between them.

When a production block has more than one output, the production function requires a way to relate how the proportions of outputs can potentially be altered. The substitutability of the two outputs is related by an elasticity of transformation, which is similar to an elasticity of substitution, but is used to describe trade-offs between outputs of a production function, whereas the elasticity of substitution relates substitutability between the inputs to a production function. Figure 2.4 shows how the substitutability of the two outputs of the

DOMEX production block is represented by an elasticity of transformation, $\sigma_{DOMEX}$.

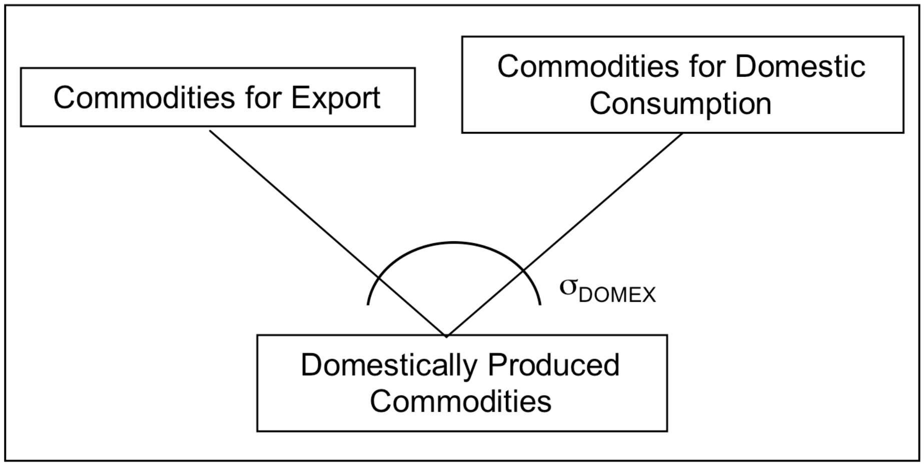



**Figure 2.4 Nesting Structure for Elasticities in DOMEX Production Block**

The IMP block is a simple production block that transforms exports into imports. It takes the goods that are exported from one region, PX(rr,r,i), and converts them into imports, PM(r,rr,i) in the other region. The costs associated with transportation of internationally traded goods are included in the incoming exports, PX(rr,r,i). This block has only one input and one output, so elasticities of substitution or transformation are not necessary.

The A production block is the Armington aggregator, which amalgamates imported commodities, PM(r,rr,i), and domestically produced commodities, PD(r,i), into Armington aggregated commodities for domestic consumption, PA(r,i). Both final demand of consumers and intermediate inputs to sectoral production are uses of the Armington aggregated goods and services. This aggregation is based on the assumption that foreign and domestic goods of the same product type are not perfect substitutes for each other because they are produced in different places (Armington, 1969). Figure 2.5 shows how the inputs in the A production block are related by an Armington elasticity of substitution, $\sigma_{ARM}$. The inputs, which are shown at the bottom of the figure, are the imported foreign commodities and domestically produced commodities.

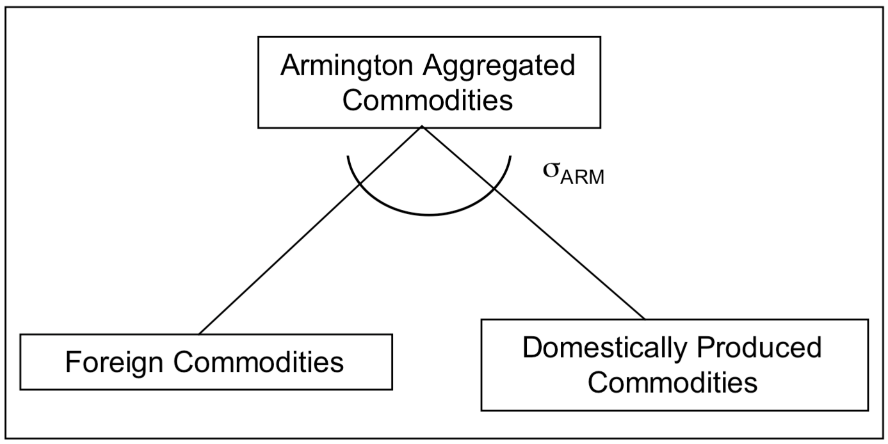



**Figure 2.5 Nesting Structure for Elasticities in Armington Block**

### 2.3.3 Carbon Emission Permits

If there is a policy that requires carbon emission permits, the CARB production block, in Figure 2.2, allocates the permits to carbon-emitting fossil fuels. It takes in fossil fuels that emit carbon, PA(r,fe), and carbon emission permits, PCARB(r), and outputs fossil fuels with attached emissions permits, PAC(r,fe). The elasticity of substitution between the two inputs is zero because the proportion of inputs cannot change; each unit of carbon-emitting fuel must have a permit for the carbon emissions it will release when combusted.

### 2.3.4 Consumption Blocks

The two blocks, C and CON, represent the activity of commodity consumption and the demands of the representative consumer.

The C production block, in Figure 2.2, amalgamates all the goods and services that consumers use into one uniform consumable good with one corresponding price. The inputs include non-emitting goods and services for domestic consumption, PA(nce), and fossil fuels with carbon permits, PAC(r,fe). The output is an aggregate good for consumption, PC(r).

The nesting structure that relates the inputs and ESUBs in the C production block is shown in Figure 2.6. At the top of the figure, $\sigma_S$ represents the ESUB between energy and non-energy commodities. On the non-energy commodity branch, $\sigma_C$ represents the ESUB between the different non-energy commodities. The left branch of the figure shows the energy commodities, where $\sigma_E$ represents the ESUB between refined petroleum products (RPP) and the other energy forms commonly used in households. $\sigma_{HOU}$ is the ESUB between the inputs of electricity and natural gas.

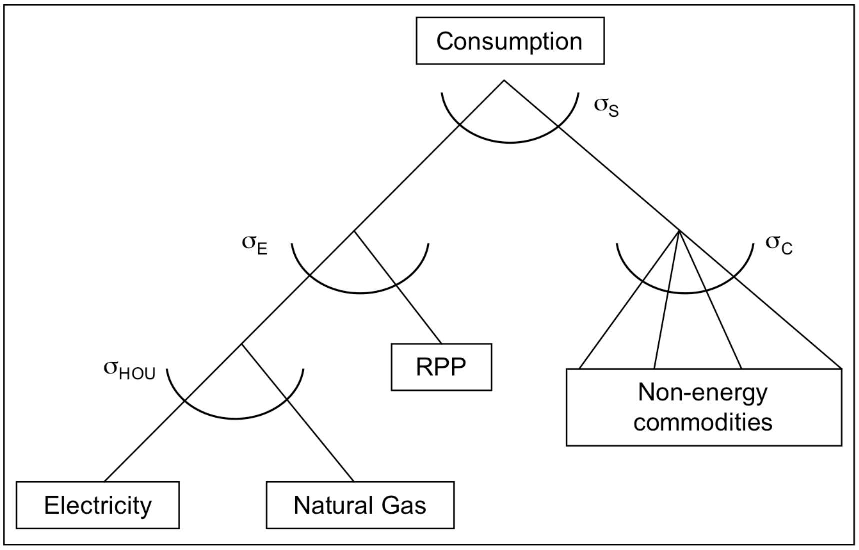



**Figure 2.6 Nesting Structure for Elasticities in C Production Block**

The CON block is a demand block and is different from the production blocks described previously. Instead of inputs and outputs, the demand block is made up of demands and endowments of various kinds. As shown in Figure 2.2, the consumer demands goods and services for consumption in the form of PC(r). There are multiple endowments, which may change depending on the features that are used in a specific simulation. First, the consumer is always endowed with factors of labour, capital, land and natural resources, PF(r,f), and these do not change when a policy is implemented. This means that consumers will work the same number of hours before and after a policy. Second, if there is a difference between the value of exports and imports in a region, then the consumer is endowed with this difference in the form of PC(r); the quantity of this endowment is called BOTDEF in the model code and Figure 2.2. This endowment of BOTDEF makes it so the balance of trade is fixed for each region even when a policy is simulated. Third, if there is a policy that creates carbon permits, PCARB(r), then the consumer is also endowed with these. Fourth, if the alternative electricity production block is in operation, then the consumer is also endowed with PQ(r,j,s), which limits the quantity of electricity that can be produced by the sector. Finally, I can also use endowments as a way to transfer funds between regions. For example, if a policy requires funds for international support of clean technology development or adaptation aid, an amount of PC(r) can be transferred from the US representative consumer, as a negative endowment, to the ROW representative consumer, as a positive endowment.

I made some assumptions when modelling the representative consumer in VERITAS-US. First, I assume that investment is incorporated in consumers' final demand. Second, I assume that the CON block portrays one representative consumer, which represents the government and households since VERITAS-US does not explicitly model government. Third, VERITAS-US does not explicitly model taxes, so tariffs and subsidies on imports and exports need special treatment. Government would normally collect tariffs and provide subsidies, but because I do not have a separate government in the model, I allocate the import tariffs, as positive endowments, and the export subsidies, as negative endowments, to the representative consumer.

### 2.3.5 Additional Features

There are two additional options in the model beyond the main model structure I have described. These are the options of (1) running the model in a global or regional mode and (2) having output-based allocation of revenue to industry. I describe each option in turn below.

### Global and Regional Modes

This option of running VERITAS-US in global or regional modes changes how the targets for emission reductions are set and whether international trading of permits is allowed. It makes it possible to address the question of how acting alone or acting in concert with other regions (by allowing trading of emission permits with other national or regional trading systems) could affect the impacts of policies.

The main differences between the global and regional modes stems from how emission reduction targets are set and whether each region has a unique carbon permit price. In the global mode, one emission reduction target is set for the world and, because trading of permits between regions is allowed, there is one global price for carbon permits. The regions are given individual reduction targets based on an allocation parameter, which allows the modeller to allot a percent of the global target to each region. This allocation parameter has a direct effect on the economic impact of a policy in each specific region. In the regional mode, the emissions reduction targets are set for each region individually and they must meet the targets alone. Because permits are not traded between regions, a unique price for carbon permits is calculated for each separate region.

### Revenue Recycling and Permit Allocation

Revenue recycling and permit allocation are important topics in the design of cap-and-trade policies to reduced GHG emissions because of the high value associated with the emission permits. In a typical run in VERITAS-US, the total value of the permits used in the US can be on the order of hundreds of billions of dollars. There are many options for how this value could be distributed and they affect the policy’s impacts. Central to the discussion of emissions permits are issues such as: will the permits be auctioned and if so how many, what will be done with the auction revenue, will the permits be given away for free and if so to whom.

If the permits are auctioned, there are multiple ways that the revenue can be used to help mitigate the impacts of the policy. For example, revenue could be used for reducing income tax or other taxes, to promote research and development or to encourage use of alternative technologies. Another option is to give the revenue to consumers as direct dividends to help mitigate the cost of a policy and address the distributional impacts between different income groups. This revenue allocation method has been referred to as ‘cap-and-dividend’ or a ‘sky trust’ (Boyce and Riddle, 2007; Burtraw et al., 2009).

Another option is that the revenue or permits could be given to industry using multiple distribution alternatives. One common example, grandfathering, is a method of allocation where permits are given out for free, based on the amount of emissions an industry or firm produced in the past. Output-based allocation is another common distribution method where permits or the revenue from the policy are allocated to firms in proportion to their output, which essentially subsidizes production (Bernard et al., 2007).

When thinking about the value of emissions permits and how it could be distributed, there are two main methods (1) auctioning the permits and distributing the revenue or (2) giving away the permits for free. Most likely climate change policies will be a combination of distribution of free permits and revenue from auctioned permits, with a shift towards all the permits being auctioned in the later years of a policy. In the rest of this study, I refer to revenue recycling as the distribution of revenue from auctioned permits because my model does not distinguish between giving away a number permits or giving away revenue from the sale of the same number of permits.

VERITAS-US has the option to recycle revenue to specific sectors, as output-based allocations, or to the consumer, as a direct dividend. The total amount of revenue available to recycle in the model is based on the total number of permits available in a given year and the value of those permits. In the model, any revenue that is not specifically designated to industry sectors is given to the consumer. In reality, the government, not the consumer would receive this money and use it to provide either government services or direct payments to consumers; however, in my model this amounts to the consumer receiving the funds directly.

In VERITAS-US the revenue recycling option allows the modeller to choose the proportion of revenue to be allocated to each sector and it is distributed among the firms as a subsidy per unit output. This gives individual firms an incentive to increase output to receive more of the subsidy. However, this incentive is balanced out in the model because the total amount of revenue that is distributed to the entire sector does not change, thus if total sector output increases, the amount of subsidy per unit of output decreases.

## 2.4 Parameter and Data Sources

Now that I have described the core structure of the model, I discuss the parameters and data I used in VERITAS-US. The main data requirements of VERITAS-US are for constructing social accounting matrices (SAMs) and both historical and forecasted amounts of fossil fuel use. The main parameter requirements are elasticities of substitution and elasticities of transformation. I discuss the data sources and the data treatment in the following sections.

### 2.4.1 Social Accounting Matrix Data

SAMs form the bulk of data necessary for a CGE model and the aggregation level of the data in the SAMs also shapes part of the model's structure. I used the Global Trade Analysis Project (GTAP) database Version 7, which is developed at Purdue University, as a basis for constructing the regional SAMs (Center for Global Trade Analysis, 2001). To do this I took the database and aggregated it into the regions and sectors described earlier and then constructed SAMs for the US and ROW. The two regional SAMs are linked through international trading; for example, the exports from ROW to the US are the exact value of imports to the US from ROW. These SAMs are for the year 2004, which is the year that GTAP Version 7 is based on.

VERITAS-US is a static model that runs in one time period, so to use the model to analyze policies to 2050, I set it up to run in multiple separate time frames. For this approach, I need a SAM for each region in each year I plan on running the model. I used the SAMs for 2004 that I made from the GTAP database and extrapolated them to 2010, 2020, 2030, 2040 and 2050 by using forecasted economic growth rates. For the US SAMs, I used the annual economic growth rate of 2.4% and for the ROW SAMs I used 3.5% (EIA, 2009a). Both of these projections were for 2006 to 2030, but I used the same rates to extrapolate to 2050. While extrapolating the SAMs, I also altered the data by including an autonomous energy efficiency index (AEEI) parameter of 1.1 for both regions. The MIT-EPPA model uses this AEEI value for six of their regions including ROW and other models tend to use AEEI values in the range of 0.5 to 2 (Azar and Dowlatabadi, 1999; Babiker et al., 2001; Bataillie et al., 2006; Grubb et al., 2002). I included the AEEI effects by reducing the amount of energy used as an input in the SAMs, while the output remains relatively constant.

By using two different economic growth rates to extrapolate the regional SAMs into future years and the AEEI parameter to reduce energy intensity, I created a problem with how the SAMs balance with respect to trade interactions and the three equilibrium conditions of market clearance, income balance and zero profit. Because of the two different economic growth rates, the trade interactions of imports and exports between regions are not balanced and the AEEI adjustment made the rest of each SAM unbalanced. There are multiple methods available for re-balancing individual SAMs that have been extrapolated, for which Fofana et al. (2002) provide a good summary. However, the problem with my SAMs was not just within the individual region's data, but also with the trade data that links the two regions.

To solve the issues with unbalanced SAMs, I used a GAMS-based program that balances SAMs by taking into account the three conditions for economic equilibrium (market clearance, income balance and zero profit) and by minimizing the sum of squared deviations between the original SAM and the new balanced SAM.[3] I recoded the program to make it compatible with my data and model format and added a constraint to balance the international trade between regions.

### 2.4.2 Fossil Fuel Forecasts

The carbon accounting in VERITAS-US is based on the physical quantities of fossil fuels that each region uses in a given year. The amount of regional $CO_2$ emissions are calculated from the quantity of fossil fuel consumed in a region multiplied by a carbon intensity value, which is a measure of $CO_2$ emitted per unit of fuel. The physical amount of fossil fuel is necessary because the data in the SAMs are in dollar values not physical quantities.

The fossil fuel use data and forecast that are in the model are from the US Energy Information Agency (EIA). The historical data on the quantity of fossil fuels used by the US in 2004 are from the Annual Energy Review (EIA, 2009b). The 2004 fossil fuel use for ROW is from the EIA's International Energy Annual (EIA, 2008). The forecasts of US fossil fuel use are from the Updated Annual Energy Outlook, which forecasts to 2030 (EIA, 2009c). The ROW fossil fuel forecasts to 2030 are from the International Energy Outlook (EIA, 2009d). I used these forecasts to extrapolate fossil fuel use in both regions for 2040 and 2050.

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[3] I thank Nic Rivers and Jotham Peters for the use of their SAM balancing program.

### 2.4.3 Elasticities of Substitution

Elasticities of substitution and transformation are important parameters in CGE models as they influence how inputs or outputs of production and utility functions are substituted for one another through various technologies and consumer preferences. The ability to substitute inputs or outputs is influential in estimating the potential cost of a policy to society and so robust estimates of these parameters are very important when trying to evaluate different policies (Böhringer, 1998; Jaccard et al., 2003). As the results of a simulation can be very dependent on the elasticity values, I include a sensitivity analysis of them in the Results section.

In many global CGE models, the same ESUB values are used for all the regions and sectors (Babiker et al., 1997, 2003; Böhringer and Rutherford, 2002; Kallbekken, 2004). However, given the importance of ESUBs in CGE models, global modelers are beginning to use some region and sector-specific ESUBs (Paltsev et al., 2005; Burniaux and Truong, 2002). The ESUB values found in the literature are sometimes estimated from historical data, but they are frequently chosen based on expert judgment (Bataille et al., 2006).

I attempted to find regional and sector specific ESUBs for use in my model and the elasticities I use in VERITAS-US are summarized in Table 2.2, Table 2.3 and Table 2.4. Many of the elasticities I use are based on the literature, as shown by the sources in the summary tables, but where possible I use CIMS-based elasticity values.

The CIMS-based values of elasticities in VERITAS-US provide an alternative to those values in the literature that are based on expert judgment and historical data. They have the benefit of capturing the numerous technologies and behavioral parameters in the CIMS model, as well as being regionally specific. Where possible, the ESUBs for the US region in VERITAS-US are from US CIMS and the ROW ESUBs are informed by values from US CIMS and Canada CIMS.

The process to calculate ESUBs from CIMS, described by Bataille (2005), involves two main steps. The first involves running the CIMS model many times with different prices for natural gas, refined petroleum products, coal, electricity and the value-added component, which is comprised of capital and labour. This process yields a large quantity of data, which capture the various sectoral responses to changes in the price of the variables listed above. These data are used in the second step, which is to estimate ESUB parameters for nested constant elasticity of substitution (CES) production and utility functions. The Energy and Material Research Group at Simon Fraser University is still improving the US CIMS model and plans to explore and verify the methods used for extracting ESUBs from CIMS models.

There are several steps in the process of generating the necessary data from CIMS. First the model must be prepared by disabling the cogeneration and CCS technologies as these disrupt the data. Also, electricity production using CCS is represented as a separate sector in the CGE model, so including this in the data used to calculate ESUBs for the conventional electricity sector would not be logical. I ran the US CIMS model 243 times with various combinations of prices. The range of energy prices, in $/GJ, used are as follows: natural gas: 6, 11, 16; RPPs: 15, 22, 29; coal: 1.5, 11, 20.5; electricity: 20, 42.2, 64.4. For the value-added component I used a price range of 90%, 100% and 110% of the original price.

The program I used to estimate the ESUBs is written in the R language and determines the ESUB parameters for the CES functions based on the data from the CIMS model. For the mathematical details of this method refer to Rivers (2009).[4] I used this program as written for the production function ESUBs. For the utility function ESUBs, I altered the nesting structure in the program to match the structure used in my CGE model.

[4] I thank Jotham Peters and Nic Rivers for their help and the use of their programs for this ESUB calcuation process.

**Table 2.2 Elasticities of Substitution for Production Functions**

| Elasticity | US | Source | ROW | Source |
|---|---|---|---|---|
| between intermediate inputs and factors/energy, $\sigma_S$ | 0 | Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 | 0 | Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 |
| between non-energy intermediate inputs | 0 | Kallbekken 2004; Paltsev et al. 2005 | 0 | Kallbekken 2004; Paltsev et al. 2005 |
| between factors and energy, $\sigma_{VAE}$ | 0.45 - 0.6 | US CIMS; Babiker et al. 2003; Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 | 0.45 - 0.6 | US CIMS; Babiker et al. 2003; Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 |
| between sluggish factors and mobile factors, $\sigma_{VA}$ | 0 | | 0 | |
| between natural resources and land, $\sigma_{SLUG}$ | 0 | | 0 | |
| between capital and labour, $\sigma_{MOB}$ | 0.2 - 1.7 | Badri and Walmsley 2008 (GTAP) | 0.2 - 1.7 | Badri and Walmsley 2008 (GTAP); |
| between fuels and electricity, $\sigma_E$ | 0.475 - 1.01 | US CIMS; Babiker et al. 2003; Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 | 0.28 - 1.8 | CIMS; Babiker et al. 2003; Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 |
| between coal and liquid fuels, $\sigma_{FUEL}$ | 0.415 - 3.95 | US CIMS | 0.415 - 2.17 | CIMS; Babiker et al. 2003; Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 |
| between liquid fuels (RPP and natural gas), $\sigma_{LQD}$ | 0.28 - 5.85 | US CIMS | 0.99 - 2.99 | CIMS; Böhringer and Rutherford 2001; Kallbekken 2004; Paltsev et al. 2005 |

Note: For the values that are given as ranges, find sector specific values in Appendix C.

As shown in Table 2.2, I use the CIMS-based ESUB values where possible, especially for those related to energy. For the ESUB between factors and energy, $\sigma_{VAE}$, I used CIMS-based ESUB values for the sectors where CIMS represents the factors more accurately. However, for some of the sectors, CIMS does not represent the factors as accurately, so I used ESUB values that were an average of those from the referenced models. For the ESUB between fuels and electricity, $\sigma_{E}$, I used the US CIMS-based values directly where possible for the US and the CIMS-based values for ROW. However, for some sectors, including refined petroleum products and transportation, the ESUB calculations produced nonsensical values and for these I used an average value from the models referenced. The range of the $\sigma_{E}$ values from the other models was 0.1 to 1, with multiple values near 0.4 to 0.5. For the ESUBs between coal and liquid fuels, $\sigma_{FUEL}$, and between RPP and natural gas, $\sigma_{LQD}$, I used the US CIMS-based values for the US. For these ESUBs in the ROW region I used CIMS-based values, but for the sectors that had lower values than the other models I surveyed, I used the average of the ESUBs from those models, which were between 0.5 and 1 for $\sigma_{FUEL}$ and between 1 and 2 for $\sigma_{LQD}$.

As shown in Table 2.3, I used US CIMS-based values for the ESUBs between RPP and household fuels, $\sigma_{E}$, and between natural gas and electricity, $\sigma_{HOU}$, for the US region. In the ROW region for $\sigma_{E}$, I used an average of the CIMS value and those from other models as the CIMS value is based on Canada and the others are from international models. These other models had values between 0.3 and 0.4 for $\sigma_{E}$. I used the CIMS-based ESUB, $\sigma_{HOU}$, for the ROW region because the other models do not use the same CES nesting structure, thus I could not use them to adjust the Canada-based value.

**Table 2.3 Elasticities of Substitution for Utility Function**

| Elasticity | US | Source | ROW | Source |
|---|---|---|---|---|
| between non-energy commodities and energy, $\sigma_S$ | 0.52 | Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 | 0.52 | Böhringer and Rutherford 2002; Kallbekken 2004; Paltsev et al. 2005 |
| between non-energy commodities, $\sigma_C$ | 0.87 | Kallbekken 2004; Paltsev et al. 2005 | 0.65 | Kallbekken 2004; Paltsev et al. 2005 |
| between rpp and household fuels, $\sigma_E$ | 0.527 | US CIMS | 0.41 | CIMS, Kallbekken 2004; Paltsev et al. 2005 |
| between natural gas and electricity, $\sigma_{HOU}$ | 1.66 | US CIMS | 1.23 | CIMS |

**Table 2.4 Elasticities for Import and Export**

| Elasticity | US | Source | ROW | Source |
|---|---|---|---|---|
| between production for domestic and export markets, $\sigma_{DOMEX}$ | 2 | Böhringer and Rutherford 2002 | 2 | Böhringer and Rutherford 2002 |
| between domestic and foreign produced goods for domestic consumption, $\sigma_{ARM}$ | 0.3 - 10 | Burniaux and Truong 2002; Gallaway 2003; Paltsev et al. 2005; Saito 2004 | 0.3 - 10 | Burniaux and Truong 2002; Paltsev et al. 2005 |

Note: $\sigma_{DOMEX}$ is an elasticity of transformation and $\sigma_{ARM}$ is an elasticity of substitution. For the values that are given as ranges, find sector specific values in Appendix C.

## 2.5 Analysis

The previous sections describe how I built VERITAS-US. In this section, I describe the climate policy scenarios I analyze to meet the second research objective and answer my research questions.

In my analysis of the policy case described below, I focus on the potential cost of meeting the GHG emission reduction targets. This study is not a full cost-benefit analysis of the policy cases I simulate because I do not attempt to analyze any benefits that may be produced from the reduction of GHG emissions. The obvious benefit of reducing GHG emission is mitigating climate change, but there are other potential benefits like reducing local air pollutants, including particulates, from fossil fuel combustion.

### 2.5.1 Policy Simulation Cases and Assumptions

**Core Policy Case**

The main policy case I analyze is an approximation of the American Clean Energy and Security Act of 2009, based on my model's ability to represent various parts of the bill. I focus on Title III, the Reducing Global Warming Pollution portion of the bill and do not analyze the other four titles: Clean Energy, Energy Efficiency, Transitioning to a Clean Energy Economy, Agriculture and Forestry Related Offsets. Details about these other sections of the bill, which mandate standards and regulations (such as renewable electricity standards, clean transportation standards, building, lighting, transportation and industrial efficiency regulations, green job and worker transition regulations) can be found in the summary by Larsen et al. (2009a).

The Reducing Global Warming Pollution portion of the bill provides details for a mandatory GHG emission cap-and-trade system. The targets for this emission cap are based on reductions from 2005 emission levels and are as follows:

- 2012 - reduce emissions to 3% below 2005 (~12% above 1990 emission levels)
- 2020 - reduce emissions to 17% below 2005 (~4% less than 1990)
- 2030 - reduce emissions to 42% below 2005 (~33% less than 1990)
- 2050 - reduce emissions to 83% below 2005 (~80% less than 1990)

In the bill, these targets apply collectively to carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, perfluorocarbons and nitrogen trifluoride. Since my model currently only tracks carbon dioxide, I do not analyse the other GHGs. The bill assumes that by 2016, the cap covers approximately 84.5% of total US emissions. For my analysis, I assume that the cap covers 100% of the US emissions from fossil fuel use.

The American Clean Energy and Security Act has a detailed permit allocation scheme, which I represent in my model by grouping permit allocations into three categories that benefit: domestic consumers, domestic industrial sectors and other countries. Table 2.5 shows the proportion of the total permit value that I allocated to various sectors and the proportion of total US permit value that is allocated to the ROW region, based on the permit distribution in the bill. In reality, international allocation of funds would go to developing countries, but in my model this goes to the ROW region without distinction between developing and developed countries.

**Table 2.5 Carbon Permit Allocation for Core Policy**

| Year | Electricity Sector | Metal Industrial Sector | Non-Metal Industrial Sector | International Allocation (US to ROW) |
|---|---|---|---|---|
| 2020 | 35.5% | 3.7% | 9.7% | 7% |
| 2030 | - | 1.9% | 4.8% | 11% |
| 2040 | - | - | - | 10% |
| 2050 | - | - | - | 10% |

The values in the rows in Table 2.5 for each year do not add up 100% and the permit value that is not allocated to industrial sectors or for international aid is given to the consumers. The permit value given to the electricity sector is given as a subsidy on electricity output, with the goal of mitigating impacts of prices increases on the consumers. The other two industrial sectors were selected because they have the highest energy intensity in the 2004 model run. Energy intensity (i.e. energy use per unit of output) is one of the criteria that the bill uses to determine which sectors maybe impacted more and thus require extra aid in the form of free permit allocations. In the model, this is represented by output-based allocation of revenue, which essentially subsidizes the output of these sectors.

The reasoning behind allocating revenue to industry revolves around the issue of maintaining industry competitiveness and the uneven application of emission reduction policies. An international example is that if the US enacts a climate change policy that is more stringent than other counties, US industries may suffer from a lack of competitiveness compared to similar industries in the counties with less stringent emissions policies. The disparity in policy strength may also result in the carbon or energy-intensive industries moving to the counties with weaker emission policies, which is an example of 'carbon-leakage'. By subsidizing energy-intensive industrial production, the policy designers attempt to address these competitiveness and carbon-leakage issues (Bernard et al., 2007).

The bill also allows for the trading of emission permits with other regions that have similarly stringent cap-and-trade policies for GHGs. I included this in my model by allowing the US and ROW to trade emission permits. Because of this international trading, there is only one permit price for the whole globe in the core policy case.

There are other aspects of the bill's cap-and-trade system that I have not included in my analysis due to limitations in the model structure. For example, I do not include banking and borrowing of permits or a strategic reserve of permits as these would require a time component that is not part of the static modelling framework of VERITAS-US. I also do not include the effects of offsets because the model does not have the ability to simulate them.[5] However, offsets are an important issue and I address them briefly later in this report.

To run a policy analysis, I assume that the rest of the world will have climate policy that aims to reduce GHG emissions. I set the ROW emission reduction pathway so that each year they reduce the same percent from their business-as-usual (BAU) emission levels as the US. For example, in 2020, if the US reduces emissions to 21% below their BAU emissions, the ROW region will also reduce emissions by 21% from their BAU. Because ROW emissions grow faster than US emissions in the BAU case, ROW will not reach the same percent emission reduction below 1990 levels as the US. However, in this scenario the two regions reach a combined reduction of 65% below 1990 emissions levels by 2050. This is in the middle of the emission reduction range recommended for stabilizing atmospheric $CO_2$e at 450ppm, which scientists believe could keep temperature change below 2.0-2.4$^{o}$C (IPCC, 2007a).

The Clean Energy Jobs and American Power Act (Kerry-Boxer bill before US Senate) contains elements that are quite similar to the American Clean Energy and Security Act (Waxman-Markey bill passed by House of Representatives). One of the main differences, and the one that I test in my modelling of the core policy run for 2020, is that the Clean Energy Jobs and

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[5] An offset is an emission reduction credit that is often associated with cap-and-trade systems. An emitter that is not covered by the cap can reduce emissions and then sell the reductions to an emitter that is covered by the cap. For example, a farmer could change her land use practices to reduce her emissions and then sell the emission reduction credit to an electricity plant with the reduction counting towards the electricity plant's reductions. Essentially it involves the electricity plant paying someone else to reduce emissions instead of doing it themselves. The attractiveness of offsets is based on them being less expensive than the purchaser's emission abatement costs.

American Power Act proposes a slightly more stringent cap of 20% below 2005 by 2020. For a summary of this bill see Larsen et al. (2009b).

The next paragraphs describe alternate variations on this core policy case, which help define the impacts of revenue recycling to industry and international permit trading. In all three variations of the core policy, there is allocation of international aid from the US to ROW.

**No International Permit Trading** - In this variation of core policy case, trading of permits between regions is not allowed, so each region must meet their targets without trading permits with the other region. The emission pathway remains the same and there is output-based allocation of revenue to industry in both regions.

**No Revenue Recycling to Industry** - This variation has international permit trading like the core policy case, but there is no revenue recycling to industries. Essentially, this is like a cap-and-dividend system where all the permits are auctioned and the revenue is allocated to the consumers.

**No Revenue Recycling to Industry or International Permit Trading** - This variation of the core policy does not allow for international trading of permits, so again each region must meet their targets without trading permits outside of the region. This scenario also allocates all revenue to consumers in a cap-and-dividend manner and thus does not have revenue recycling to industries.

# 3: SIMULATION RESULTS

In this chapter, I present key results from the model simulations and Section 3.1 includes results from the business-as-usual (BAU) scenario. I present marginal abatement curves for the US in Section 3.2. In Section 3.3, I show the results from analysis of some current US legislation. Section 3.4 provides the results from a sensitivity analysis of the ESUBs and some parameters in the CCS sector. Throughout this chapter, I display results for the US, as it is the focus of this project and the ROW region in VERITAS-US is quite aggregated.

## 3.1 Business-as-Usual Simulation Results

The BAU simulation shows the model's representation of the economy if the regions continue on their current paths without GHG emission reduction policies. The data and assumptions in the data treatments described in Section 2.4 have a significant role in shaping the BAU simulation. The BAU is important as it gives a baseline that the scenarios with GHG emission reduction policies are compared against. The amount of $CO_2$ emissions a region produces and the gross domestic product (GDP) of a region are two measures that I use to compare BAU and policy simulations.

The $CO_2$ emissions in VERITAS-US are from the combustion of fossil fuels, with US emissions shown in Figure 3.1. These emissions are based on the fossil fuel use forecast from the Updated Annual Energy Outlook, so Figure 3.1

incorporates the impacts of the American Recovery and Reinvestment Act and recently changing macroeconomic environment (EIA, 2009c). The $CO_2$ emissions in the US increase at a rate of 0.36% per year from 2010 to 2050.

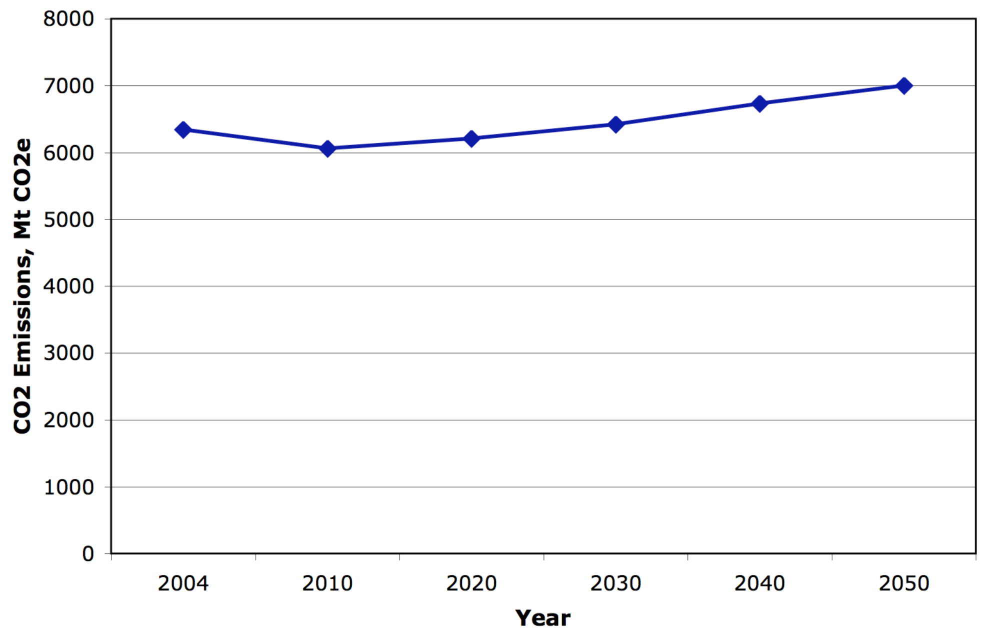


**Figure 3.1 US Business-as-Usual $CO_2$ Emissions**

In the BAU run of VERITAS-US, the $CO_2$ emissions from fossil fuel use in the ROW region grow from 22.76 Gt in 2004 to 46.05 Gt in 2050. This growth is equal to an average increase of 1.18% per year from 2004 to 2050.

The US GDP in the model's BAU run, shown in Figure 3.2, grows from 11.44 to 34.05 trillion 2004 US$ from 2004 to 2050. The average annual percent increase of GDP in the US during this period is 2.4%. The GDP of the ROW region in the BAU model run grows from 26.90 to 130.92 trillion 2004 US$ over the period of 2004 to 2050, which represents an average annual GDP increase of 3.5%.

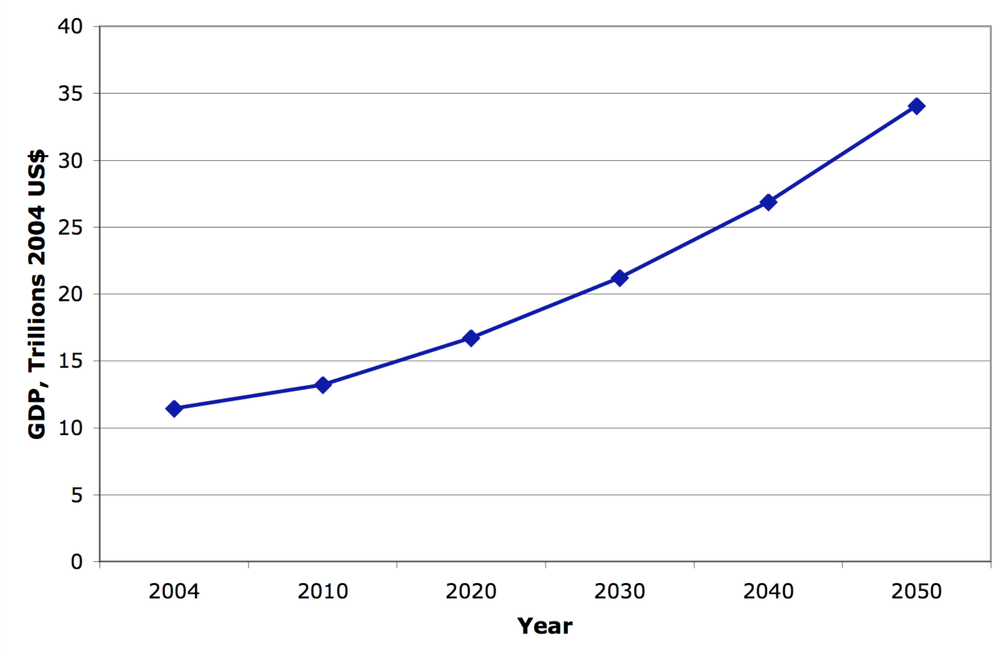


**Figure 3.2 US Business-as-Usual Gross Domestic Product**

## 3.2 Marginal Abatement Cost Curves

Marginal abatement cost (MAC) curves provide a visual representation of the relationship between emission reductions and the cost of carbon permits. Marginal abatement cost refers to the cost of reducing emissions by an additional unit. A MAC curve can be made by graphing the cost of a carbon permit against corresponding emission reductions for a given time and region (Morris et al., 2008).

While MAC curves can provide a simple visualization of the relationship between emissions reductions and permit prices, they can also be misleading, especially when used with multi-regional models. The curves are sensitive to conditions, for example policies, in the other regions in the model. They are also affected by the types of GHGs that are included in the model as inclusion of more types of GHGs expands the abatement opportunities, especially in the lower range of marginal abatement cost. Therefore, MAC curves should be used with caution, and only interpreted in the context of the specific policies applied when the model is run to generate a curve (Morris et al., 2008).

To create the MAC curves for the US in Figure 3.3, I assumed that ROW would also have a carbon abatement policy. In the curve for 2020, ROW is fixed at a reduction of 20.9% below the model BAU, while in the 2050 curve ROW is fixed at a reduction of 85.7% below the model BAU. These percent reductions are consistent with those used in the policy simulations in the rest of this report. Also, the model was set so there was neither revenue recycling to industry nor international trading of permits. By prohibiting international permit trading, we can see the marginal abatement cost of reducing emissions in the US specifically.

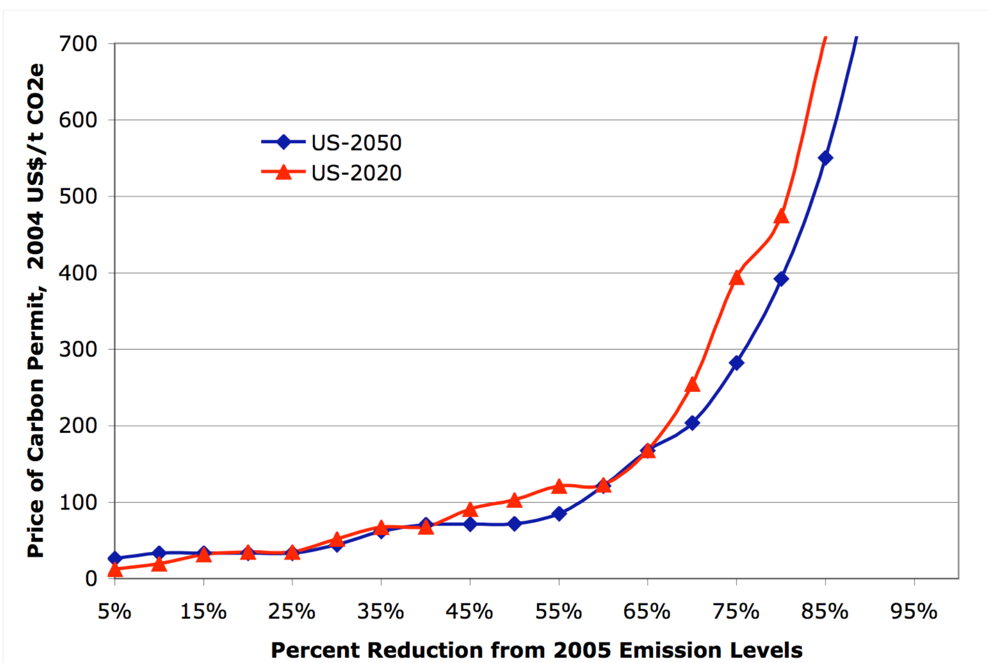


**Figure 3.3 US Marginal Abatement Cost Curves**

There are a couple of things to keep in mind with Figure 3.3. First, the emissions reductions are relative to 2005 emissions levels. Second, the emissions forecasted for 2050 are higher than the emissions forecasted for 2020. Therefore, the absolute amount of emissions that is reduced at each point on the 2050 curve is larger than the amount reduced at each point on the 2020 curve. This difference complicates a direct comparison; however, even though more reductions are required in the 2050 curve, the price of permits is generally equal to or less than the price in the 2020 curve. This is because in the 2050 run there is more flexible capital available, which makes the emissions reductions easier than they are in the 2020 run. Another trend that the MAC curves show is that the price of permits increases significantly at emissions reductions beyond 60% below business-as-usual. This indicates an increasingly higher cost for each additional unit of emissions reduction as the cheaper options are used up.

## 3.3 Policy Simulation Results

The emission reduction pathway for the approximation of the American Clean Energy and Security Act that I use in my analysis is shown in Figure 3.4. This shows the targets set out in the bill for 2012, 2020, 2030 and 2050. I assume a linear emissions reduction between 2030 and 2050, as the bill does not set a target specifically for the year 2040. This pathway does not take into account the offsets allowed in the bill.

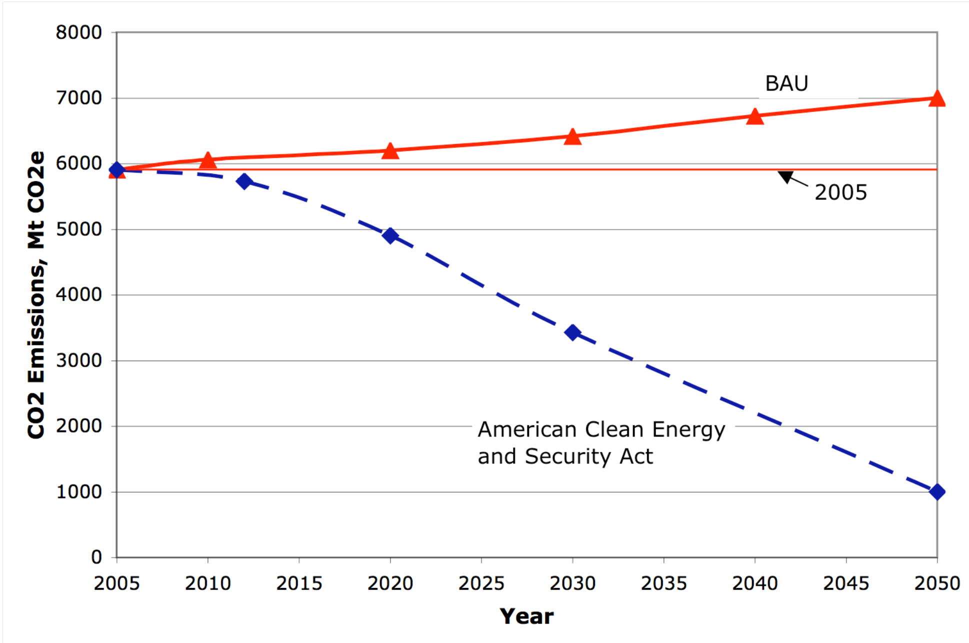


**Figure 3.4 US $CO_2$ Emission Reduction Pathway for the American Clean Energy and Security Act**

The carbon permit prices that result from this emission reduction pathway are shown in Figure 3.5. This figure only has one global permit price because international trading of permits is allowed. The price rises from 32 to 103 \$/ t $CO_2$e (2004 US \$) from 2020 to 2040. By 2050 the carbon permit price rises significantly to 357 \$/ t $CO_2$e as the deeper emissions reductions occur and options for abatement are used up.

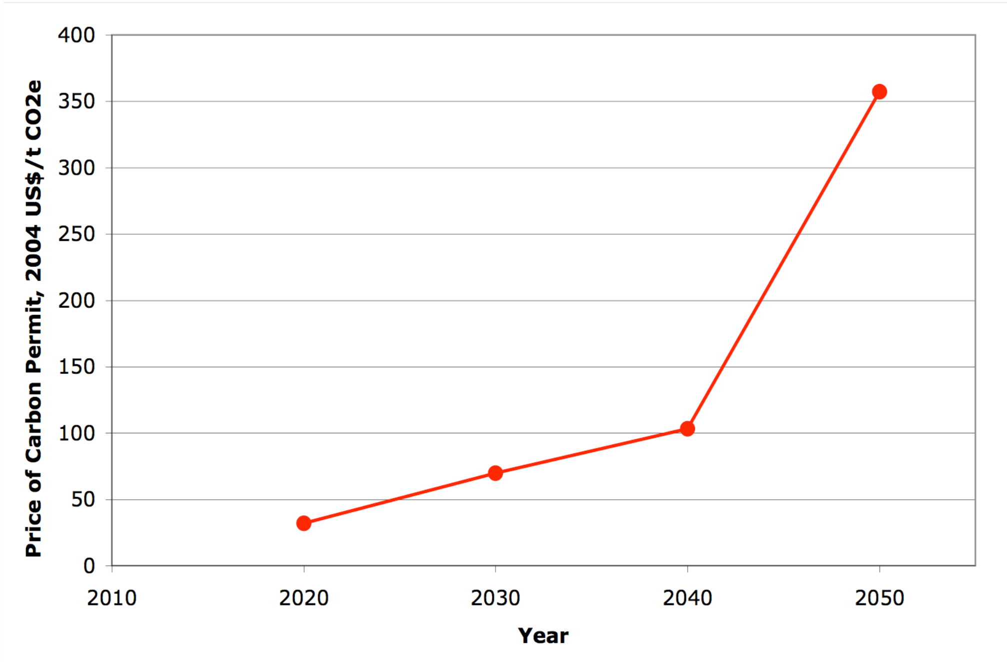


**Figure 3.5 Global Carbon Permit Price for Core Policy**

The Clean Energy Jobs and American Power Act (the Kerry-Boxer bill) has a slightly more stringent cap for 2020 than the core policy case. To demonstrate the effect of this bill's target for 2020, I also ran the core policy with a 20% reduction from 2005 in 2020. The carbon permit price for this run was 33 \$/ t $CO_2e$. This is an increase of 1 \$/ t $CO_2e$ over the permit price for the core policy case, which is my approximation of the American Clean Energy and Security Act.

Equivalent variation is a method I use to estimate the potential economic impact of the policy on consumers. This is a standard economic measure of consumer welfare, which is based on the assumption that a consumer acts optimally to maximize their welfare (this is an assumption that is prevalent in economic theory, but is not necessarily a true representation of reality). From this assumed optimal starting point, equivalent variation is an increase or decrease in income that would be necessary to produce the same consumer welfare level that the policy produces. In other words, the consumer would be indifferent to the new policy situation versus a new adjusted income. Figure 3.6 shows the percent change in US equivalent variation from the BAU situation because of the core policy. In 2020, there is a slight equivalent variation increase of 0.1%, which is likely related to international trading and the impacts of the different policy strengths in the US and ROW. The decreases in equivalent variation in 2030 and 2040 are -0.3% and -0.4%, and in 2050 the decreases is -1%. This means that in the BAU run for 2050, the consumer welfare was at 100% and in the policy run for 2050 it is at 99% of the BAU welfare.

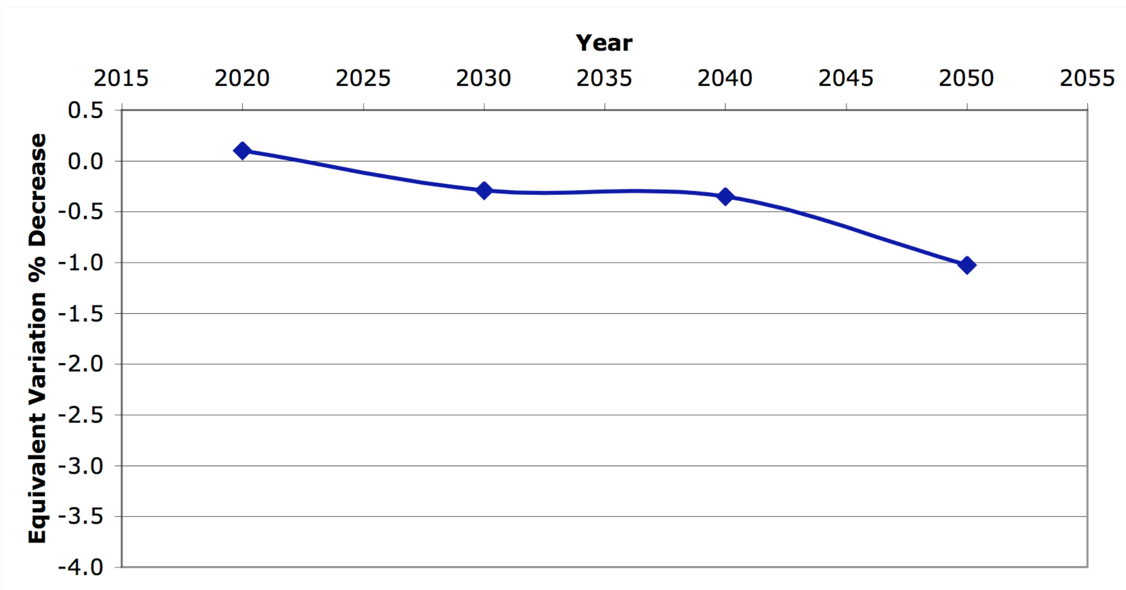


**Figure 3.6 US Equivalent Variation % Decrease for Core Policy**

Change in gross domestic product (GDP) relative to the BAU GDP is another way to measure the economic impact of a policy and Figure 3.7 shows the impact that the core policy could have on US GDP. In this report, I use a method of GDP calculation that includes the value of carbon permits as allowed in the Organization for Economic Co-operation and Development system of national accounts (OECD, 2008). The percent change in GDP is also relative to the BAU GDP for each year. The initial decrease in GDP for 2020 is moderate, at -0.6%. The GDP decrease stabilizes at -1.3 and -1.6% in 2030 and 2040, and by 2050 reaches -3.6%. Thus the BAU GDP in 2050 is 100% and the GDP in 2050 for the policy run is 96.4%. The percent change in GDP follows a similar trend to the change in equivalent variation, although the percentage GDP change is larger.

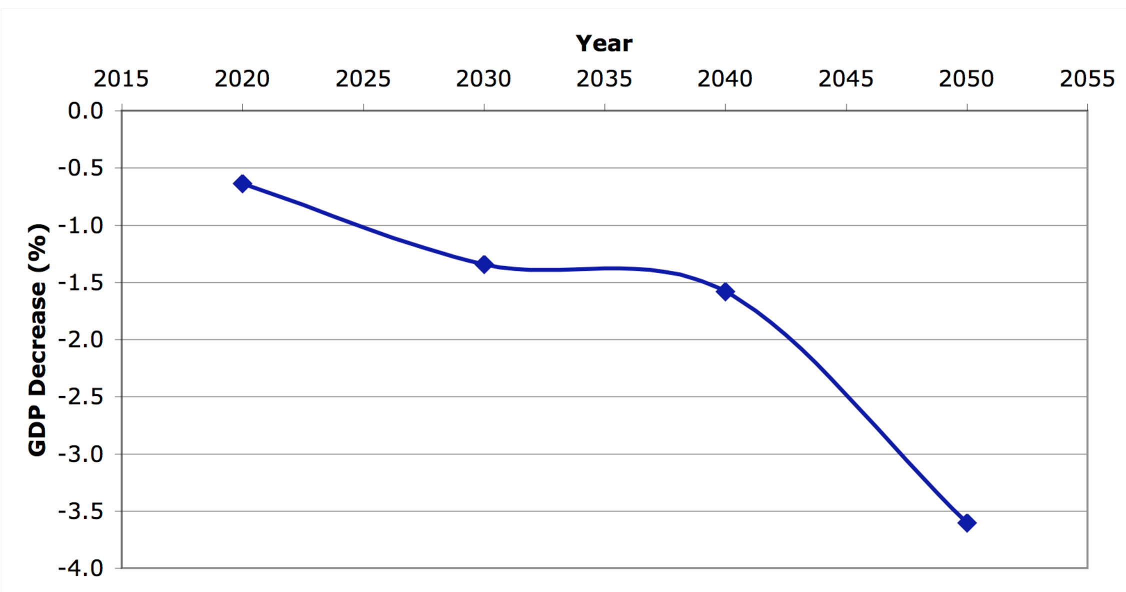


**Figure 3.7 US GDP % Decrease for Core Policy**

### Impact of International Trading

To demonstrate the impact of allowing carbon permit trading between US and the rest of the world, I contrast the core policy simulation with one that does not allow international carbon permit trading. The permit prices of both simulations are shown in Figure 3.8. When the US is not allowed to trade with ROW, the US permit price is comparable to the global price in 2020 and 2030. By 2040 the US price is about 30 \$/t $CO_2$e higher than the global price. In 2050 the US price is 484 \$/t $CO_2$e, which is 127 \$/t $CO_2$e higher than the global price of 357 \$/t $CO_2$e.

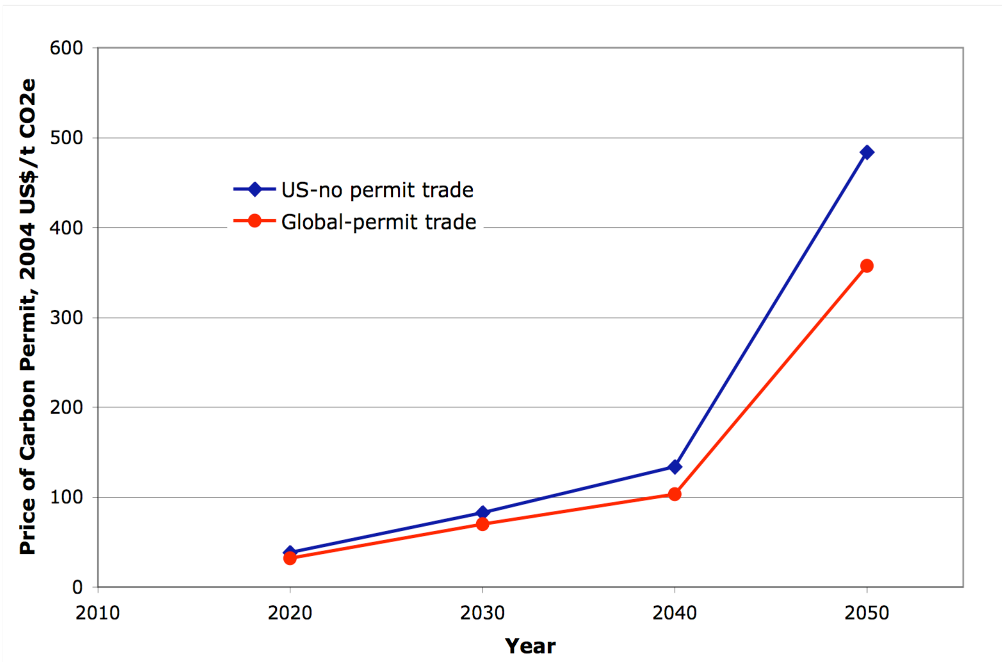


**Figure 3.8 Carbon Permit Prices With and Without International Permit Trading**

The welfare impacts of these policy cases are shown in Figure 3.9 and Figure 3.10 as percent change in equivalent variation and GDP. The percent change of equivalent variation in both cases follows a similar trend, although the case that involves trading of permits has a slightly larger percent decrease in equivalent variation. When permits are traded between regions, the values of percent change in equivalent variation are +0.1% for 2020 and -1% for 2050. Without permit trading, the values of percent change in equivalent variation for 2020 and 2050 are +0.2% and -0.8%.

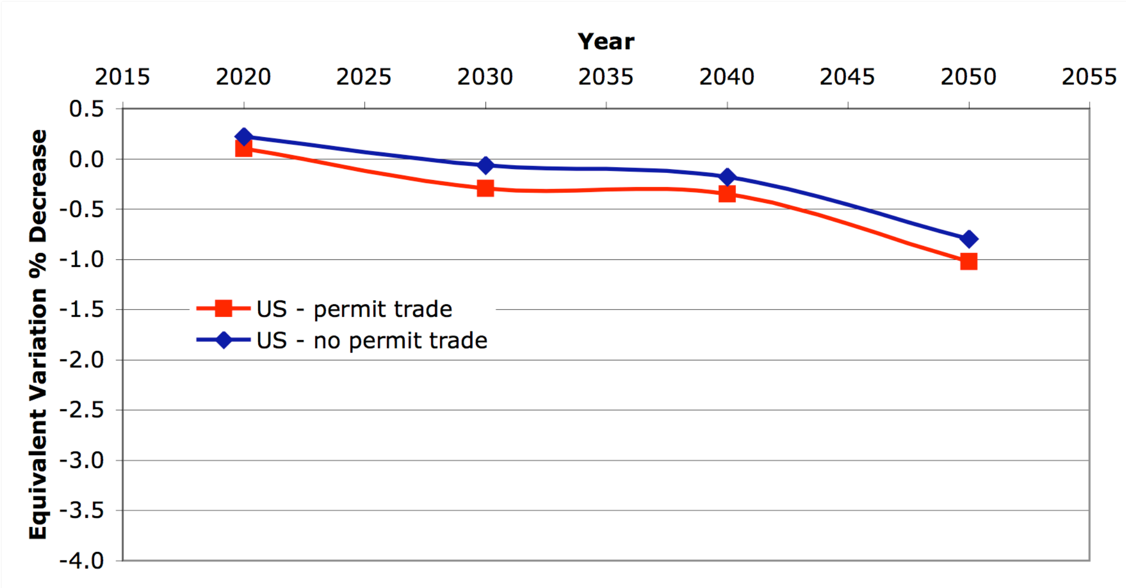


**Figure 3.9 US Equivalent Variation % Decrease With and Without International Permit Trading**

The percent decrease in GDP in the cases with and without international carbon permit trading (Figure 3.10) follows trends that are not as similar as those seen in the equivalent variation data. In the case where there is trading of permits, the percent decrease of GDP is generally larger with values of -0.6% for 2020 and -3.6% for 2050. In the case where permit trading is not allowed, the percent changes in GDP values are +0.2% for 2020 and -3.3% for 2050.

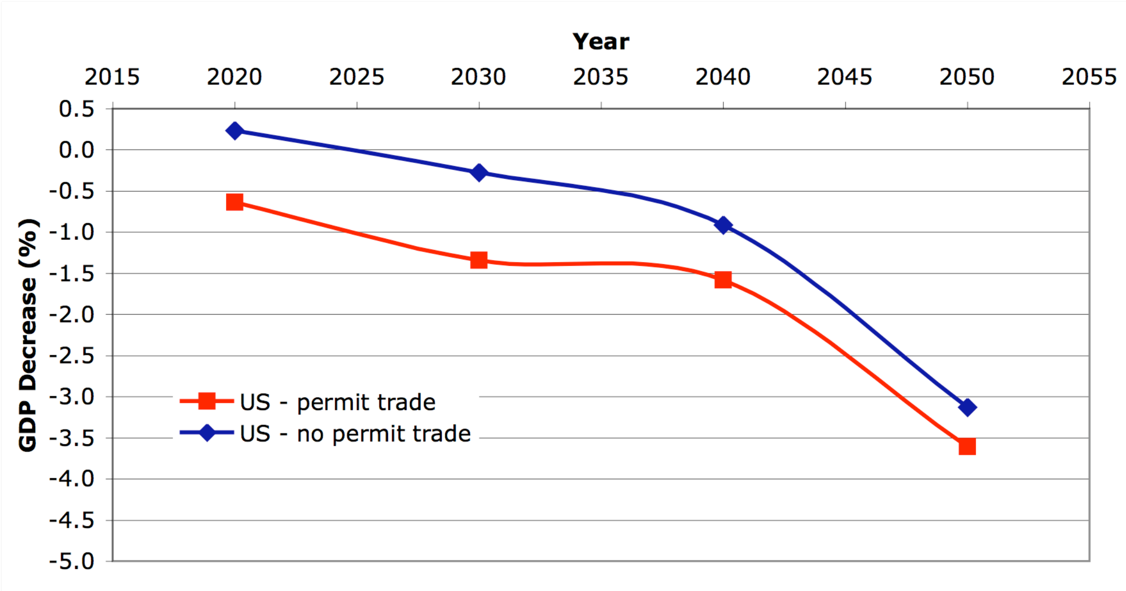


**Figure 3.10 US GDP % Decrease With and Without International Permit Trading**

For both the GDP and equivalent variation, the case with no international permit trading shows a smaller percent decrease. This means that the case with the higher carbon permit price has less negative impact on GDP and equivalent variation than the case with the lower carbon price and international trading. This result for the two metrics for consumer welfare is unexpected and I present possible explanations in the Discussion section.

### Impact of Revenue Recycling to Industry

To demonstrate the impact that output-based allocation of revenue to industry has on the carbon permit price and economic welfare, I focus on the simulations where permit trading between regions is not allowed and contrast those with and without output-based allocation of revenue to industry. When there is revenue recycling to industry in VERITAS-US, the portion of revenue that is not specifically designated to industry sectors is given directly to the consumer.

This case, with output-based allocation of revenue to industry, is contrasted with the situation without revenue allocation to industry where all revenue is given to the consumer, as in a cap-and-dividend scheme.

The carbon permit prices for the US with and without output-based allocation of revenue to industry are displayed in Figure 3.11. In this figure, I only display the results from 2020 and 2030 as the allocation of permits to industry does not extend to 2040 and 2050 in the American Clean Energy and Security Act. In 2020, when there is more allocation of revenue to industry than in 2030, there is a larger difference in the two permit prices; with output-based allocation of revenue to industry the carbon permit prices is 39 \$/t $CO_2$e and without it the permit price is 35 \$/t $CO_2$e. In 2030, when the amount of revenue allocated to industry is smaller, the permit price with and without revenue allocation to industry is essentially the same at 83 \$/t $CO_2$e.

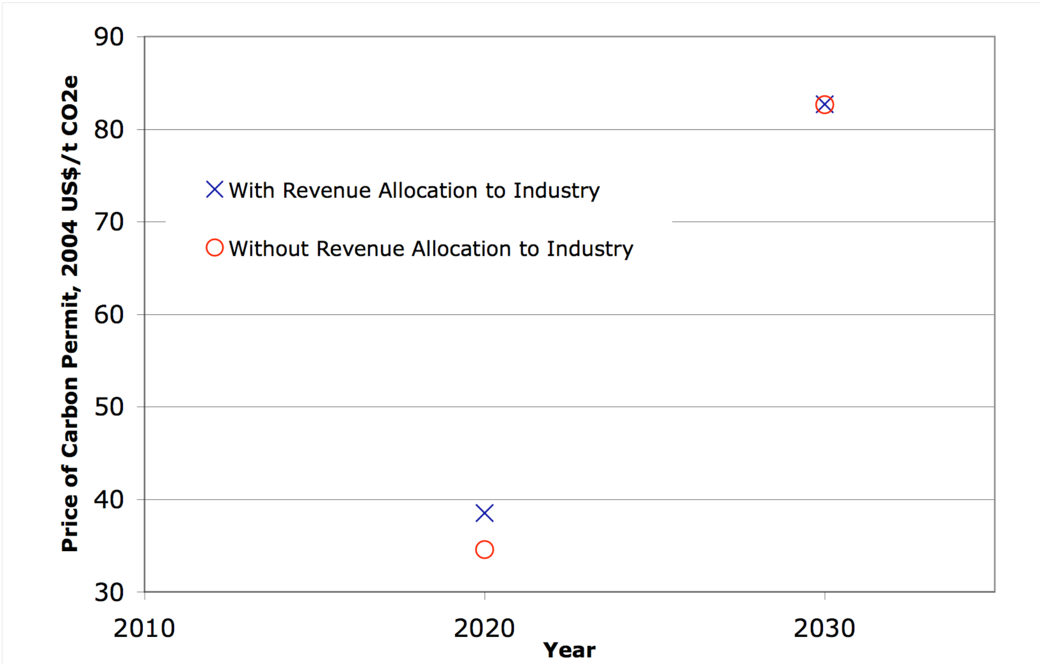


**Figure 3.11 US Carbon Permit Price With and Without Output-Based Allocation of Revenue to Industry**

The welfare and GDP impacts of the policy with or without output-based revenue allocation to industry are minimal enough that they are indiscernible on a graph.

I also looked at the impact of output-based allocation of revenue to industry when permits are allowed to be traded between the US and ROW. In 2020 the global carbon permit price with revenue allocation to industry is 2.7 $/t $CO_2$e higher than the global carbon permit price without revenue allocation to industry. The impact of output-based allocation of revenue to industry on the global carbon price in 2030 is negligible.

## 3.4 Sensitivity Analysis

The results from CGE models are generally sensitive to the parameters used in them, especially the ESUBs. To answer my final research question, I carry out a sensitivity analysis on the ESUBs and on some of the key assumptions I made about CCS in the alternate electricity sector.

### Elasticity of Substitution Values

For the ESUB sensitivity analysis model runs, I compare the results from the sensitivity analysis runs with those of the core policy simulation. To test how robust the model is to ESUB values, I run the model in 2050 with the ESUBs values changed by +/- 40%. I chose this range because many of the ESUB values in the various models I surveyed were generally within it. I chose to run the model in the 2050 time period because it was the final time period that I use the model to analyze. The results of this analysis are shown in Table 3.1.

**Table 3.1 Sensitivity Analysis of ESUB Values for 2050 Simulation**

| Change in ESUBs | Change in Global Permit Price | Change in US Equivalent Variation | Change in US GDP |
|---|---|---|---|
| + 40% | - 46.2% | + 0.4% | + 1.6 % |
| - 40% | + 211.8% | - 2.2% | - 7.4% |

The results of this analysis show that the model's response to policies is quite sensitive to changes in ESUB values. In general, changes in ESUBs affect, in percentage terms, the carbon permit price much more than the GDP or equivalent variation and the decrease in ESUB values had a particularly large impact on the permit price. The confidence I have in the model results would be improved by using CIMS-based ESUBs that have gone through more rigorous testing procedures. The Energy and Materials Research Group at Simon Fraser University is currently working on testing the impact that various parameters in the CIMS model have on the ESUBs values calculated from CIMS data.

### CCS Costs and Capacities

I made multiple assumptions when building the CCS alternative electricity sector and I test some of these assumptions to determine how sensitive the model is to them. The various components of CCS, like capture, transport and storage of $CO_2$, have been used separately in commercial settings, generally by the oil and gas industry. However, the use of all the CCS components together as one scaled-up system with the goal of preventing $CO_2$ from entering the atmosphere is still in the demonstration phase, of which there are currently four operational commercial facilities (IEA, 2009). Because of the uncertainty about the rate of widespread deployment of CCS, I run VERITAS-US in 2050 with changes to the amount of CCS available. This analysis includes the cases where there is 40% less CCS capacity available, 40% more CCS and also no CCS allowed in the model. Because CCS is still in the early phases of demonstration and the cost projections are uncertain, I also test a 40% increase and a 40% decrease for the CCS costs in 2050.

I used two methods to test the model's sensitivity to the available quantity of electricity produced using CCS. First, I ran the core policy for 2050, then increased and decreased the quantity of CCS available in the model by 40%. When the CCS quantity is increased by 40%, the carbon permit price decreases by 39%, and when the CCS quantity is decreased by 40%, the carbon permit price increased by 80%. The model was unable to reach a new equilibrium when I ran the core policy without the option of CCS, indicating that the model could not make 85.7% emissions reductions from the BAU without the CCS technologies. These results indicate that the model is quite sensitive to the quantity of CCS available.

I also ran the model without international trading to make MAC curves for the US in 2050. These show how changes in availability of CCS could impact the carbon permit prices associated with various emissions reductions and are displayed in Figure 3.12. In these runs, I assumed that the ROW region would reduce emissions by 85.7% as in the core policy. However, for the run with no CCS, I had to change the emission reduction target for ROW to 75% so the model would solve. Because ROW only reduces emissions by 75% in the no CCS case, it is not a perfect comparison for the other curves in the graph. However, it appears that the curve is not likely to shift much with the change in ROW emission reductions; at most the permit price would change by a couple of dollars at any given percent reduction on the no CCS curve.

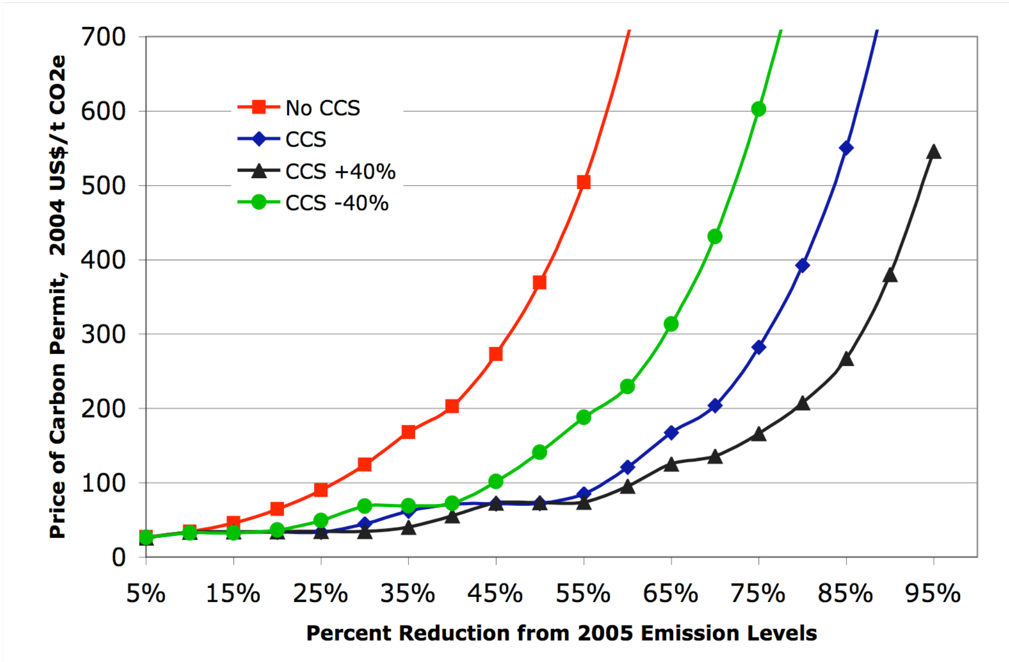


**Figure 3.12 US Marginal Abatement Curve 2050 - Change in Quantity of CCS Available**

The MAC curves show that the available quantity of CCS has a large impact on the carbon permit price. As the quantity of available CCS capacity increases, the cost of carbon permits decreases especially with targets for deeper emission reductions.

The cost of CCS technologies is also an area of uncertainty and to test the sensitivity of VERITAS-US to these costs, I ran the model for 2050 using the core policy settings with the cost of CCS increased and decreased by 40%. I found that when the cost of CCS is increased by 40% in 2050, the carbon permit prices increases by 6.3%. When I decreased the cost of CCS, the carbon permit price decreased by 16.4%. This shows that the permit price is somewhat sensitive to the cost of CCS. I also ran the model without international permit trading to create MAC curves for the US in the 2050 time period. In these runs, ROW is assumed to reduce emissions by 85.7%, which is the same as the core policy. These MAC curves, in Figure 3.13, show the impact of changing the cost of CCS on the carbon permit price.

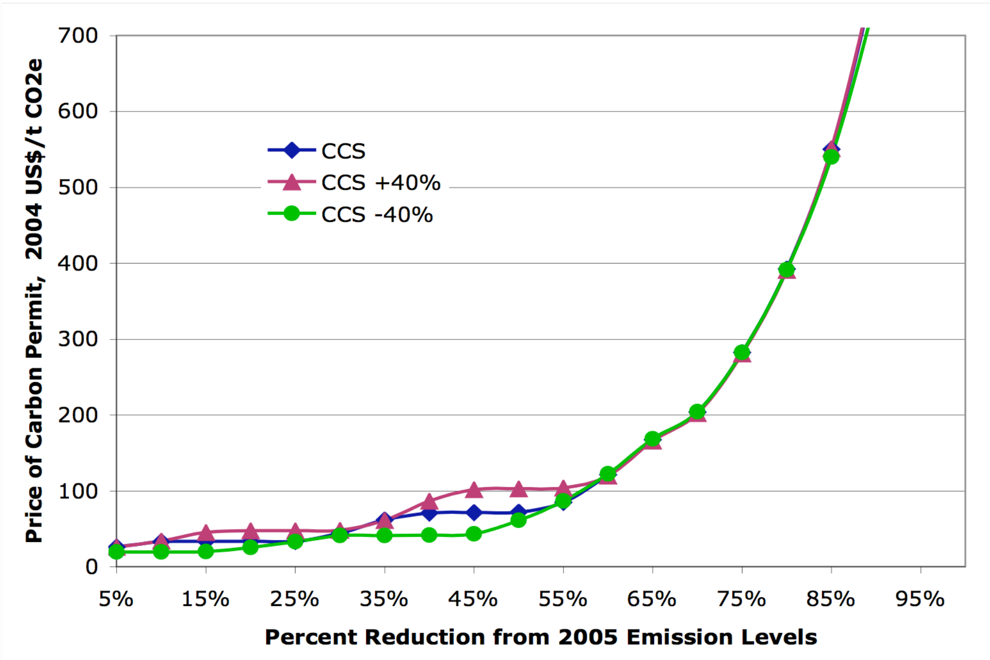


**Figure 3.13 US Marginal Abatement Curve 2050 - Change in Cost of CCS**

This analysis shows that the permit price is marginally sensitive to the change in CCS costs and that most of the sensitivity occurs in the range of percent reductions below 55%. In this range, the permit price follows similar trends to the cost of CCS, where an increase in CCS cost corresponds to an increase in permit price. This is likely because the model is actively taking up the first two steps of CCS in this range. For 60% emissions reductions and higher, the CCS cost changes do not affect the permit price as much because the uptake of CCS slows dramatically. This occurs because the capacity of the first two steps is used up and biomass CCS becomes increasingly expensive because of land use constraints leading to increases in the price of land. After 60% reductions from 2005 levels, the price of land begins to increase exponentially. In the simulations with normal CCS costs, the increase in land price is slightly less rapid than in the simulations with the CCS cost reduced by 40%. It seems that the reduction in CCS costs induce faster increases in the price of land. The biomass CCS capacity is not exhausted even as emission reductions reach 90%, but the uptake of the technology is very slow, especially in the US. This is likely because of the link between the cost of land and the costs of biomass CCS, where demand for biomass CCS increases land prices so much that very little biomass CCS is actually used. In the ROW region, more of the biomass CCS capacity is used, but again the model does not use all the available capacity as it is limited by increasing land costs. Suggestions for improving the representation of biomass CCS, especially with respect to land use and limiting increase of land prices, are included in Section 5.2.

At the upper limit of permit prices shown in Figure 3.13, the line representing a 40% decrease in CCS cost begins to diverge from the other two scenarios. This indicates that at extreme carbon permit prices, more biomass CCS is used when the cost is reduced, however this effect is subtle.

This analysis indicates that the model results are sensitive to both the cost of CCS and the quantity of CCS that is available. However, changing the quantity of CCS that is available has a much bigger effect on the carbon permit price than changing the cost of CCS technologies.

# 4: DISCUSSION

The previous chapter displayed key results from the VERITAS-US model simulations. In this chapter, I examine these results and in some cases compare them to findings from other models. In Section 4.1, I compare the VERITAS-US business-as-usual (BAU) and policy simulations to the reference cases and policy simulations of other models. This section also includes a discussion of the importance of offsets in emission reduction policies. In Section 4.2, I discuss the implications of international permit trading and revenue recycling to industry in the VERITAS-US policy simulations. In Section 4.3, I address the uncertainty inherent in this project. I discuss some of the limitations and challenges of using a static CGE model to analyze policies over long timeframes in Section 4.4.

## 4.1 Comparison with Other Models

### 4.1.1 Business-as-Usual $CO_2$ Emissions and GDP

The BAU simulation case is very important when using models to analyze policy because the BAU emissions are the basis for the magnitude of reductions necessary to meet targets. The BAU economic circumstances are also the basis for estimating the potential economic impacts of the policies. In this section, I compare the BAU simulation of VERITAS-US to the reference cases of other similar models.

I compare the US GDP in the BAU run of VERITAS-US to the reference case GDP in the MIT-EPPA[6] and ADAGE[7] models, as shown in Figure 4.1. The three forecasts of GDP are quite similar as the ADAGE and MIT-EPPA GDP are within 5% of VERITAS-US GDP from 2010 to 2040. It is only in 2050 when the MIT-EPPA forecast is beyond this range and is 7% larger than the VERITAS-US GDP.

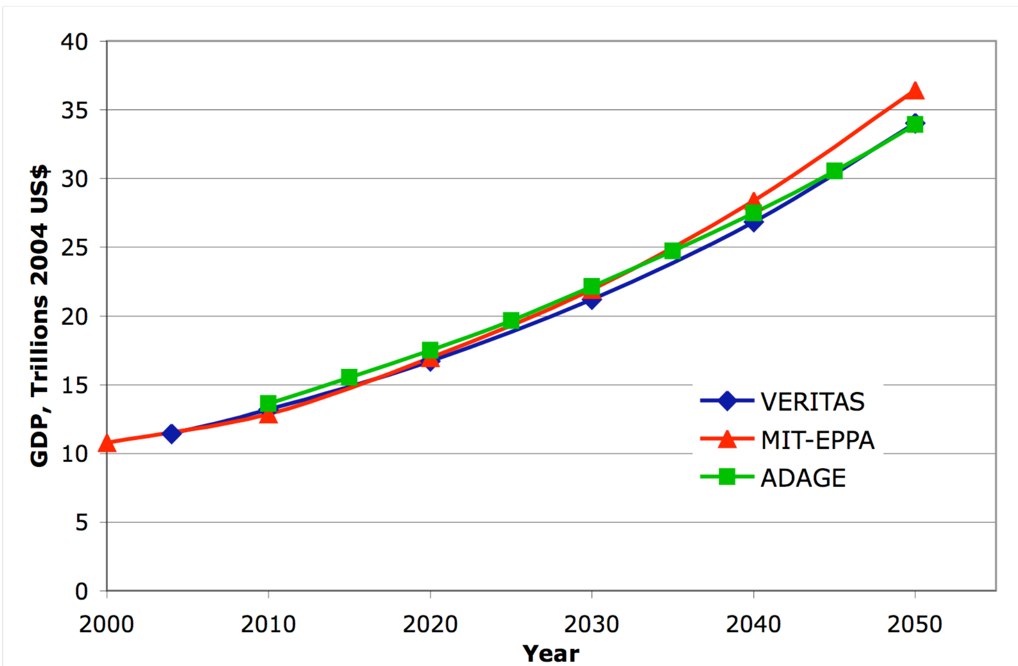


**Figure 4.1 Comparison of Business-as-Usual GDP for the US by VERITAS, MIT-EPPA and ADAGE**

Sources: Paltsev et al. (2009) and Ross (2008)

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[6] MIT-EPPA is a recursive-dynamic multi-regional general equilibrium model of the world economy. It is developed and used by the Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology. MIT-EPPA is designed to develop projections of economic growth and anthropogenic emissions of greenhouse related gases and aerosols and can be used in conjunction with the MIT Integrated Global Systems Model (Paltsev et al., 2005).

[7] ADAGE is a dynamic computable general equilibrium model capable of examining many types of economic, energy, environmental, climate-change mitigation and trade policies at the international, national, U.S. regional and U.S. state levels. It is developed by RTI International (Ross, 2008).

The BAU $CO_2$ emissions of VERITAS-US are compared to reference case $CO_2$ emission in the MIT-EPPA, ADAGE and EIA-NEMS[8] models in Figure 4.2. The $CO_2$ emissions for EIA-NEMS and VERITAS-US are based on fossil fuel combustion only, whereas the MIT-EPPA and ADAGE data in the figure show $CO_2$ from fossil fuel combustion and $CO_2$ from non-combustion sources, like agriculture and industrial processes. The $CO_2$ emissions from VERITAS-US match the MIT-EPPA and EIA-NEMS forecasts fairly well in the first few decades, however the MIT-EPPA emissions are 24% higher than the VERITAS-US emissions by 2050. The ADAGE data show the emissions being consistently higher than VERITAS-US, which could be attributed to ADAGE accounting for $CO_2$ beyond fossil fuels use. The MIT-EPPA model also covers $CO_2$ emissions from sources other than fossil fuel use, but I think it is unlikely that the MIT-EPPA difference in emissions in 2050 is solely because of non-fossil fuel $CO_2$ emissions as it increases more rapidly in the later decades. The emissions in the VERITAS-US BAU may be lower than MIT-EPPA in 2040 and 2050 because they are based on an extrapolation of the EIA fossil fuel use data that cover 2006 to 2030. As shown in the graph, the MIT-EPPA emissions grow much faster in the period after 2030 than the EIA-NEMS emissions in the period up to 2030.

[8] The EIA-NEMS model is a technology rich, computer-based, energy-economy modelling system of U.S. It is designed and implemented by the Energy Information Administration (EIA) of the U.S. Department of Energy. EIA-NEMS is used to project the energy, economic, environmental and security impacts of alternative energy policies on the United States (EIA, 2009e).

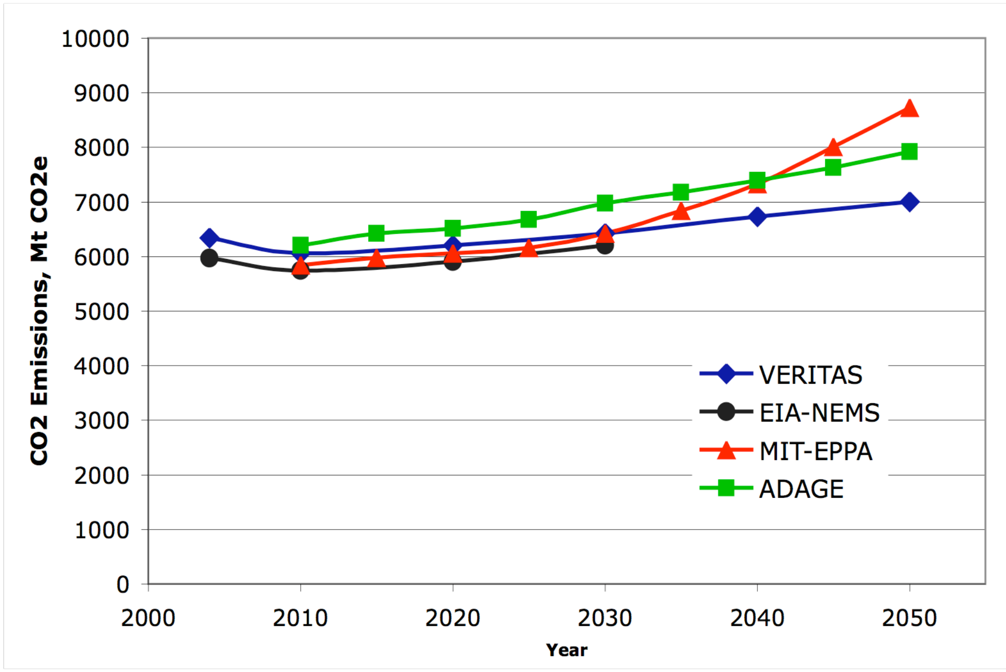


**Figure 4.2 Comparison of Business-as-Usual CO2 Emissions for the US by VERITAS-US, EIA-NEMS, MIT-EPPA and ADAGE**

Sources: EIA (2009b, 2009c), Paltsev et al. (2009) and Ross (2008)

### 4.1.2 Emission Reduction Policies

In this section, I compare the results of my policy simulations with results from other models that have been used in similar studies. First, I compare results from studies that do not use offsets and have emission reduction pathways similar to my approximation of current US legislation. Next, I summarize some of the analyses of current US legislation by models that can simulate offsets and discuss their importance in climate change policy.

### Comparison of Simulations Without Offsets

Ross et al. (2009), Paltsev et al. (2009) and Tuladhar et al. (2009) used the ADAGE, MIT-EPPA and MRN-NEEM[9] models to analyze an emission reduction pathway that results in approximately 167 billion Mt of cumulative GHG emissions between 2012 and 2050. This pathway is essentially a linear reduction of emissions from 2012 until 2050, reaching an annual reduction of 80% below 1990 emissions levels in 2050, which is quite similar to the reduction pathway I used in my approximation of the American Clean Energy and Security Act. The trading of permits between international regions is not included in the studies by Ross et al. (2009), Paltsev et al. (2009) and Tuladhar et al. (2009), so I compare them to my simulation of VERITAS-US that does not have international trading of carbon permits (Figure 4.3).

[9] MRM-NEEM is an integration of MRM, a top-down dynamic computable general equilibrium model, and NEEM, a technology-rich bottom-up model of the US electricity sector. This combination is developed by CRA International for analysis of US greenhouse gas policies (Tuladhar et al., 2009).

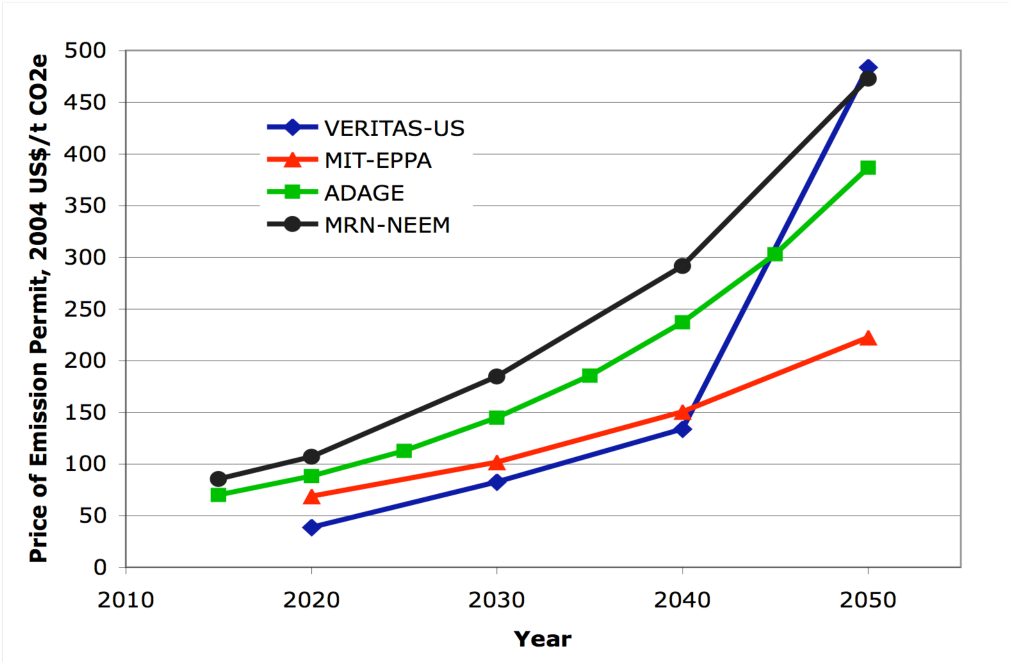


**Figure 4.3 Comparison of Emission Permit Prices for the US by VERITAS-US, MIT-EPPA, ADAGE and MRN-NEEM**

Sources: Paltsev et al. (2009), Ross et al. (2009) and Tuladhar et al. (2009)

Figure 4.3 shows a wide range in the permit prices forecasted by these models. VERITAS-US starts out with permit prices at the low end of the estimates in the early decades and has a permit price at the high end in 2050. There are multiple factors that may be contributing to these results.

One reason that the other models have a smaller range and a more gradual increase in permit prices over the time period of the policy could be that they involve the option of banking and borrowing permits. This is a cost containment measure that helps manage the permit price by allowing the use of saved permits from past years and the limited use of permits from future years. In a comparison of a policy scenario with and without banking and borrowing of permits, Tuladhar et al. (2009) found that without banking the permit price was lower in the initial years of the policy and that in later years, when there are more stringent targets, the permit price is much higher. This describes the pattern seen in the VERITAS-US results compared to the other models that have banking and borrowing of permits. While I think the absence of banking and borrow permits could explain part of the wide range of permit prices in the VERITAS-US results, I think there are other factors that contribute.

VERITAS-US only covers $CO_2$ emissions from fossil fuels while the other models include additional GHGs and $CO_2$ emissions from both fossil fuel combustion and non-fossil fuel sources. Thus, the other models could have GHG abatement options that change the permit price compared to the abatement options when only $CO_2$ from fossil fuel combustions is considered (Morris et al. 2008).

The use of CCS in the alternative electricity sector is another potential reason for the wide range of permit prices in VERITAS-US. My representation of CCS technologies is based on three aggregated steps and is simplistic compared to most of the other models, which have specific CCS technologies with more detailed constraints in their electricity-producing sectors. In the 2030 run, the price may be low in comparison because my model takes up about a third of the CCS capacity available. VERITAS-US also takes up the majority of the CCS that is allowed in the 2040 run, which might be faster than is realistic. Potential improvements to address this limitation of the CCS sector are suggested in Section 5.2. In the 2050 run, there is a small increase in the amount of CCS that is used compared to the 2040 run, but the model seems to run out of CCS capacity and other cheaper options for reducing emissions. This may explain why the permit price in 2050 is so much higher than the price in 2040.

The ESUB values used in the different models are another factor that could contribute to the difference in forecasted permit prices. The impact of ESUB values is most likely more apparent in the 2050 results, as the uptake of CCS in 2020 to 2040 likely has a large influence on the permit price in these years. The ESUB values related to substituting fuels, especially those between fuels and electricity, $\sigma_{E}$, and between coal and liquid fuels, $\sigma_{FUEL}$, seem like they could explain part of the price range in 2050 shown in Figure 4.3. The MIT-EPPA model has a value of 1 for both of these ESUBS, whereas the US values of $\sigma_{E}$ and $\sigma_{FUEL}$ in VERITAS-US are less than 1 for most sectors. This could partly explain the lower permit price forecast by the MIT-EPPA model in 2050 as higher ESUB values allow for easier substitution and potentially lower permit prices. The value of $\sigma_{E}$ in the ADAGE model is 0.5, which is closer to the US values in VERITAS-US, and might explain the similar permit prices of VERITAS-US and ADAGE in 2050. ADAGE does not have similar nesting structure for the $\sigma_{FUEL}$ ESUB so I could not make a comparison of this parameter. The three models, VERITAS-US, ADAGE and MIT-EPPS, have similar ESUB values, in the range of 0.4 to 0.5, for the substitution between factors and energy, $\sigma_{VAE}$.

These models estimate similar ranges for the economic and welfare impacts of this emissions reduction pathway. In VERITAS-US, the changes in GDP and equivalent variation, which is a measure of welfare, are decreases of 3.1% and 0.8% in 2050. The MIT-EPPA model shows decrease in welfare of

2.5% in 2050 (Paltsev et al., 2009). The MRN-NEEM model shows a decrease in GDP of 3.09% and decrease in welfare of 1.96% in 2050 (Tuladhar et al., 2009). The ADAGE model shows the impact on GDP and welfare as a change in annual average growth in GDP and consumption. These annual average growth rates change from 2.31% in the BAU to 2.11% for GDP and 2.33% to 2.18% for consumption (Ross et al., 2009). The models all show small decreases in the GDP and welfare in 2050 because of reducing GHG emissions to 80% below 1990 levels in 2050.

### Simulations With Offsets

Offsets are an important issue in GHG emission reduction policy and the American Clean Energy and Security Act allows for the annual use of 2000 Mt $CO_2$e of them. Half of this amount must be acquired domestically and half can be from international sources. To put these allowable offsets in perspective, in 2005 the US emitted approximately 7100 Mt $CO_2$e. By allowing the use of such a significant amount of offsets, the actual reductions required from the sectors of the US economy covered by the cap-and-trade system are much less than if no offset were allowed. Figure 4.4 shows the emission reduction pathway prescribed by the targets in the bill and the amount of allowed offsets. This figure includes GHGs beyond the $CO_2$ from fossil fuel combustion that my model tracks.

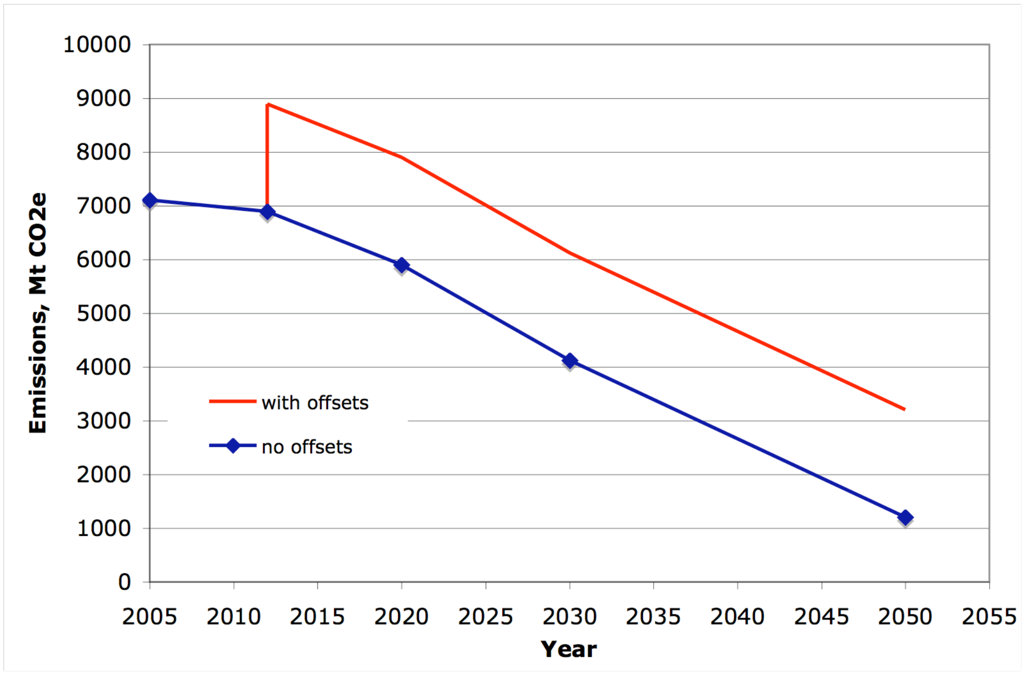


**Figure 4.4 Emission Reduction Pathway for the American Clean Energy and Security Act Targets With and Without Offsets**

The amount of offsets included in a policy can have a large impact on the price of emission permits. Figure 4.5 shows the emission permit prices determined by models that analyzed the American Clean Energy and Security Act. The MIT-EPPA model, the ADAGE model (for Environmental Protection Agency's analysis) and the Energy Information Administration's NEMS model were all used to simulate a version of the bill with full offset use and with partial offset use, often by limiting the international offsets. In the MIT-EPPA model, it is assumed that the price of offsets starts at 5$/t $CO_2$e in 2015 and then increases at 4% per year, which equals close to 20$/t $CO_2$e in 2050 (Paltsev et al., 2009). The ADAGE model includes the assumption that domestic offset prices are equal to the permit price for the full-offset case, which starts at 13 $/t $CO_2$e in 2015 and rises to 70 $/t $CO_2$e in 2050. The international offset prices in ADAGE are assumed to be a bit lower, starting at 10 \$/t $CO_2$e in 2015 and rising to 55 \$/t $CO_2$e in 2050 (Environmental Protection Agency, 2009). For the EIA-NEMS base case analysis, they assume offset prices of 32 \$/t $CO_2$e in 2020 and 65 \$/t $CO_2$e in 2030 (EIA, 2009f). The restriction of offsets to half their allowed value increases the permit price in the MIT-EPPA and ADAGE models by about 60 \$/t $CO_2$e (2004 US\$) by 2050. The EIA model forecasts to 2030 and in this year the permit price increases by approximately 60 \$/t $CO_2$e when offsets are restricted to 1000 Mt $CO_2$e.

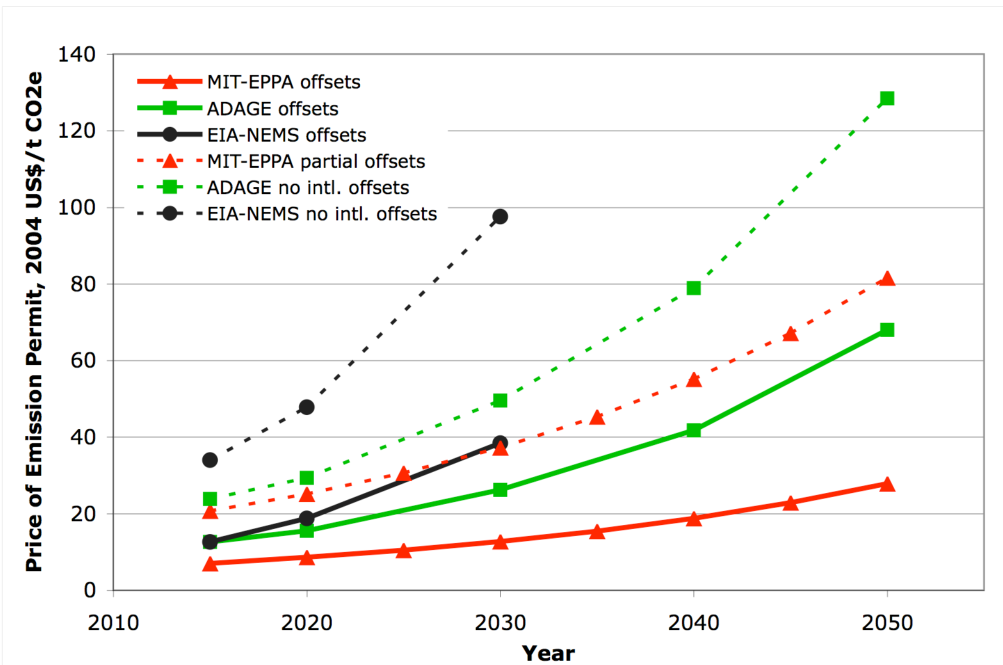


**Figure 4.5 Emissions Permit Price for the American Clean Energy and Security Act Analysis by MIT-EPPA, ADAGE and EIA-NEMS for Full Offset and Limited Offset Cases**

Sources: Paltsev et al. (2009), EIA (2009f) and Environmental Protection Agency (2009)

On one hand, offsets could be viewed as beneficial because they reduce the number of emissions reductions the capped sectors have to make by shifting the reductions to non-capped sectors, thus reducing permit prices. On the other hand, they can thwart actual emissions reductions for a couple of reasons. First, one problem with offsets is similar to that of subsidies, which is the difficulty of ensuring that the offsetting action would not have occurred even if the policy were not in place. Second, there is the potential problem of trying to reduce emissions by using offsets when they might not represent permanent reductions; for example if trees are planted and then later cut down. If the offsets are not additive, i.e. do no contribute real reductions in the absolute amount of a society's emissions, the total amount of emissions the policy reduces could be much less significant than indicated by the targets. An example of this is the potential of Kyoto's Clean Development Mechanism to make it look like the Protocol's targets are being met, yet undermining effectiveness if the projects are not delivering truly additional emissions mitigation (Wara, 2006). While the American Clean Energy and Security Act requires that the offsets be accredited, it may not be possible to guarantee that they are actually causing additional and permanent emissions reductions.

## 4.2 Alternative Policy Cases

### International Trading

The core policy case allows for international trading of carbon permits, which I compare with a variation where international trading is not allowed. In the core policy case, the global carbon permit price in 2050 is 127 \$/t $CO_2$e less than the US carbon permit price when the US is not allowed to trade permits with the ROW region (Figure 3.8). By allowing international trading it makes the reduction of emissions more cost efficient for the global community as a whole. Because countries that can abate emissions at lower costs will abate more than counties with higher abatement costs, it allows for a given emission reduction target to be reached at a lower total economic cost. This is an application of the equi-marginal principle, which in this case asserts that the cost to society for reducing emissions is minimized when each source of emissions (or emitting country) reduces emissions up to the point where their marginal abatement costs of further reductions are the same.

The comparison of VERITAS-US international trading simulations (Figure 3.9 and Figure 3.10) shows some initially counterintuitive results. First, in the 2020 simulations the equivalent variation for both permit trading cases is higher than in the business-as-usual (BAU) case and the GDP for the case without international permit trading is also higher than the BAU GDP. Second, the US consumer welfare and GDP are higher when international permit trading is not allowed compared to when it is allowed in the core policy case. This result is unexpected, as one might think that consumers would be better off with lower carbon permit prices. I discuss each of these anomalies in the following paragraphs.

The increase of equivalent variation and GDP beyond the values in the BAU simulations in the 2020 time period, are unexpected as they represent a double dividend. Double dividend refers to the situation where the revenue from an environmental policy is used to reduce the impacts of an already existing distortionary tax, such as income, payroll or sales taxes, leaving the consumer better off than before the environmental policy. The two dividends, with respect to the term, are the benefits of (1) reducing environmental harm and (2) reducing the distortionary cost of the existing tax system (Goulder, 1995). However, in VERITAS-US there are no initial distortionary taxes in the business-as-usual simulation, so it seems odd that there would be a double dividend situation. There is a difference in the stringency of the emission reduction as the US and ROW have different reduction requirements. The increase in welfare and GDP in 2020 could be explained by energy-intensive industry moving production to the US or because of the improvement of the US terms of trade, which are the relative price of a country's exports to imports. Because the US is a net energy importer, it could benefit from lower oil prices because of reduced global demand induced by the cap-and-trade system.

Based on the results in Figure 3.9, the US consumer is slightly better off, i.e. equivalent variation is higher, when international trading of permits is not allowed and the carbon permit price is higher, when compared to the simulation where international permit trading is allowed. This could potentially be explained by improvement in the US terms of trade and changes in trading of commodities other than emissions permits. The effects trading permits could also contribute to this result as the US becomes a net permit buyer when international trading of permits is allowed, which causes large flows of funds out of the US.

The structure of my model might exaggerate the effect of the lost domestic income on consumer welfare. Because government services are not modelled specifically, the consumer is given the revenue from all permits unless the revenue is designated to an industrial sector. In reality, the revenue that is not designated to industry could be used for many things, like green technology development funds or reducing national debt. While these activities benefit the consumers, they might not have as drastic welfare impacts as when the entire amount is given directly to the consumer.

The higher GDP in the case without permit trading (Figure 3.10) may be connected to the higher permit price associated with this case. As mentioned before, the GDP measurement in VERITAS-US includes the value of carbon permits, so a higher permit price could contribute to a higher value for GDP. The lower GDP in the international trading case could also be attributed to a variation in the model. There is a slight difference in how permits are allocated between the global version of the model, which is used for the case with international permit trading, and the regional version of the model, which is used for the case that does not allow permit trading. In the global version, the number of permits that are allocated to the international community, as part of the permit distribution in the American Clean Energy and Security Act, are subtracted from the total number of permits endowed to the US consumer. In the regional version, the full amount of permits allocated to the US is endowed to the US consumer and then a lump sum transfer of funds is made from the US consumer to the ROW consumer to represent the bill's allocation of permit revenue to the international community. This means that in the regional version (no international permit trading) the US consumer is initially endowed with more permits than in the global version (international permit trading). Since the value of carbon permits is included in the GDP, this difference in the method of permit endowment could also contribute to the slightly higher GDP for the case without international permit trading.

The impacts of linking a US cap-and-trade system to other international cap-and-trade systems would likely go beyond the potential reduction in emission permit price that my model predicts. Jaffe and Stavins (2008) describe some of the other consequences of linking cap-and-trade systems, including that this can limit the amount of control a government has over its country's system. Linking can also cause distributional effects within systems and across linked systems that may be undesirable, such as large flows of capital between regions. It also opens up various system attributes, like offsets and price safety valves to other connected systems. If a system with a firm emissions cap links with one that has an intensity-based cap, the linked systems may not achieve the same level of emissions reductions compared to the un-linked systems. The trade offs of all these impacts must be considered carefully when design the linkages between cap-and-trade systems (Jaffe and Stavins, 2008).

### Revenue Recycling to Industry

I also looked at output-based allocation of revenue to industry and the impact that it could have on the cost of a policy. I found that in the 2020 and 2030 runs of the core policy simulation, the carbon permit price is higher with revenue allocation to industry (Figure 3.11). This finding is consistent with an analysis of output-based rebating by Fischer (2001), where she found that for a given amount of emissions reductions, output-based rebating increases the marginal cost of emission reduction relative to a policy without rebating. This occurs because the output-based rebating leads to higher than optimal production of output, as firms have an incentive to increase output in order to maximize the subsidy they receive. The comparison of the 2020 simulations shows a decrease of 4 \$/t $CO_2$e in the carbon permit price when revenue is not allocated to industry, but rather given entirely to consumers. The output-based allocation of revenue to industry that is considered in this case is approximately 49% of total permit revenue and is used to subsidize electricity and industrial output.

Fischer (2001) compares the output-based allocation to industry with a socially optimal policy, where welfare is optimized and emissions are reduced to the point were society, as a whole, would not benefit from further reductions. In comparison to this optimal policy, or the 'first-best' policy, output-based rebating to industry decreases the economic efficiency. For my analysis of output-based allocation of revenue to industry, I compare it with the case where all revenue is given to the consumer. I assume that this 'cap-and-dividend' case is not a socially optimal policy as it has uneven reduction requirements for the different regions. If a policy is not socially optimal, the addition of output-based allocation of revenue can actually improve the economic efficiency of the policy (Fischer and Fox, 2009). In the simulations I explore for this analysis, the output-based allocation of revenue to industry could improve the policy by increasing the competitiveness of the US industry, which could improve US welfare, and by preventing leakage of emissions to ROW. However, my analysis does not include the optimization of revenue allocation amounts, so I am not certain whether the output-based allocation in this simulation increases or decreases overall economic efficiency of the policy.

Even though output-based allocation of revenue to industry increases the carbon permit price of a policy, public and industry support for the policy will likely be more important than the small increase in permit price. Acceptance of the policy is especially important in the near term so the policy will actually be implemented. In the American Clean Energy and Security Act this is addressed, as revenue recycling to industry is included in the first years of the policy and then phased out beginning in 2025. By 2040 and 2050 there is no revenue recycling to industry (all revenue is given to the consumer).

To further explore the impacts of revenue recycling, beyond subsidies to industry, I could potentially have dealt with some of the permit allocations in the bill more realistically, by including subsidies for CCS or by lower income tax and tax credits. These options were too detailed for the framework of my model and went beyond the scope of this project.

## 4.3 Uncertainty

Modelling is inherently an uncertain practice, as each model is a representation that never truly captures the actual system under examination. If we try to increase the realism of our models by adding more parameters, we may actually increase the uncertainty (Oreskes, 2003). The uncertainty related to forecasting also generally increases as our forecasts go further into the future.

This section describes the main sources of uncertainty in this project and how I accounted for them.

Structural uncertainty occurs because all models are simplified representations of more complex real-world systems and because we use approximations to represent these systems (Morgan and Henrion, 1990). For example, in this project I assume that nested constant elasticity of substitution functions represent the real world where firms produce goods and people and firms consume goods and services. I also use an amalgamated ROW region and assume that it represents all the countries in the world, excluding the US. Often these assumptions accompany trade-offs between realism and the simplicity of a model.

There is also uncertainty in the parameters that are used in models, which involves how well a numerical variable represents elements of the system being modelled (Oreskes, 2003). Using historical data and judgement to estimate ESUBs and AEEI and then using them to forecast also adds uncertainty.

The data that I use also have uncertainty associated with them. While the historical data I used are likely the least uncertain, they still have uncertainty because of potential measurement and communication errors. The forecasted data I used for my fossil fuel consumption were generated by another model with all of its associated uncertainty. The extrapolation of my SAMs for use in the various time periods that I model also increases the uncertainty from the data used in the project.

There are several ways that I accounted for the uncertainty in this project. I used established methods for constructing the model and reliable sources for my data. I tried to decrease the uncertainty of using historically based parameters to forecast future trends by using ESUBs from CIMS. While this theoretically reduces uncertainty by providing ESUBs that are based on technologies that could be used in the future, it introduces the uncertainty of using parameters based on forecasts from estimated relationships in the CIMS model. I also compare my results to those from models that have various different parameter values and modelling approaches. The final way that I address uncertainty is by subjecting VERITAS-US to a sensitivity analysis.

When using results from models like VERITAS-US, it is important to keep in mind that specific numbers are less important than general trends. Also the results are quite variable depending on assumptions and methods of modelling policies. The results are heavily based on assumptions about technologies and behaviours in the future, meaning that the model results for 2040 and 2050 are especially vulnerable to the likelihood that the model is missing key technologies that have not yet been invented.

## 4.4 Challenges of Static CGE Modelling

I briefly discussed the challenges of modelling carbon capture and storage (CCS) in a static CGE model in the Methods section, but there are other difficulties associated with using a static modelling framework. These difficulties are inherent when using a static model to analyze policies over long time frames as static models represent one time period per simulation and each time period is not connected to previous or future time periods.

The main limitations and challenges of using a static model over long time frames relate to this lack of connection between time periods. For example, the 2050 run has no dependence on capital stock built, prices, or any other aspect of the 2040 run of the model. This lack of time continuity makes it difficult to model processes that depend on previous actions. For example, tracking the quantity and quality of CCS sites that are used over time is not possible in a static model. Because of the lack of time continuity, my model also does not track investment and savings explicitly. The time element would also be necessary for including banking and borrowing of emission permits in the model. The data in each SAM are also based on extrapolation from the 2004 data and are not affected by the previous SAMs or previous impacts of the policy. These limitations must be kept in mind when interpreting results from VERITAS-US. While there are many limitations of using a static model, its simplicity made this research project feasible in a reasonable time scale.

# 5: CONCLUSIONS

In this research project, I built a global energy-economy model for analyzing climate change policy with a focus on the United States. The model is called VERITAS-US and I built it using a static CGE framework that was enhanced by parameters informed by CIMS technology simulation models. I used VERITAS-US to analyze climate change policy that is currently relevant to American and international situations. In Section 5.1 of this chapter, I review the findings from my analysis with respect to my research questions. I present some options for improving the VERITAS-US model and suggest directions for future research in Section 5.2.

## 5.1 Summary of Research Findings

**What are the potential economic and environmental impacts of currently proposed US climate policy?**

To answer this question, I did an analysis of the core policy case, which is an approximation of the American Clean Energy and Security Act of 2009. I found that the cost of carbon permits for my approximation of the bill without offsets would be 32 $/ t $CO_2e$ (2004 US$) in 2020, 70 $/ t $CO_2e$ in 2030, 103 $/ t $CO_2e$ in 2040 and 357 $/ t $CO_2e$ in 2050. I also found that the welfare of the US consumer would decrease by 1.02% in 2050 because of the costs of the policy. The decrease in GDP for the US under the core policy would be 3.60% in 2050.

This research only attempts to analyze the costs of the policy and does not attempt to quantify the benefits.

In this project, I equate the environmental impacts of a policy with the GHG emissions reductions the policy could cause. The core policy case involved a reduction of GHG emissions to 83% below 2005 levels by 2050, which is approximately an 80% reduction below 1990 levels by 2050. These reductions are significant and would put the US well along the path required to do its part in stabilizing the atmospheric concentrations of GHG at a level that could keep the average global temperature increase below $2^oC$. However, the bill allows for a large number of offsets, which could undermine the emissions reductions it proposes in the targets. If the offsets used in the bill are not truly additive or permanent, the policy's emission reduction targets could be exceeded by up to 2000 Mt $CO_2e$ annually.

**What are the potential effects of trading carbon permits internationally versus the option of the US acting alone without international permit trading?**

I compared the core policy case, which allows international trading of permits, with a simulation where international permit trading was not allowed. In this second case, I found that the carbon permit price in the US increased by about 30 $/t $CO_2e$ in 2040 and by 127 $/t $CO_2e$ by 2050. Although the carbon permit price increased when permit trading was not allowed, I found that US GDP and welfare were actually higher without international permit trading. GDP in 2050 was 0.3% higher without international trading than it was in the core policy case. Welfare in 2050 was 0.2% higher in the case without international permit trading. There are many other potential effects of linking a US cap-and-trade system to international systems through trading of permits and these should be weighed carefully when designing the structure of the linkages.

**What are the potential impacts of revenue recycling or permit allocation within the US?**

I compared the core policy simulation, which uses output-based allocation of permit revenue to approximate the American Clean Energy and Security Act's allocation of permits, with a simulation that allocates all the permit revenue directly to the consumer. I found that the core policy case, with revenue recycling to industry, required higher carbon permit prices to reach the same emission reduction target than the case where all the revenue was recycled to the consumer. In 2020 when about 49% of total permit revenue was recycled to industry, the carbon permit price was 4 \$/t $CO_2$e higher than the case without revenue recycling to industry. By 2030, a much smaller amount of total permit revenue was given to industry and the permit price difference was negligible. From my analysis, it seems like the potential impact of output-based allocation of revenue to industry on the permit price is small enough that it would be worth pursuing to increase industry support for the policy.

**How robust is the model to different values for elasticities of substitution and the assumptions made regarding carbon capture and storage costs and capacity?**

In my sensitivity analysis of the ESUBs in VERITAS-US, I found the model is quite sensitive to changes in the ESUB values. The carbon permit price was more sensitive to decreases in the ESUB values than to increases in ESUBs. In the 2050 model run, a 40% decrease in the ESUB values caused a 212% increase in the carbon permit prices, whereas a 40% increase in the ESUB values caused a 46% decrease in the permit price. The ESUB value changes also impacted the GDP and welfare but to a much lesser extent.

I also did a sensitivity analysis on the alternative electricity production sector with CCS and I found that the model is quite sensitive to my assumptions about the quantity of CCS available and the cost of CCS. The analysis showed that the carbon permit price was most sensitive to changes in the quantity of CCS available and that the cost of CCS had a smaller impact.

The main conclusions that I have drawn from this research are:

*A policy that aims to achieve significant reductions in GHG emissions will have real economic costs*. In the near term the negative impact that a policy, like the American Clean Energy and Security Act, will have on US consumer welfare is likely to be relatively minimal. The forecasts further in the future show slightly larger impacts on welfare but are also more uncertain.

*Linking a US cap-and-trade system with other similar systems, through international trading of permits, could decrease the cost of permits in the US.*

However, the implications of linking a cap-and-trade system to other systems are numerous. The types of linkages and their effects should be researched thoroughly before implementation.

*Output-based allocation of revenue to industry will increase the permit price required to meet specific targets*. However, I think that if revenue recycling to industry increases support for a policy, it will likely be worth a small increase in permit price, especially if it means that a policy will actually be implemented. This would particularly hold true if the revenue recycling to industry is phased out in later years of the policy.

My analysis looks at the total impacts on GDP and welfare because of carbon permit prices arising from cap-and-trade systems. This does not account for the distribution of the impacts and there are significant equity issues involved with this. Any policy should have ways to protect those most vulnerable, for example low-income households and those employed in sectors that are negatively impacted by the cap-and-trade policy. Climate change policies should also have regularly scheduled reviews and opportunities for alteration to ensure they are meeting social, economic and environmental goals.

## 5.2 Future Model Development and Research

The sensitivity analysis indicated that the model is sensitive to ESUB values and the assumptions I made regarding the CCS sector. Because of this analysis, I suggest these key areas for improving the model:

- reducing the uncertainty relating to the ESUB values, especially by testing and improving the method for generating ESUBs from CIMS models;
- improving the alternative electricity sector and the model's representation of CCS. For example, include specific CCS technologies, nuclear, renewables and improve the representation of biomass energy and land use feedbacks and potentially add in constraints on the increase of land prices. Also, including constraints to limit the amount of each technology in given time periods will likely be quite important as the model results were more sensitive to quantity of CCS available than cost of CCS.

There are other changes that I recommend to improve VERITAS:

- include a method for modelling offsets,
- test/alter permit allocation methods in Regional and Global modes to ensure the permit allocation methods result in consistent GDP,
- make it a dynamic model,
- include GHGs other than $CO_2$ (like methane, nitrous oxide, sulphur hexafluoride, perfluorocarbons),
- add $CO_2$ emissions from cement, agriculture, waste etc.,
- make a separate agriculture sector by removing it from the Rest Of Economy (ROE) sector,
- include investment and government separate from the consumer, and
- include a labour/leisure option for consumers.

There are many interesting areas of research that this model could potentially be used in, especially once some of the recommended improvements are made. If the multi-regional aspects of VERITAS were combined with the more complicated theory of single region dynamic model, to create a multi-regional dynamic model, it could eventually be linked with CIMS-Global or any other CIMS regional model. This could help resolve some of the ESUB and CCS technology issues in VERITAS.

It would also be interesting to focus on North America with either this model or a dynamic version of it. This type of research could explore a North America wide cap-and-trade system and could elaborate on how the nuances of policy design affect the various countries involved.

# APPENDICES

# Appendix A: VERITAS-US Code in GAMS/MPSGE

```
*VERITAS-US - a static global CGE model with trade between two regions (US and
ROW) for analysis of climate change policy

*Base year of the model is 2004

SET         a(*)    commodities and factors,
            i(a)    commodities ,
            j(*)    sectors,
            fd(*)   final demand,
            f(a)    factors;

SET r /US, ROW/;
SET a(*) /OIL, ELEC, GAS, COAL, RPP, MET, NMET, OMAN, TRANS, ROE, K, L, LN, NR
/;
SET i(a) /OIL, ELEC, GAS, COAL, RPP, MET, NMET, OMAN, TRANS, ROE/;
SET j(*) /OILJ, ELECJ, GASJ, COALJ, RPPJ, METJ, NMETJ, OMANJ, TRANJ, ROEJ/;
SET f(a) /K, L, LN, NR/;
SET FD(*) /FDEM, INV/;

ALIAS(i,ii) ; ALIAS(r,rr) ; ALIAS(j,jj);


Scalar  year   time period to run model in (base 2004 - other options 2010
2020   2030   2040   2050);

*both of these need to be changed for the model to run!!
$set year 2050
Year  =   2050;
***************change policy and Atech files too!!!!!**************

*Load social accouting matrix
$INCLUDE           "GDX to Gams BALSAM_%year%.gms"


*Sets whether you use global or regional option,
* if OPT = 1, the model uses global abatement
* if OPT = 2, regions act alone.

PARAMETER
OPT      Regional or global abatement option;
*When you change OPT - make sure the model loads the correct policy file (the
flagging didn't work...)
*opt = 1 global
*opt = 2 regional
OPT =  1;

*Load althernative tech data for YA elec sector
*$INCLUDE        Atech Nov16 2020-2030 2009J.txt
$INCLUDE        Atech Nov16 2040-2050 2009J.txt


PARAMETERS

X0(r,i,j)        Benchmark intermediate inputs,
Y0(r,i,j)        Benchmark outputs,
F0(r,f,j)        Benchmark factors,
FDEM0(r,i)       Benchmark final demand,
IM0(r,rr,i)      Benchmark import world price,
IMM0(r,rr,i)     Benchmark import market price,
EX0(r,rr,i)      Benchmark export world price,
EXM0(r,rr,i)     Benchmark export market price,
VTWR(r,rr,i)     Benchmark trade margins;
```

```
 X0(r,i,j)     = inputTable(r,i,j);
 Y0(r,i,j)            = outputTable(r,i,j);
 F0(r,f,j)     = inputTable(r,f,j);
 FDEM0(r,i)           = (sum (fd, fdTable(r,i,fd)));
 IM0(r,rr,i)          = importTable(r,rr,i);
 IMM0(r,rr,i)         = importmTable(r,rr,i);
 EX0(r,rr,i)          = exportTable(r,rr,i);
 EXM0(r,rr,i) = exportmTable(r,rr,i);
 VTWR(r,rr,i) = VTWRTable(r,rr,i);


 SET
         sf(f)   sluggish factors ie sector-specific  / NR /;

 PARAMETERS

 TC0(r)            Total consumption for each country,
 E0(r,f)           K and L and NR and LN endowed to the consumer for each
country,
 COMPROD(r,i)      Benchmark production by commodity,
 SECPROD(r,j)      Benchmark production by sector,
 USE0(r,i)         Benchmark domestic use of each commodity (including
intermediate use),
 BOTDEF(r)         Benchmark balance of trade deficit,
 totalexm(r)       total exports market price,
 totalimm(r)       total imports market price;

 E0(r,f)           = SUM(j, F0(r,f,j));
 TC0(r)            = SUM(i,FDEM0(r,i));
 COMPROD(r,i)      = SUM(j,Y0(r,i,j));
 SECPROD(r,j)      = SUM(i,Y0(r,i,j));
 USE0(r,i)         = SUM(j,X0(r,i,j)) + FDEM0(r,i);
 BOTDEF(r)         = (SUM(rr,(SUM(i,(IM0(r,rr,i)-EX0(r,rr,i)-VTWR(rr,r,i))))));
 totalexm(r)       = sum(i,(sum(rr, EXM0(r,rr,i))));
 totalimm(r)       = sum(i,(sum(rr, IMM0(r,rr,i))));

 DISPLAY X0, Y0, F0, FDEM0, E0, IM0, IMM0, EX0, EXM0, VTWR, TC0, COMPROD,
SECPROD, USE0, BOTDEF, totalimm, totalexm;

 * Capital stock split over time
 *(numbers based on capital depreciation 4% per year - see file: Depreciation
Rates - Aug 09.xls)
 Parameter
 FlexCapPer        Percent of capital stock that can move between sectors,
 FixCapPer         Percent of capital stock that is fixed in a specific sector,
 FlexCap           Flexible capital stock,
 FixCap            Fixed capital stock,
 test             sum of capital stock;

 If   (year = 2004,
 *        FlexCapPer = 0.8;
        FlexCapPer = 0.059;
 Elseif (year = 2010),
        FlexCapPer = 0.305;
 Elseif (year = 2020),
        FlexCapPer = 0.621;
 Elseif (year = 2030),
        FlexCapPer = 0.793;
 Elseif (year = 2040),
        FlexCapPer = 0.887;
 Elseif (year = 2050),
        FlexCapPer = 0.939;
 Else
```

```
        abort "error with year value";
 );


 FixCapPer        = (1-FlexCapPer);
 FlexCap(r)       = sum(j,(F0(r,"K",j)*FlexCapPer));
 FixCap(r,j)      = F0(r,"K",j)*FixCapPer;


 Display FlexCap, FixCap, test, E0,  FlexCapPer, FixCapPer;


 * Carbon Accounting Sector

 SET
 * We treat oil as a material feedstock for all sectors (i.e. oil is non
emitting)
        e(i)    energy goods only /  ELEC, GAS, COAL,  RPP/,
        fe(i)   final energy goods that emit carbon only / COAL, GAS, RPP /,
        lfe(i)  liquid final energy goods that emit carbon only  / GAS, RPP /,
        ne(i)   non energy goods only / OIL,  MET,  NMET,  OMAN,  TRANS,
ROE/,
        nce(i)  non carbon emitting goods only / OIL,  MET,  NMET,  OMAN,
TRANS, ROE, ELEC/,
        ele(i)  electricity only / ELEC /;

 ALIAS (fe,ff);

 PARAMETERS

        CARB_INT_GJ(r,fe) Emission of CO2 in tonnes per GJ of fuel consumed,
        FUEL_PJ0(r,fe)   Consumption of fuel in PJ,
        CO2EMIT0(r,fe)   Benchmark total CO2 emission by fuel in MT,
        CARBONCOEF(r,fe) Emission of CO2 by fuel in MT per dollar,
        TOTALCARB0(r)    Benchmark total CO2 emissions in MT,
        SECTORCARB0(r,j) Benchmark sector CO2 emission in MT,
        HOUSECARB(r)     Benchmark household CO2 emission in MT,
        ABATE(r)         Percentage of total emissions to be reduced,
        GLOBALABATE      Percentage of global emissions to be reduced;

 ABATE(r)$(opt=2) = 0;
 GLOBALABATE$(opt=1) = 0;

 * CO2 intesity for each fuel (these are from file: Carbon Content of fossil
fuels 2009.xls )  I calculated values form EIA CO2 intensities
 CARB_INT_GJ("US","COAL") = 0.09240;
 CARB_INT_GJ ("US","GAS") = 0.05029;
 CARB_INT_GJ ("US","RPP") = 0.06883;

 *These are based on the IPCC values for calcualting emissions
 CARB_INT_GJ("ROW","COAL") = 0.0901;
 CARB_INT_GJ ("ROW","GAS") = 0.0513;
 CARB_INT_GJ ("ROW","RPP") = 0.0718;

 *Fuel Forecast
 *1st line of US fuel #s are from 2004 EIA historical records - consumption of
fuel by source
 *1st line of ROW fuel #s are from 2004 EIA - International energy annual -
historical records - consumption of fuel by source
 *numbers from 2010 - 2050 from EIA and IEO see file: Energy Data Forecasts Aug
2009.xls   - I am concerned about RPP numbers - they are total RPP - not just
combustible ones

 If   (year = 2004,
```

```
          FUEL_PJ0("US","COAL") = 23848.4129;    FUEL_PJ0("US","GAS") =
24193.9932;     FUEL_PJ0("US","RPP")  = 42512.7909;
             FUEL_PJ0("ROW","COAL")= 98064.69402;   FUEL_PJ0("ROW","GAS")=
84757.39354;    FUEL_PJ0("ROW","RPP") = 133364.8097;

 Elseif (year = 2010),
             FUEL_PJ0("US","COAL") = 23447.81983;    FUEL_PJ0("US","GAS") =
23822.03281;     FUEL_PJ0("US","RPP")  = 39176.62979;
         FUEL_PJ0("ROW","COAL")= 124893.033;         FUEL_PJ0("ROW","GAS")=
101202.0857;        FUEL_PJ0("ROW","RPP") = 145141.6277;

 Elseif (year = 2020),
          FUEL_PJ0("US","COAL") = 25663.75749;    FUEL_PJ0("US","GAS") =
23357.8506;     FUEL_PJ0("US","RPP")  = 38636.86231;
             FUEL_PJ0("ROW","COAL")= 144938.7739;    FUEL_PJ0("ROW","GAS")=
126143.5637;    FUEL_PJ0("ROW","RPP") = 166254.9843;

 Elseif (year = 2030),
          FUEL_PJ0("US","COAL") = 26577.75836;    FUEL_PJ0("US","GAS") =
25486.72554;     FUEL_PJ0("US","RPP")  = 39036.01752;
             FUEL_PJ0("ROW","COAL")= 174093.8648;    FUEL_PJ0("ROW","GAS")=
141212.0992;        FUEL_PJ0("ROW","RPP") = 188539.5299;

 Elseif (year = 2040),
          FUEL_PJ0("US","COAL") = 27799.22816;    FUEL_PJ0("US","GAS") =
28399.8669;     FUEL_PJ0("US","RPP")  = 39721.01343;
             FUEL_PJ0("ROW","COAL")= 197096.4774;    FUEL_PJ0("ROW","GAS")=
162701.127;         FUEL_PJ0("ROW","RPP") = 210478.6796;

 Elseif (year = 2050),
          FUEL_PJ0("US","COAL") = 28950.46951;    FUEL_PJ0("US","GAS") =
30821.37895;     FUEL_PJ0("US","RPP")  = 40357.32044;
             FUEL_PJ0("ROW","COAL")= 222047.3178;    FUEL_PJ0("ROW","GAS")=
182121.9522;        FUEL_PJ0("ROW","RPP") = 232599.2338;

  Else
        abort "error with year and fuel value";
 );

 *Emission of CO2 if there is a carbon intensity value (if it actually emits
carbon)
 CO2EMIT0(r,fe)$CARB_INT_GJ(r,fe)         = FUEL_PJ0(r,fe) * CARB_INT_GJ(r,fe);
 CARBONCOEF(r,fe)$USE0(r,fe)              = CO2EMIT0(r,fe) /USE0(r,fe);

 TOTALCARB0(r)                      = SUM(fe, CO2EMIT0(r,fe));
 SECTORCARB0(r,j)                   = SUM(fe, X0(r,fe,j) * CARBONCOEF(r,fe));
 HOUSECARB(r)                       = SUM(fe, FDEM0(r,fe) * CARBONCOEF(r,fe));

 *Alternative sector for CCS
 SET

 s        Steps for CCS sector  /1,2,3/,
 q        Quantity of capacity for CCS sector /q/;

  PARAMETER

 ATechf(r,j,s,f)          Factor adjustment data for alternative CCS sector,
 ATechfe(r,j,s,fe)        Fuel (carbon emitting) adjustment data for
alternative CCS sector,
 ATechq(r,j,s)            Quantity of alternative CCS sector available,
 ATechcs(r,j,s)           Carbon sequestion (percent of fuel used that is
sequestered),
 altsec(r,j)              CCS sector indicator,

 CS0(r,j,s)                Carbon sequestration,
```

```
 XA0(r,j,s,i)              Benchmark fuel inputs to CCS sector,
 YA0(r,j,s,i)              Benchmark output from alternate sector,
 FA0(r,j,s,f)              Benchmark factors for CCS sector,
 EA0(r,j,s)                Endowments of capacity for CCS sector,
 ASECPROD(r,j,s)    secprod with (s);

 altsec(r,j)        =0;
 altsec(r,"ELECJ")  =1;

 ATechf("ROW",j,s,f) = ROWATech(j,s,f);
 ATechf("US",j,s,f)  = USATech(j,s,f);

 ATechfe("ROW",j,s,fe) = ROWATech(j,s,fe);
 ATechfe("US",j,s,fe)  = USATech(j,s,fe);

 ATechq ("US",j,s) = USATech(j,s,"Q");
 ATechq("ROW",j,s) = ROWATech(j,s,"Q");

 ATechcs("ROW", j, s)  = ROWATech(j,s,"CS");
 Atechcs("US", j, s)   = USATech(j,s,"CS");


 XA0(r,j,s,fe)$altsec(r,j)       = (X0(r,fe,j)*
(ATechfe(r,j,s,fe))*Atechq(r,j,s));
 XA0(r,j,s,i)$altsec(r,j)        = (X0(r,i,j)*Atechq(r,j,s));
 Sumxao(r,j)                     = sum(fe,(sum(s,(xa0(r,j,s,fe)))));
 YA0(r,j,s,i)$altsec(r,j)        = (Y0(r,i,j) * (ATechq(r,j,s)));
 ASECPROD(r,j,s)$altsec(r,j)     = sum(i,YA0(r,j,s,i)$altsec(r,j));
 FA0(r,j,s,f)$altsec(r,j)        = (F0(r,f,j) *
(1+Atechf(r,j,s,f))*Atechq(r,j,s));
 FA0(r,j,s,"LN")$altsec(r,j)     =
(Atechf(r,j,s,"LN")*YA0(r,"ELECJ","3","ELEC"));

 EA0(r,j,s)$altsec(r,j)          = (SECPROD(r,j) * Atechq(r,j,s));
 CS0(r,j,s)$altsec(r,j)          = (sum(fe,(CARBONCOEF(r,fe)*(XA0(r,j,s,fe)))*
ATechcs(r,j,s)));
 CS0(r,j,"3")$altsec(r,j)        = (Atechcs(r,j,"3") *
YA0(r,"ELECJ","3","ELEC"));


 *Revenue recycling
 PARAMETER      PR(r,j)    Percentage of carbon tax revenue recycled to sectors
instead of being given to households;

 PR(r,j) = 0;

 *International fund transfer - for use in regional mode to transfer money from
US to ROW
 PARAMETER   PT  percent for interntation fund transfer;
 PT$(opt=2)  = 0;


 *Permit allocation to different regions - use to allocate permit value to
different regions in global mode
 PARAMETER    allo    allocation of revenue to regions ;

 allo("US")$(opt=1)        = (TOTALCARB0("US")/(sum(r, TOTALCARB0(r))));
 allo("ROW")$(opt=1)       = (1 - allo("US")) ;


 *Load elasticities of substitution
 $INCLUDE                Elas_US_ROW Nov 12.txt
```

```
 Display  CO2EMIT0,FUEL_PJ0, CARB_INT_GJ,  FUEL_PJ0, esub_s, esub_ii, esub_vae,
esub_va, esub_cva, esub_slug, esub_mob, esub_e, esub_fuel, esub_lqd, edem_s,
edem_c, edem_e, edem_hou, esub_domex , esub_arm;


*MPSGE section

 $ONTEXT
 $MODEL:TRADE

 $SECTORS:

 Y(r,j)                    !Production from each sector from flexible capital
 X(r,j)$FixCap(r,j)        !Production from each sector from fixed capital
 Ya(r,j,s)$altsec(r,j)     !Alternative production of Electricity (CCS)
 CARB(r,fe)                !Production of carbon taxed energy commodities
 AR(r,i)                   !Armington aggregator for each commodity
 DOMEX(r,i)                !Domestic production for export or Armington
 C(r)                      !Consumption aggregate
 IMP(r,rr,i)$IM0(r,rr,i)   !Domestic import transformation sector

 $COMMODITIES:

 PY(r,i)                    !Price index for each commodity
 PLab(r)                    !Price index for Labour
 PflK(r)                    !Price index for flexible capital
 PLN(r)$E0(r,"LN")          !Price index for land
 PfixK(r,j)$FixCap(r,j)     !Price index for fixed capital (sector-specific) ie.
indexed over j
 PSF(r,sf,j)$F0(r,sf,j)     !Price index for natural resources (sector-specific)
ie. indexed over j
 PA(r,i)                    !Price index for Armington good
 PC(r)                      !Price index for aggregate consumption
 PD(r,i)                    !Price index for production for domestic consumption
 PX(r,rr,i)$EX0(r,rr,i)     !Price index for exports
 PM(r,rr,i)$IM0(r,rr,i)     !Price index for imports
 PAC(r,fe)                  !Price index for Armington goods with a carbon permit
 PCARB(r)$(ABATE(r) AND (opt=2))        !Price index of carbon permits
 PCARBGLOBE$(GLOBALABATE AND (opt=1))   !Price index of carbon permits for the
globe
 PQ(r,j,s)$altsec(r,j)      !Price index for capacity at alternative steps

 $AUXILIARY:

 LS(r,j)$(ABATE(r) and PR(r,j))             !Output subsidy transfer rate for
region r, sector j for regional permit method
 LS(r,j)$(GLOBALABATE and PR(r,j))          !Output subsidy transfer rate region
r, sector j for global permit method
 *TRN("US")$(PT AND ABATE("US"))         !Percent of of perimt revenue
transfered to international - Lump sum transfer of PC
 TRN$(PT)                          !Percent of of perimt revenue transfered to
international - Lump sum transfer of PC


 $CONSUMERS:

 CON(r)          !Representative agent
```

```
 $PROD:Y(r,j)    S:ESUB_S(r,j)   vae(s):ESUB_VAE(r,j)  ii(s):ESUB_II(r,j)
va(vae):ESUB_VA(r,j) e(vae):ESUB_E(r,j) slug(va):ESUB_SLUG(r,j)
mob(va):ESUB_MOB(r,j)  fuel(e):ESUB_FUEL(r,j) lqd(fuel):ESUB_LQD(r,j)

         I:PLab(r)                   Q:F0(r,"L",j)     mob:
         I:PflK(r)                   Q:F0(r,"K",j)     mob:
         I:PLN(r)                    Q:F0(r,"LN",j)    slug:
 `       I:PSF(r,sf,j)               Q:F0(r,sf,j)      slug:
         I:PA(r,nce)                 Q:X0(r,nce,j)     ii:$(not e(nce))
e:$ele(nce)
         I:PAC(r,"coal")             Q:X0(r,"coal",j)  fuel:
         I:PAC(r,lfe)                Q:X0(r,lfe,j)     lqd:
         O:PY(r,i)$(opt=2)           Q:Y0(r,i,j)       A:CON(r)
N:LS(r,j)$(ABATE(r) AND PR(r,j))        M:(-1)$(ABATE(r) AND PR(r,j))
         O:PY(r,i)$(opt=1)           Q:Y0(r,i,j)       A:CON(r)
N:LS(r,j)$(GLOBALABATE AND PR(r,j))     M:(-1)$(GLOBALABATE AND PR(r,j))


 $PROD:X(r,j)$FixCap(r,j)  s:0

         I:PLab(r)                   Q:F0(r,"L",j)
         I:PfixK(r,j)                Q:F0(r,"K",j)
         I:PLN(r)                    Q:F0(r,"LN",j)
 `       I:PSF(r,sf,j)               Q:F0(r,sf,j)
         I:PA(r,nce)                 Q:X0(r,nce,j)
         I:PAC(r,"coal")             Q:X0(r,"coal",j)
         I:PAC(r,lfe)                Q:X0(r,lfe,j)
         O:PY(r,i)$(opt=2)           Q:Y0(r,i,j)       A:CON(r)
N:LS(r,j)$(ABATE(r) AND PR(r,j))        M:(-1)$(ABATE(r) AND PR(r,j))
         O:PY(r,i)$(opt=1)           Q:Y0(r,i,j)       A:CON(r)
N:LS(r,j)$(GLOBALABATE AND PR(r,j))     M:(-1)$(GLOBALABATE AND PR(r,j))

 $PROD:Ya(r,j,s)$altsec(r,j)  cs1:0  cs(cs1):0   cvae(s):0
cva(cvae):ESUB_CVA(r,"ELECJ")  ce(cvae):ESUB_E(r,j)  cslu(cva):0   cmob(cva):0
cfue(ce):ESUB_FUEL(r,j)  clqd(cfue):ESUB_LQD(r,j)     T:0

         I:PLab(r)                   Q:FA0(r,j,s,"L")      cmob:
         I:PflK(r)                   Q:FA0(r,j,s,"K")      cmob:
         I:PLN(r)                    Q:FA0(r,j,s,"LN")     cslu:
 `       I:PSF(r,sf,j)               Q:FA0(r,j,s,sf)       cslu:
         I:PA(r,ele)                 Q:XA0(r,j,s,ele)      ce:
         I:PA(r,ne)                  Q:XA0(r,j,s,ne)       cs1:
         I:PAC(r,"COAL")             Q:XA0(r,j,s,"COAL")   cfue:
         I:PAC(r,lfe)                Q:XA0(r,j,s,lfe)      clqd:
         I:PQ(r,j,s)$altsec(r,j)     Q:ASECPROD(r,j,s)
         O:PY(r,i)                   Q:YA0(r,j,s,i)
         O:PCARB(r)$(ABATE(r) AND (opt=2))             Q:CS0(r,j,s)
         O:PCARBGLOBE$(GLOBALABATE AND (opt=1))        Q:CS0(r,j,s)

 $PROD:CARB(r,fe)           s:0

         I:PA(r,fe)                                 Q:USE0(r,fe)
         I:PCARB(r)$(ABATE(r) AND (opt=2))
Q:((CARBONCOEF(r,fe)*USE0(r,fe)))
         I:PCARBGLOBE$(GLOBALABATE AND (opt=1))
Q:((CARBONCOEF(r,fe)*USE0(r,fe)))
         O:PAC(r,fe)                                Q:USE0(r,fe)

 $PROD:DOMEX(r,i)       T:ESUB_DOMEX(r,i)

         I:PY(r,i)                     Q:COMPROD(r,i)
         O:PX(r,rr,i)$EXM0(r,rr,i)     Q:EXM0(r,rr,i)
         O:PD(r,i)                     Q:(COMPROD(r,i)-(sum(rr,EXM0(r,rr,i))))

 $PROD:IMP(r,rr,i)$IM0(r,rr,i)
```

```
        I:PX(rr,r,i)$EX0(rr,r,i)              Q:(EX0(rr,r,i)+ VTWR(r,rr,i))
        O:PM(r,rr,i)                          Q:IM0(r,rr,i)

 $PROD:AR(r,i)$USE0(r,i)    S:ESUB_ARM(r,i)

        I:PD(r,i)       Q:(COMPROD(r,i)-(sum(rr,EXM0(r,rr,i))))
        I:PM(r,rr,i)    Q:IMM0(r,rr,i)
        O:PA(r,i)       Q:(COMPROD(r,i)-(sum(rr,EXM0(r,rr,i))) +
(sum(rr,IMM0(r,rr,i))))

 $PROD:C(r)  S:EDEM_S(r)       c(S):EDEM_C(r)        e(S):EDEM_E(r)
hou(e):EDEM_HOU(r)

        I:PA(r,nce)              Q:FDEM0(r,nce)        c:$(not e(nce))
hou:$ele(nce)
        I:PAC(r,"coal")          Q:FDEM0(r,"coal")     e:
        I:PAC(r,"gas")           Q:FDEM0(r,"gas")      hou:
        I:PAC(r,"rpp")           Q:FDEM0(r,"rpp")      e:
        O:PC(r)                  Q:TC0(r)



 $DEMAND: CON(r)

      D:PC(r)                     Q:(TC0(r))
      E:PLab(r)                   Q:E0(r,"L")
      E:PflK(r)$E0(r,"K")         Q:FlexCap(r)
      E:PfixK(r,j)                Q:FixCap(r,j)
      E:PSF(r,sf,j)$F0(r,"NR",j) Q:F0(r,"NR",j)
      E:PLN(r)$E0(r,"LN")         Q:E0(r,"LN")
      E:PX(r,rr,i)                Q:((-1)*((EXM0(r,rr,i)-EX0(r,rr,i)-
VTWR(rr,r,i))))
      E:PM(r,rr,i)                Q:(IMM0(r,rr,i)-IM0(r,rr,i))
      E:PCARBGLOBE$(GLOBALABATE AND (opt=1))  Q:((1-
GLOBALABATE)*(SUM(rr,(SUM(fe,(CARBONCOEF(rr,fe)*USE0(rr,fe))))))*allo(r))
      E:PCARB(r)$(ABATE(r) AND (opt=2))       Q:((1-
ABATE(r))*(sum(fe,(CARBONCOEF(r,fe)*USE0(r,fe))))
      E:PC("US")$(BOTDEF(r))                  Q:(BOTDEF(r))
      E:PQ(r,j,s)$altsec(r,j)                 Q:(EA0(r,j,s))
      E:PC("US")$(PT)                         Q:(-1) R:TRN
      E:PC("ROW")$(PT)                        Q:1    R:TRN


 $REPORT:
         V:TotalFuelDemand(r,fe)         O:PAC(r,fe)          PROD:CARB(r,fe)
         V:NumberofGlobalPermits(r,fe)$(opt=1)        I:PCARBGLOBE
PROD:CARB(r,fe)
         V:Imports(r,rr,i)             O:PM(r,rr,i)        PROD:IMP(r,rr,i)
         V:Exports(r,rr,i)             O:PX(r,rr,i)        PROD:DOMEX(r,i)
         V:FlexCapDem(r,j)             I:PflK(r)           PROD:Y(r,j)
         V:FlexCapDemYa(r,j,s)$altsec(r,j)   I:PflK(r)     PROD:Ya(r,j,s)
         V:FixCapDemX(r,j)$FixCap(r,j)       I:PfixK(r,j)   PROD:X(r,j)
         V:FacDemS(r,sf,j)             I:PSF(r,sf,j)       PROD:Y(r,j)
         V:FacDemSX(r,sf,j)            I:PSF(r,sf,j)       PROD:X(r,j)
         V:FacDemSYa(r,sf,j,s)$altsec(r,j)   I:PSF(r,sf,j)  PROD:Ya(r,j,s)
         V:FinDem(r,nce)               I:PA(r,nce)         PROD:C(r)
         V:FinDemCarb(r,fe)            I:PAC(r,fe)         PROD:C(r)
         V:LabDem(r,j)                 I:PLab(r)           PROD:Y(r,j)
         V:LabDemYa(r,j,s)$altsec(r,j) I:PLab(r)           PROD:Ya(r,j,s)
         V:LabDemX(r,j)                I:PLab(r)           PROD:X(r,j)
         V:LNDem(r,j)                  I:PLN(r)            PROD:Y(r,j)
         V:LNDemX(r,j)                 I:PLN(r)            PROD:X(r,j)
         V:LNDemYa(r,j,s)$altsec(r,j)  I:PLN(r)            PROD:Ya(r,j,s)
         V:Qij(r,i,j)                  O:PY(r,i)           PROD:Y(r,j)
```

```
        V:QijX(r,i,j)                   O:PY(r,i)           PROD:X(r,j)
        V:QijYa(r,i,j,s)$altsec(r,j)  O:PY(r,i)           PROD:Ya(r,j,s)
        V:Capacity(r,j,s)$altsec(r,j) I:PQ(r,j,s)         PROD:Ya(r,j,s)
        V:SectorFuelUse(r,fe,j)       I:PAC(r,fe)         PROD:Y(r,j)
        V:SectorFuelUseX(r,fe,j)      I:PAC(r,fe)          PROD:X(r,j)
        V:SectorFuelUseYa(r,fe,j,s)$altsec(r,j)  I:PAC(r,fe)  PROD:Ya(r,j,s)
        V:SectorPAUseY(r,nce,j)       I:PA(r,nce)          PROD:Y(r,j)
        V:SectorPAUseX(r,nce,j)       I:PA(r,nce)          PROD:X(r,j)
        V:SectorPAUseYa(r,nce,j,s)$altsec(r,j)   I:PA(r,nce)  PROD:Ya(r,j,s)
        V:SectorPCarb(r,j,s)$(opt=2)  O:PCARB(r)           PROD:Ya(r,j,s)
        V:SectorPCarbGlobe(r,j,s)$(opt=1)        O:PCARBGLOBE  PROD:Ya(r,j,s)
        V:EqVar(r)                    W:CON(r)
 * EqVar - similar to consumer surplus

 $CONSTRAINT: TRN$(PT)
 TRN*PC("US")  =e= PCARB("US")*(1-
ABATE("US"))*(SUM(fe,(CARBONCOEF("US",fe)*USE0("US",fe))))*PT;

 * Application of an output subsidy as a tax rate. It is divided by total
output in order to get a RATE, which is applied to the output of the sector.
 *In both LS equations, both sides are divided by PC, so they cancel out. In
the policy file the PC is retained in the term with secprod and asecprod.

 $CONSTRAINT: LS(r,j)$(ABATE(r) AND PR(r,j))
 LS(r,j)*(sum(i,((((Y(r,j)+
X(r,j))*SECPROD(r,j))+(sum(s,(Ya(r,j,s)$altsec(r,j)*ASECPROD(r,j,s)))))*PY(r,i)
)))=e= PCARB(r)*PR(r,j)*((1-ABATE(r)))*(SUM(fe,(CARBONCOEF(r,fe)*USE0(r,fe))));


 $CONSTRAINT: LS(r,j)$(GLOBALABATE AND PR(r,j))
 LS(r,j)*(sum(i,(((((Y(r,j)+ X(r,j))*SECPROD(r,j))
+(sum(s,(Ya(r,j,s)$altsec(r,j)*ASECPROD(r,j,s)))))*PY(r,i)))))=e=
PCARBGLOBE*(SUM(rr,(SUM(fe,(CARBONCOEF(rr,fe)*USE0(rr,fe))))))*(1-
GLOBALABATE)*allo(r)*PR(r,j);

 $OFFTEXT

 $SYSINCLUDE MPSGESET     TRADE

 * set Numeraire
 PLab.FX ("US")       = 1 ;

 *This statement imposes a lower bound on industry output in the counterfactual
(hopefully prevents LS(r,j) from crashing)
 Y.LO(r,j) =  0.001;

 *Include policy file
 $INCLUDE "globalpoliciesDec3.gms" ;
```

## Appendix B: Set j - Sectors in VERITAS-US

| Sector | Description of Sectoral Activities |
|---|---|
| **OILJ** | Crude Oil: Extraction of crude petroleum |
| **ELECJ** | Electricity: electricity production and distribution |
| **GASJ** | Natural Gas: gas extraction, manufacture and distribution |
| **COALJ** | Coal: coal mining and agglomeration |
| **RPPJ** | Refined Petroleum Products: refined petroleum products and coke |
| **METJ** | Metal Industry: metal mining and manufacture (minerals, ferrous metals, other metals, metal products) |
| **NMETJ** | Non-Mental Industry: wood products, paper products and publishing, chemical, rubber, plastic products, non-metal mineral products |
| **OMANJ** | Other Manufacture: food and beverage manufacture and processing, textile, leather and clothing manufacture, motor vehicle parts and transportation equipment, electronics, machinery and equipment, other manufacture |
| **TRANJ** | Transportation: sea, air and other transport |
| **ROEJ** | Rest of Economy: trade, insurance, communication, financial services, business services, recreation, public administration, defence, health, education, dwellings, construction, water, fishing, forestry, agriculture (producing raw products) |

## Appendix C: Sector Specific Elasticities of Substitution for the US and ROW

| US Elasticities | | | | | | |
|---|---|---|---|---|---|---|
| **Sector** | between factors and energy, $\sigma_{VAE}$ | between capital and labour, $\sigma_{MOB}$ | between fuels and electricity, $\sigma_{E}$ | between coal and liquid fuels, $\sigma_{FUEL}$ | between liquid fuels, $\sigma_{LQD}$ | between domestic and foreign goods, $\sigma_{ARM}$ |
| OILJ | 0.45* | 0.2 | 0.75 | 0.64 | 1.23 | 10 |
| ELECJ | 0.45* | 1.3 | 0.475* | 3.95 | 5.85 | 0.3 |
| GASJ | 0.53 | 0.7 | 1.01 | 0.75* | 0.85 | 2.8 |
| COALJ | 0.60 | 0.2 | 1.20 | 0.40 | 0.28 | 2.3 |
| RPPJ | 0.45* | 1.3 | 0.475* | 0.75* | 2.75 | 2.3 |
| METJ | 0.52 | 1.3 | 0.90 | 0.42 | 1.33 | 2.6 |
| NMETJ | 0.48 | 1.3 | 0.31 | 1.93 | 2.57 | 1.9 |
| OMANJ | 0.49 | 1.2 | 0.48 | 3.38 | 5.66 | 1.5 |
| TRANJ | 0.45* | 1.7 | 0.475* | 0.75* | 1.00 | 2.59 |
| ROEJ | 0.42 | 1.2 | 0.58 | 0.75* | 1.95 | 2.1 |

*Indicates use of default value based on references from Table 2.2 and Table 2.4

| ROW Elasticities | | | | | | |
|---|---|---|---|---|---|---|
| **Sector** | between factors and energy, $\sigma_{VAE}$ | between capital and labour, $\sigma_{MOB}$ | between fuels and electricity, $\sigma_{E}$ | between coal and liquid fuels, $\sigma_{FUEL}$ | between liquid fuels, $\sigma_{LQD}$ | between domestic and foreign goods, $\sigma_{ARM}$ |
| OILJ | 0.45* | 0.2 | 0.475* | 0.75* | 1.01 | 10 |
| ELECJ | 0.45* | 1.3 | 0.475* | 2.17 | 1.00 | 0.3 |
| GASJ | 0.53 | 0.7 | 0.475* | 1.00 | 1.6* | 2.8 |
| COALJ | 0.60 | 0.2 | 1.20 | 0.75* | 0.99 | 2.8 |
| RPPJ | 0.45* | 1.3 | 0.475* | 0.75* | 2.75 | 1.9 |
| METJ | 0.52 | 1.3 | 0.90 | 0.42 | 1.33 | 2.8 |
| NMETJ | 0.48 | 1.3 | 0.31 | 1.93 | 2.57 | 1.9 |
| OMANJ | 0.49 | 1.2 | 0.28 | 0.75* | 2.99 | 2.59 |
| TRANJ | 0.45* | 1.7 | 0.475* | 0.75* | 1.00 | 2.59 |
| ROEJ | 0.42 | 1.2 | 1.80 | 0.80 | 1.24 | 2.1 |

*Indicates use of default value based on references from Table 2.2 and Table 2.4

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