

EVALUATION OF INTERNATIONAL CLIMATE CHANGE ARCHITECTURES USING A COMPUTABLE GENERAL EQUILIBRIUM MODEL

by

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B.Sc. (Env.), University of Guelph, 2006

PROJECT SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF RESOURCE MANAGEMENT

In the
School of Resource and Environmental Management

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SIMON FRASER UNIVERSITY
Spring 2010

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ABSTRACT

This study employs a computable general equilibrium model to explore the effects of various components of an international climate change architecture on global and regional emissions price paths and welfare. Within a universally adopted cap-and-trade system, I assess the effects of changing the method of emissions permit allocation, co-ordination of trading systems amongst regions, and ambition of the emissions reduction target.

I find that wealth effects may increase the global emissions price required to reach a specified reduction target when permits are allocated to regions with higher consumer emissions intensity, namely developing regions. All regions benefit from global permit trading although the regions with higher marginal abatement costs, namely industrialized and transition economy regions, experience greater welfare gains. Lastly, reaching an aggressive reduction target requires a significantly higher global emissions price and results in greater welfare losses in most regions.

Keywords: international climate change architecture; computable general equilibrium model; energy-economy model; cap-and-trade system

ACKNOWLEDGEMENTS

I would like to thank Mark Jaccard, for his insightful guidance and support throughout this process. I am indebted to Nic Rivers for his invaluable technical support and constant willingness to help. I would also like to thank Noory Meghji for her positive and lively presence.

Thanks to Jodie Capling for going through this process with me, without whom undertaking this project would have been less fun and taken much longer.

I am grateful for the funding provided for this project by Simon Fraser University, the Government of British Columbia, the National Science and Engineering Research Council (NSERC), and the Pacific Institute for Climate Solutions (PICS).

Lastly, I would like to give Pat a special thanks for his ongoing support.

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GLOSSARY

AEEI	Autonomous Energy Efficiency Index
AMELA	Africa, Middle East, and Latin America.
ASIA	Developing Asia region
BAU	Business-as-usual
CAN	Canada
CHN	China
CGE	Computable General Equilibrium
EEU	Eastern Europe and former Soviet Union region
EIA	Energy Information Administration
ESUB	Elasticity of substitution
EV	Equivalent variation
GAMS	General Algebraic Modelling System
GDP	Gross Domestic Product
GTAP	Global Trade Analysis Project
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MPS/GE	Mathematical Programming System for General Equilibrium
OECD	OECD regions, including Europe, the Pacific, and Mexico
RPP	Refined petroleum product
SAM	Social Accounting Matrix
tCO₂	Tonnes of CO ₂
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

VERITAS

Evaluation of **E**missions **R**eductions in **I**nternational
Abatement **S**cenarios

1: INTRODUCTION

Climate change has become a prioritized issue in the international political arena, with the nature and magnitude of climate change effects now predicted to become even greater than originally asserted by the scientific community (Intergovernmental Panel on Climate Change, 2007). In December 2009, representatives of countries from around the world attended a meeting in Copenhagen, Denmark, to negotiate the components of a new global agreement to address climate change, set to succeed the first commitment period of the Kyoto Protocol, which expires in 2012.

It is apparent that the successful negotiation of a post-Kyoto agreement will require the careful examination of a number of factors, which broadly include considerations of economic efficiency, environmental effectiveness, and equity. This study aims to use a global computable general equilibrium economic model to assess various characteristics of post-Kyoto policy architectures, including welfare impacts, regional abatement costs, and greenhouse gas emission reductions in various world regions.

A unique trait of this study is that the model employed uses specific parameters generated within a hybrid energy-economy model CIMS, which provides unique insights into understanding the effects of greenhouse gas reduction policies within an economy.

1.1 International Climate Change Policy: A Background

Climate change has emerged as one of the most pressing and prioritized international issues today. Ban Ki-Moon, Secretary-General of the United Nations, has stated that climate change is “simply, the greatest collective challenge we face as a human family” (Ban, 2009). Accumulation of greenhouse

gases (primarily carbon dioxide) in the Earth's atmosphere is producing effects on the global climate, which are being manifested in myriad ways. Average global temperatures have risen since pre-industrial levels and, for the past half a century, humans contributed substantially to this effect. According to the Intergovernmental Panel on Climate Change (IPCC), “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.” Other current and projected effects of climate change include melting of sea ice, sea level rise, changes in precipitation amounts, increased intensity of cyclones, and prolonged droughts (IPCC, 2007a).

The United Nations Framework Convention on Climate Change (UNFCCC) is an international treaty that was created in 1992 with the purpose of addressing climate change multilaterally. It entered into force in 1994 and enjoys almost universal participation, with 192 countries having ratified the treaty. The UNFCCC is the only international agreement with the direct mandate for addressing climate change.

The Convention establishes non-binding commitments for countries to reduce their greenhouse emissions, with the ultimate goal to “prevent dangerous anthropogenic interference with Earth's climate system” (UN, 1992). In relating this goal to a specific temperature target, the European Union first adopted a goal of preventing a 2°C rise above pre-industrial levels in 1996. Since then, 2°C has established itself as a de facto temperature target for the international community, supported by science presented through the IPCC.

Under the umbrella of the UNFCCC, the Kyoto Protocol was negotiated in 1997 and entered into force in 2005. The major feature of the Protocol is that it establishes legally binding commitments for 37 industrialized countries to reduce greenhouse gas emissions by an average of 5% below 1990 levels, in the first commitment period of 2008-2012. It served as the first multilateral treaty, which set legally binding greenhouse gas emissions targets for nations.

The UNFCCC also defined the need for “common but differentiated responsibilities” of nations to address climate change, explicitly stating that developed nations should take the lead in acting (UN, 1992). With respect to emissions mitigation, this principle asserts that although all nations have a role to play in reducing global greenhouse gas emissions, responsibilities are differentiated based on historical responsibility and ability to pay for emission reductions. This text has helped define the language around equity within the international climate change forum; however, it is apparent that the principle of “common but differentiated responsibilities” can be interpreted in various ways.

Each year, the parties of the UNFCCC meet at the Conference of Parties (COP) in order to progress on the mandate of the Convention. The Copenhagen meeting comprised the fifteenth meeting of this kind and is therefore referred to as COP15. The international community agreed at COP13 in Bali, Indonesia, that a successful post-Kyoto agreement would be negotiated by the end of the Copenhagen talks in December 2009.

A legally binding and ratifiable treaty did not emerge from COP15, although progress was made on certain aspects of an international architecture for agreement. Developing nations, for the first time, have taken on commitments to mitigate greenhouse gas emissions. Developed nations have also agreed upon aggregate numbers for financial commitments, in both the short- and long-term, to help developing nations in the capacities of mitigation and adaptation. The Accord also formalized the global temperature target of preventing a 2 °C rise above pre-industrial levels. Despite these progressions, the Copenhagen Accord is largely seen as simply a first step in defining global actions on climate change for the post-2012 period. Negotiations will continue in Bonn, Germany at two intersessional meetings and COP16 will take place in Cancun, Mexico in December 2010. There is a fair amount of anticipation for the 2010 year to bring about the progress needed to solidify a new deal by the end of COP16, which is the implicit new deadline for agreeing on a post-Kyoto international architecture.

1.2 Issues of Equity

Some of the dominant challenges of reaching an international greenhouse gas emissions agreement relate to equity issues, and it is largely recognized that an international agreement that does not adequately address issues of distribution and equity will not be accepted by the majority of the international community. One issue to address is, given that industrialized countries have primarily contributed to the current accumulation of atmospheric greenhouse gases, how should abatement costs and emission targets be distributed? Furthermore, do we (and if so how do we) account for each country's differential ability to pay and the economic effects on each country?

Most studies examining equity issues in climate change use allocation-based or outcome-based criteria for assessment of equity (Bodansky et al., 2004; den Elzen and Lucas, 2005). Allocation-based equity relates to fair distribution of emission rights, such as emission permits. Outcome-based equity focuses on the effects of a regime and relates to fair distribution of the economic or welfare effect.

Equity in allocating emissions rights can be measured according to various principles. The *egalitarian* principle asserts that since every person has equal right to use the atmosphere, each individual (or each country on a per capita basis) should be allocated equal emission rights. The *sovereignty* principle states that since each country has the same right to use the atmosphere as they do now (status quo), current emissions should be used as the baseline for reductions. According to the *historical responsibility* principle, the countries responsible for the greatest cumulative greenhouse gas emissions should bear the greatest burden in emissions reductions or economic obligation. In other words, countries with the greatest historic emissions (industrialized countries) face the greatest reduction requirements and are allocated proportionately few emissions rights. Lastly, the *capability/ability to pay* principle states that those countries with higher wealth should face greater reduction obligations due to higher capacity to pay for emissions reductions. Thus, these countries are

allocated proportionately few emission rights compared to countries with low income. As an extension of this, the *basic need* principle asserts that the least capable countries should be exempt from any reductions in order to secure their basic needs, thereby resulting in allocation of emissions rights that do not constrain growth in these regions (den Elzen and Lucas, 2005; Peterson and Klepper, 2009).

It is apparent that conceptualizations of what is “fair” or “equitable” can vary tremendously, and one of the most apparent divides exists amongst global North and global South countries. In a generalization, Ikeme (2003) states that the global North (the industrialized world) focuses more upon consequentialist, or outcome-based, notions of equity such as principles of market efficiency and GDP-based and welfare-based outcomes of climate policies. On the other hand, the global South (the developing world) focuses on equity principles such as redistributive justice and historical responsibility, egalitarianism, and polluter pays. These equity principles place greater emphasis on process-based equity, which includes fair allocation of emissions rights.

As definitions of what is “fairest” vary widely, this analysis will not attempt to evaluate the equity of various climate architectures. Instead, I employ various allocation-based principles in policy scenarios and discuss the potential trade-offs with other policy goals, in particular economic efficiency.

1.3 A Hybrid Energy-Economy Model: CIMS

Energy-economy models aim to represent the complex relationships between the environment and human behaviour within an economy. Drawing from the famous quote by Box and Draper (1987), “all models are flawed, but some are useful,” energy-economy models help generate our best guesses at the potential effects of certain environmental policies.

CIMS is one of the energy-economy models employed in this study. It is referred to as a hybrid model, because it contains characteristics of conventional top-down and bottom-up energy-economy models.

Top-down models tend to represent the economy in terms of aggregate inputs. Relationships are specified by the modeller for these inputs and their relative costs, as well as for their linkages to broader equilibrium feedbacks (Jaccard, 2005). As a result of aggregation, top down models conventionally contain little technological detail, but represent dynamic feedbacks throughout the economy.

The output of top-down models is determined by key parameters, notably the elasticities of substitution, which define the substitutability between two inputs in the production of a commodity. These values are important in defining how responsive firms and households are to changing price signals that may be caused by a new policy. Elasticities of substitution are sometimes derived through econometric estimation from historical data and therefore top-down models contain a level of behavioural realism. However, the use of historical data in determining these parameters results in an inability to account for future drivers of technological change, as future technologies and consumer priorities may differ significantly (Bataille, 2005). This becomes of greater concern the farther into the future the model simulates. This is why top-down models tend to overestimate the costs of reaching a level of emissions reduction, especially if their parameters fail to fully account for the adaptability of future economies to carbon constraints, for instance, through the invention and adoption of new low-carbon technologies (Rivers and Jaccard, 2005).

On the other hand, bottom-up models conventionally contain a high level of technological detail and can represent a wide array of technologies. These models favour technologies with the lowest financial costs. In this approach, technologies providing the same energy service (such as transporting one person one kilometre) are considered perfectly substitutable except for their financial costs and their environmental impacts (ie. greenhouse gas emissions) (Jaccard, 2005). However, important non-financial considerations, such as consumer preference and risk, are not included in the process of technology choice. Using the same example of providing the energy service of transportation, non-financial factors, such as aesthetics (or image) and brand

loyalty, are important in the decision of purchasing a vehicle. Therefore, bottom-up models tend to poorly represent certain behavioural realities.

Due to the complexity in technology representation, they also lack comprehensive equilibrium feedbacks. By excluding intangible costs of technological change and capital stock inertia, bottom-up models tend to overestimate the ease and thus underestimate the cost of transitioning to more energy-efficient technologies (Rivers and Jaccard, 2005; Murphy et al., 2007).

CIMS was created as a bottom-up, technologically explicit energy-economy model and has since been developed to incorporate behavioural parameters as well as partial equilibrium feedbacks. Behaviour of consumers and firms is modelled by including considerations beyond financial costs of technologies. These include intangible costs and benefits of different technologies, time preference for any given energy service demand, and heterogeneity in the market to reflect differences in life cycle costs (including both financial and intangible costs) of technologies providing the same energy service (Rivers and Jaccard, 2005). Thus, CIMS attempts to bring together the benefits of bottom-up models with technological detail and benefits of top-down models, namely equilibrium feedbacks and behavioural realism. Furthermore, CIMS has recently been expanded to represent all global regions beyond its previous applications to Canada, the US, and China. The regions in this modelling study are consistent with the seven global regions in CIMS.

1.4 Elasticities of Substitution

A computable general equilibrium model, which subscribes to the top-down modelling approach, was created in order to simulate different climate policy scenarios for this study. This model is informed by parameters from CIMS, called elasticities of substitution (ESUBs). The sensitivity of computable general equilibrium models to exogenously set ESUB values has been widely recognized (Wigle, 1991; Bataille, 2005; Hertel et al., 2007). It is therefore important to seek

rigorous procedures for estimating ESUB values and, in any case, to perform sensitivity analyses on these uncertain parameters.

ESUBs quantify the ease of substituting between two inputs with a change in their relative prices, for example, between capital and labour in the production of a commodity. Specifically, they indicate the relative change in the quantity of two inputs to production resulting from a relative change their prices. A higher ESUB value between two inputs indicates greater ease of substitutability.

In this modelling study, ESUBs are important for determining the responsiveness of the economy to an emissions price stimulus. ESUBs quantify the ease of switching between production inputs when the cost of producing carbon emissions increases, for example, in substituting fossil fuels with electricity. A higher ESUB value between these inputs indicates that sectors or consumers will replace fossil fuels with electricity more readily. ESUBs are therefore critical in understanding the effects of an emissions reduction policy, by determining the emissions price signal required to reach a certain reduction target or the welfare losses experienced by an economy.

The ESUB values used in this study are constant elasticities of substitution. They are referred to as *constant* because they remain the same over any proportion of inputs. For example, in producing a commodity using capital and labour, the two inputs are assumed to exhibit the same substitutability, whether there are 10 units of capital and 1 unit of labour, or vice-versa. On the output side, constant elasticities of transformation (CET) describe the differentiation in the output of commodities, for example between production of commodities for domestic consumption or export.

Elasticities of substitution (elasticities of transformation are much less common) are often derived either subjectively by expert judgment or through econometric estimation from historical data. Although the latter method is more empirically sound as compared to the former, historical data can only go so far in providing information to models that attempt to project into the future.

Deriving these values from CIMS can offer added benefits over these two methods, by incorporating potential future abatement technologies and by using more empirically robust techniques beyond simple judgment. Thus, using ESUBs from CIMS can help translate insights about input substitutabilities from CIMS to the modelling simulations in this study.

1.5 Research Goal and Questions

In designing and negotiating components of an international climate change architecture, policymakers require sound information on the potential impacts of different policy choices. This study aims to provide a timely contribution to the climate change discourse, given the attention on the climate issue in the international arena and the desire for robust analyses on region-specific policy implications.

Thus, the primary goal of this study is to elucidate the regional abatement costs and welfare impacts of various characteristics of a global climate change architecture, by creating a computable general equilibrium model appropriate for assessing aggregate impacts of international climate policy. In reaching this goal, I aim to answer the following research questions:

1. What are the global and regional effects of varying methods of emissions permit allocation in a global permit trading system?
2. What are the regional effects of varying coordination (trading) amongst regional permit systems?
3. What are the relative marginal abatement costs in each global region?
4. What are the global and regional effects of varying the global emissions reduction target?
5. How sensitive is model output to assumptions in key parameters?

1.6 Report Outline

In Chapter 1, I have provided the rationale for conducting research on international climate change architectures at a time when political and public attention on global climate change is heightened and significant climate change decisions at the international and national levels are being made. I have also described the importance of considering various principles of equity within a future international framework.

Chapter 2 describes the computable general equilibrium model I created for assessing various architectures characteristics. I then outline the policy scenarios simulated in the model, as well as the methodology for analyzing uncertainty in key model parameters.

Chapter 3 presents the results and analysis of the model simulations, mostly in the form of graphs showing carbon emissions price paths and regional effects on welfare. This chapter also includes results of the sensitivity analysis for addressing model uncertainty.

Chapter 4 provides a deeper discussion of the findings. Firstly, I compare the business-as-usual forecasts used in this study with those from other sources. I then discuss certain themes that have emerged from the model simulations, including the importance of international trade effects in determining regional welfare impacts. Chapter 4 concludes with a discussion of study limitations and potential improvement for future work.

This report ends with a summary of key findings and study conclusions in Chapter 5.

2: METHODS

In this chapter, I describe the methodology used for creating a computable general equilibrium (CGE) model designed for evaluating international climate change architectures. The model is called VERITAS, which is an acronym for the **E**valuation of **E**missions **R**eductions in **I**nTernational **A**batement **S**cenarios¹. I begin by providing a brief overview of CGE modelling in general, followed by a description of VERITAS, including its basic structure, method for emission accounting and the uniqueness of its elasticity of substitution values. I then describe each of the policy simulations as well as the sensitivity analyses performed on uncertain parameters within the model.

2.1 Computable General Equilibrium Modelling

In broad terms, general equilibrium in an economy is characterized by a situation where agents cannot be better off given their constraints and preferences, known as Pareto optimality, as well as where specific equilibrium conditions are met (for example, where supply equals demand for each commodity) (Markusen, 2005). Agents in an economy are generally identified as households and firms.

General equilibrium modelling is based on conceptualizing the economy as closed with circular flows, as is represented in Figure 1 (Sue Wing, 2009).

¹Veritas is the Roman goddess of truth.

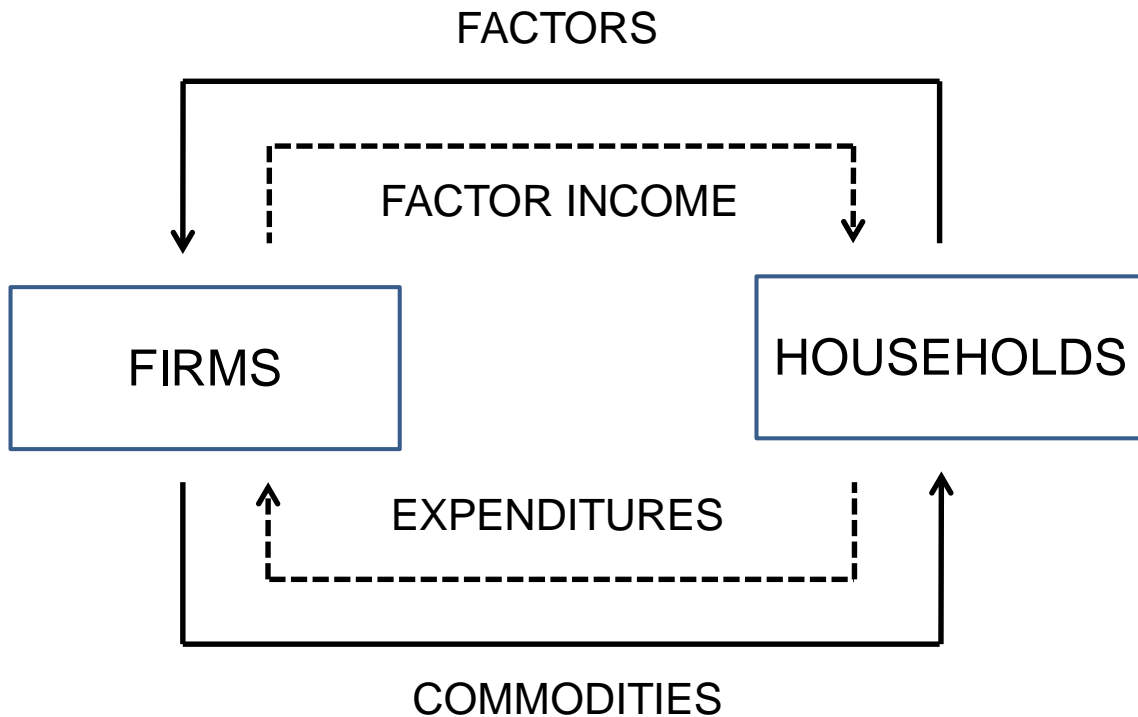


Figure 1 Representation of a closed, circular economy

In Figure 1, the solid lines represent the transfer of goods and services and the dotted lines represent the transfer of payments. Following the solid lines, households rent out factors, such as labour and capital, to firms to produce commodities. Households (also known as consumers or representative agents) consume these commodities. Following the dotted lines, firms pay households for the use of factors, while households pay firms for commodities they consume. A government can also be added as an agent in the economy, though it is excluded here on the assumption that it acts simply as an intermediate transfer for commodities and payments between firms and households

In this circular representation of the closed economy, three conditions must be satisfied in order to maintain conservation of both value and product and for general equilibrium in the economy to be achieved (Sue Wing, 2004). In the following set of equilibrium equations, let i represent the set of commodities $\{1, \dots, N\}$, let j represent the set of sectors $\{1, \dots, N\}$, and let f represent the set of

factors $\{1, \dots, F\}$. Assume there is a single household (representative consumer), which consumes commodities in the form of final demand.

Furthermore, let y represent the quantity of gross output, let d represent the quantity of final demand, let v represent the quantity of a factor, let x represent the quantity of intermediate inputs, let p represent the price of a commodity and let w represent the price of a factor. Also, there are a number of assumptions that:

- 1) the consumer's endowments are fully comprised of factors and no other endowments;
- 2) one sector produces only one good, and it is the only sector to produce that good;
- 3) there are no tax distortions, so firms and consumers face the same prices; and
- 4) there are constant returns to scale of sector production, where production efficiency does not change with quantity of production.

The three conditions for general equilibrium are specified as follows. Note that in each expression, value is the product of quantity and an associated price.

1. **Market clearance:** For each commodity produced, it is used in its entirety either by other firms or consumers. Specifically, total value of output of commodity i equals the total value of intermediate inputs of commodity i used by all sectors, plus the total value of the commodity demanded by the consumer (Equation 1). Market clearance represents conservation of product.

$$p_i y_i = \sum_{j=1}^N p_i x_{ij} + p_i d_i \quad (1)$$

For each commodity i :

value of output = value of intermediate inputs into all sectors j + value of final demand

Also in satisfying the market clearance condition, the total value of the consumer's endowments of a single factor f is fully employed by sectors (Equation 2).

$$w_f v_f = \sum_{j=1}^N w_f v_{fj} \quad (2)$$

For each factor f :

value of consumer endowments = value employed by all sectors j

2. Zero profit: For each sector, total revenue equals total expenditures.

Specifically, total revenue received by sector j for the production of commodities, equals expenditures to pay consumers for factor rental and to pay other firms for intermediate goods (Equation 3). For each sector, the value sold of a unit of commodity i equals the value of all inputs used to produce it. Said in another way, if we assume the commodity quantity is constant, the marginal cost of producing a commodity is greater than or equal to the price of the commodity. Therefore, firms make no profit, thus representing the conservation of value across the economy.

$$p_j y_j = \sum_{i=1}^N p_i x_{ij} + \sum_{f=1}^F w_f v_{fj} \quad (3)$$

For each sector j :

**value of output = value of intermediate inputs of all commodities i
+ value of inputs of all factors f**

3. Income balance: For the consumer, total income equals total expenditures.

Household income, derived from the rental of factor endowments, is fully employed to purchase final demand goods (Equation 4). This reflects the consumer's balanced budget, where no funds are left idle. In this study, the consumer cannot save any income for future use.

$$\sum_{f=1}^F w_f v_f = \sum_{i=1}^N p_i d_i \quad (4)$$

For the consumer:

value of income from all factor endowments f = value of final demand expenditures on all commodities i

The fulfilment of these three conditions implies perfect competition, where firms continue to enter the market until long-run profits equal zero. The CGE model solves for the prices of commodities and activity levels for firms and consumers, which are supported by the fulfillment of the three-above conditions. However, if only two of these conditions are fulfilled, the third will automatically be satisfied, if a “numeraire” term is also defined (Sue Wing, 2004). Money is not explicitly represented in the model, and therefore equilibrium prices are shown in relative terms based on the value of an exogenously defined and fixed “numeraire” term, which all other outputs are defined in relative terms to. In this modelling study, the numeraire is defined as the US wage rate.

A CGE model first solves for a benchmark scenario, which represents a “business-as-usual” case in the absence of any policy experiment. (Note that in this study, the terms “business-as-usual” and “benchmark” are used interchangeably). Then, counterfactual scenarios are simulated, where the economy is perturbed in some way, for example, by the implementation of a price on carbon emissions. The model then solves a system of equations, the core of which are derived from equations (1)-(4), in order to generate a new equilibrium from which price and quantity information can be extracted. CGE models are valuable in quantifying aggregate changes in welfare, production levels, and distributional impacts of policies that traverse multiple sectors.

2.2 VERITAS

2.2.1 Overview of Structure

VERITAS is a static general equilibrium model of the global economy, designed specifically for this study to evaluate aggregate impacts of international climate change policies. It is written in the General Algebraic Modelling System (GAMS) language and also uses a subsystem called the Mathematical Programming System for General Equilibrium (MPS/GE), developed by Rutherford (1987). MPS/GE allows for efficient shortcuts to be made in formulating cost functions, specifying constant elasticity of substitution structures and ensuring fulfilment of general equilibrium conditions.

VERITAS covers one representative consumer, seven regions, and ten sectors. Data for VERITAS were aggregated from the Global Trade Analysis Project (GTAP) - 7 database, which contains bilateral trade, transportation, production, input, and demand information for 113 world regions, 57 sectors, and five factors. The database is for 2004, which is the base year used in this study. The regions and sectors represented in VERITAS are listed in Table 1 and Table 2, respectively. The seven regions correspond with those in CIMS. (For a complete list of countries within each region see Appendix A).

Table 1 VERITAS region names and descriptions

Region (r) name	Region description
CAN	Canada
US	United States
OECD	OECD-Europe, the Pacific, and Mexico
EEU	Transition Economies (Eastern Europe, former Soviet Union)
AMELA	Africa, Middle East, and Latin America
ASIA	Developing Asia
CHN	China

Table 2 VERITAS sector names and descriptions

Sector (j) name	Sector description
OILJ	Extraction of crude petroleum
ELECJ	Electricity production, collection, and distribution
COALJ	Mining and agglomeration of coal
RPPJ	Refined petroleum products and coke oven products
GASJ	Extraction and distribution of natural gas
METJ	Mining, production and casting of ferrous and non-ferrous metals
NMETJ	Non-metal manufacturing, including wood, chemical, and non-metallic mineral products
OMANJ	Other manufacturing, including food, textile, and machinery products
TRANSJ	Air, water, road, and rail transport
ROEJ	Rest of the economy, including services and agriculture

The consumer in VERITAS is endowed primarily with factors (labour, capital, land, and natural resources) and carbon permits. All factors in VERITAS are region-specific. Labour is characterized as a mobile factor, as it can move amongst sectors within a region. Natural resources and land are labelled as sluggish factors, as they are sector-specific. Capital is categorized as either flexible or fixed in VERITAS and thus can be specified as either mobile or sluggish.

The consumer rents factors to sectors, which in turn use them to produce commodities in combination with intermediate inputs, which are goods used as inputs in the production of other goods as opposed to being used for final consumption. As was assumed in specifying general equilibrium equations (1)-(4), sectors in VERITAS are unique in the production of commodities, where each sector produces a single commodity and is the only sector that produces it.

VERITAS is a static model, meaning that sectors and consumers are myopic and make decisions based on a single time period. Thus, if the model is run for the year 2020, consumers only act on information based within 2020. In contrast, in dynamic models, investment, savings and other allocation decisions made in one time period are based on future modelled time periods. For

example, the agent may make investment decisions in the current time period based upon anticipated investment return rates in the future. Thus, consumers in these models have foresight and processes such as capital accumulation over time can be represented. Since VERITAS solves for a single point in time with each simulation, it is run separately for each test year: 2004 (benchmark year), 2010, 2020, 2030, 2040, and 2050.

2.2.2 Model Structure Specifics

A schematic representation of VERITAS is shown in Figure 2. Blocks represent production activities, while arrows represent the flow of commodities between production blocks. A production activity block serves to convert inputs into outputs, as Figure 2 illustrates. I will describe the function of each production block, in turn, beginning at the tri-partitioned rectangle on the right where three types of sector production are represented: Y, X, and Ya.

Sectors use inputs of production factors (PF) such as capital and labour, to output the commodity PY. Conventional commodity production is divided into production using fixed capital (X block) or flexible capital (Y block). The representation of two types of capital allows VERITAS to model the transition of fixed to flexible capital over time. This allows for a more realistic representation of the limited amount of capital stock turnover due to fixed capital that may occur in any time period. Thus, VERITAS incorporates a putty-clay representation of capital, likening mouldable putty (flexible capital) to hardened clay (fixed capital).

Fixed capital represents durable assets, such as land or buildings, which belong to a firm for a longer period of time and are generally not used up in the production of commodities. On the other hand, flexible capital represents more fluid assets, such as labour, which can be more easily manipulated by the firm and are used more in proportion to the production of commodities.

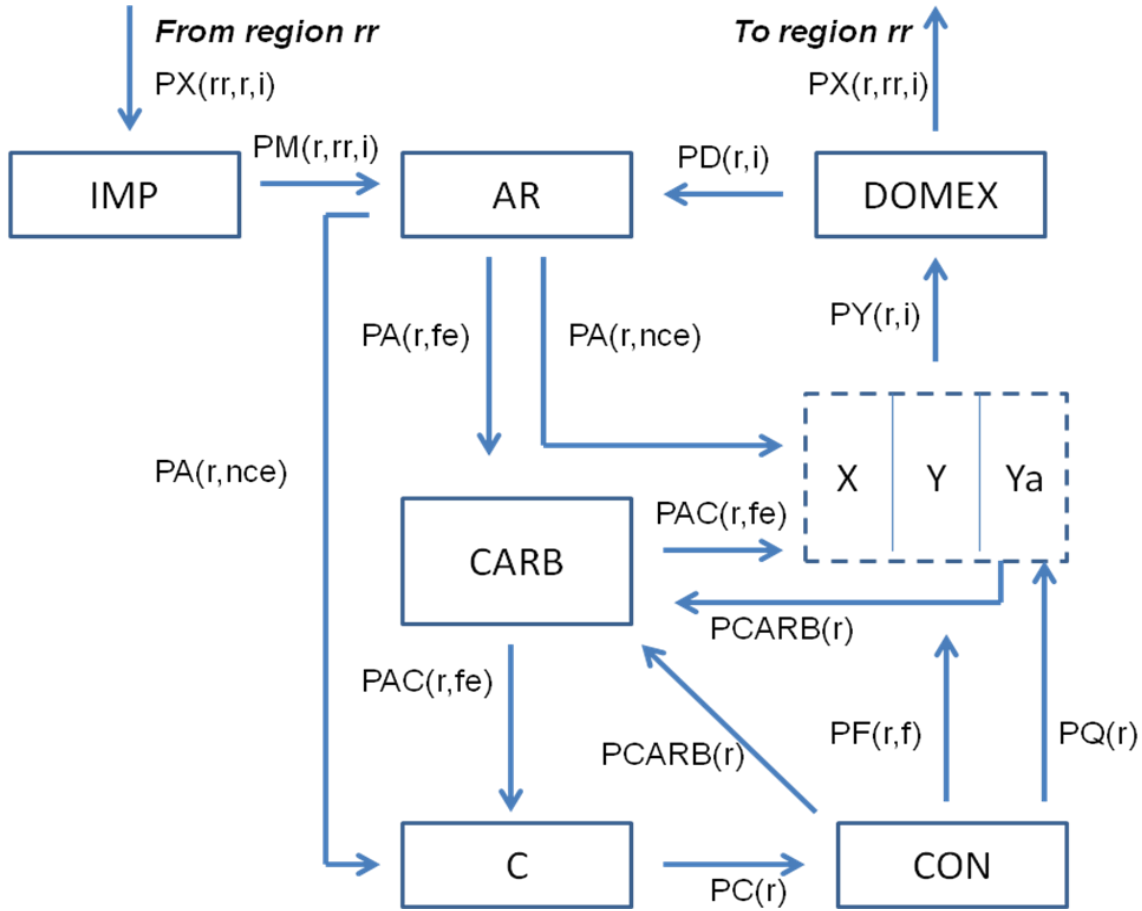


Figure 2 Schematic of a single region, r , within VERITAS

The third type of sector production (Y_a) represents the alternative production of electricity using carbon capture and storage (CCS). An alternative production activity is only available to the electricity sector. This sector production block is the only one of the three that is able to output carbon permits (PCARB) through the use of CCS with biomass inputs. It is also the only one that requires the input of CCS capacity (PQ).

Moving counter-clockwise, the DOMEX block inputs PY to produce goods for either export to another region rr , or for domestic consumption. The IMP block inputs commodities exported from region rr , (PX) to produce imported goods (PM). The AR block aggregates both imported goods and domestically produced goods to produce domestically consumed commodities (PA) for use by

consumers, by entering the C block, or by sectors, by entering the X or Y blocks. If these commodities do not have associated carbon emissions (ie. if they are not fossil fuels), then they can be used directly and are indexed by *nce*.

For commodities that have associated carbon emissions, there is one diversion they must take. Fossil fuel commodities (indexed as the set, *fe*), must have each unit of emissions paid for in an amount based on the price of carbon emissions. Thus, they flow into the CARB block, which also inputs units of carbon permit or carbon tax (PCARB) to produce PAC, a commodity that has had its emissions price “paid”.

The C production block simply inputs all carbon and non-carbon emitting commodities in order to produce a single, aggregate consumption good (PC), which the consumer in VERITAS demands.

The consumer CON block is not a production block, but rather a demand block that optimizes its consumption of PC. In VERITAS, the representative agent is endowed with factors (PF), carbon permits (PCARB) and capacity for carbon capture and storage (PQ). Excluded from Figure 2 is the endowment of the balance of trade. Essentially, this is the difference between total imports to a region and the total exports and is endowed to the consumer in the form of PC.

A description of each commodity transferred between production blocks is summarized in Table 3. The variable associated with each commodity is its price index rather than its quantity, which is why each commodity is referred to in terms of its price.

Table 3 Price index names and descriptions

Price index name	Description
PY	Price index for commodities
PD	Price index for goods domestically consumed
PM	Price index for goods imported
PA	Price index for Armington good (no carbon emissions price paid)
PAC	Price index for Armington good (with carbon emissions price paid)
PCARB (PCARBGLOBE)	Price index for carbon (price of carbon emissions permit). (Where a single global price exists, PCARBGLOBE is used)
PC	Price index for aggregate consumption
PQ	Price index for carbon capture and storage capacity
PF	Price index for factors

Table 4 lists the set names and descriptions used to index within VERITAS. For example, if commodity PY is indexed over r as in $PY(r)$, this means that commodity PY exists for each region r within the model. PY is therefore region-specific, and $PY(\text{"US"})$ can have a different price than $PY(\text{"CAN"})$. The full model code in GAMS, including a complete list of model sets, can be found in Appendix B.

Table 4 Set names and descriptions

Set name	Description
r (alias rr)*	Regions
i	Commodities
j	Sectors
fe	Energy goods producing emissions
nce	Non carbon-emitting goods
f	Factors

* An alias refers to an alternative name for referring to the same set. The modeler may wish to refer to a set that has already been defined, for example, in calculating the gross output from region r , as a proportion of the sum of output in all regions rr . Since the single region r has already been defined, I use rr to refer to the other regions.

2.2.3 Carbon Market

A method of carbon accounting in VERITAS is integral for ensuring proper tracking of carbon emissions by commodity and sector. In VERITAS, only emissions arising from the combustion of fossil fuels are accounted for, which are coal, natural gas, and refined petroleum products (RPPs). Crude oil is used primarily as feedstock in the production of RPPs and is therefore not considered a carbon-emitting fuel. Process and agricultural emissions are also excluded.

Carbon emissions in the benchmark are calculated based on quantity of fuel use, multiplied by a carbon emission factor for each fuel.

For each fuel in each region:

$$CO2EMIT(r, fe) = FUELPJ0(r, fe) \times CARB_INT_GJ(r, fe) \quad (5)$$

**benchmark carbon emissions (Mt) = fuel use (PJ) x
carbon emission factor (tCO₂/GJ of fuel consumed)**

I derived carbon emission factors for fuels (CARB_INT_GJ) from a number of sources. Values for the US are from the Energy Information Administration (2009a), those for Canada came from Natural Resources Canada (2009), and values for the rest of the regions were derived from the IPCC's National Greenhouse Gas Inventories (IPCC, 2006).

The fuel use (FUELPJ0) values in each region, both for the base year and projected values, are from CIMS fuel use estimates (Goggins, 2008; Goldberg, 2009, Melton, 2008; Wolinetz, 2009, Bataille et al., 2008). Values for Canada are from Natural Resources Canada (2009) and those for the US are derived from the updated Annual Energy Outlook (EIA, 2009c).

After generating the CO2EMIT parameter value for each fuel in each region, I used it to calculate an assumed carbon coefficient, which is the amount of carbon emissions from each fuel, per dollar output of each region. The carbon coefficient is sometimes referred to as the carbon intensity of a region's economy.

For each fuel in each region:

$$CARBONCOEF(r, fe) = CO2EMIT0(r, fe) / USE0(r, fe) \quad (6)$$

carbon coefficient (Mt CO₂/\$ output) = benchmark emissions (Mt) /fuel use (\$)

CARBONCOEF is an important parameter, as it is used to calculate the emissions in any year from a sector or a region with information on the value of fuels used (USE0). In other words, CARBONCOEF quantifies the amount of emissions resulting from each dollar of fuel used in a given region.

VERITAS can simulate the carbon market either as a carbon tax or a cap-and-trade system. With a carbon tax, a specific duty is levied on the quantity of carbon emissions, either as a global duty for all regions, or with specific duties for each region. With a cap-and-trade system, a global emissions abatement level is defined exogenously, where emissions permit trading occurs freely amongst regions. Alternatively, different regions can have varying abatement levels, and there is no permit trading. In other words, regions act alone and can only distribute permits amongst sectors within the region.

A carbon abatement level is modelled as a specified endowment to the consumer. In a cap-and-trade scenario, consumers are endowed with permits equal to the quantity of emissions in the economy as specified by a policy. In a carbon tax scenario, the consumer is also endowed with a specified value of emissions and the model operates under an added constraint where emissions decrease until the price of carbon emissions equals an exogenously defined carbon tax value.

In scenarios with a single global price on emissions (either a global carbon tax, or a global permit trading system), revenues from the tax or sale of permits can be allocated differentially to regions. Each region is endowed with a percentage of this global revenue and therefore the sum of allocation percentages for all regions cannot exceed 1.

This allocation function allows for the modelling of politically-determined permit allocation, or tax revenue allocation, which can be thought of as simple wealth transfers between regions. It is likely that such wealth transfers will exist

in any potential architecture characterized by a single global carbon emissions price, in order to compensate regions with lower financial capacity and lower responsibility to reduce emissions.

A function for revenue recycling also exists in the model, where any specified portion of a region's revenue (again, from a tax or permit sales) can be recycled back to specified sectors. Each sector within a region may receive a specific percentage of its region's allocated revenues, otherwise they go to the consumer. The sum of these percentages cannot exceed 1 in each region. The recycled revenue is modelled as an output-based subsidy (to production blocks X and Y). An output-based subsidy provides a subsidy on production, based on each unit of output. Thus, those sectors with larger proportional output within the economy receive a greater subsidy. Any revenue not recycled is maintained by the consumer. Whereas the allocation function represents revenue distributions *amongst* regions, this revenue recycling function represents the allocation of revenue *within* a region between firms and consumers.

Alternative Sector for Electricity Generation

An alternative production sector (Ya) was created to represent carbon capture and storage (CCS) technology. It represents an alternative method of production for the electricity sector, requiring more capital and fuel inputs, but resulting in fewer emissions for each unit of electricity output. CCS enters endogenously: if it becomes competitive as a result of the increasing price on carbon emissions, then this production block will activate. This sector only inputs flexible capital, as it is assumed there is no fixed CCS capital in the benchmark scenario. All CCS costs in the model exclude transport and storage costs, as these are small compared to capture costs and therefore often excluded in cost estimates (IPCC, 2005; Al-Juaied and Whitmore, 2008).

This alternative sector was designed according to a three-step function, where the inputs required for each unit of output increase at each step. This step-function was designed to represent a supply curve for electricity with CCS.

In VERITAS, each step requires a mark-up of inputs representing the percentage of capital or fuel inputs beyond what is required in conventional electricity generation. The first step requires the smallest mark-up inputs thus representing the implementation of CCS at more favourable sites, characterized by greater accessibility to markets and storage sites, and therefore lower costs. Once the capacity units in the first step have been exhausted, the capacity in Step 2 becomes available at a greater mark-up for fuel inputs and capital inputs. This second step represents CCS implemented on less favourable sites, thus requiring greater inputs.

Step 3 represents biomass CCS, which requires the greatest fuel and capital inputs but produces a net decrease in emissions. Since biomass is relatively carbon neutral (depending on its treatment prior to entering the CCS process), biomass CCS has the potential to produce net negative emissions, or in other words, create net removal of greenhouse gases from the atmosphere (IPCC, 2005). CCS using biomass inputs is therefore recognized as a potentially significant contribution to greenhouse emissions reductions, particularly when attempting to achieve deep reductions in the long-term.

Table 5 summarizes the characteristics of each step in the alternative electricity production sector for the early simulation years of 2010 and 2020. A separate set of data was used to parameterize CCS technology in later simulation years, in attempts to represent changing CCS costs over time.

Table 5 Characteristics of CCS steps in the alternative electricity sector for years 2010 and 2020

Ya step	Capital mark-up	Fuel mark-up	Land requirement	Capacity
1: CCS	0.42	0.17	0	0.65
2: CCS	0.80	0.30	0	0.01
3: biomass CCS	1.60	--	0.19	0.33

In the first two columns, capital and fuel mark-up values are presented as proportions of inputs beyond what is required in the conventional electricity sector. Biomass CCS requires land in order to represent the land requirement for growing biofuel products. This land requirement (third column) is specified as a proportion of all inputs required in the biomass CCS step. The capacity column represents the capacity available for CCS as a proportion of conventional electricity. Since the values for available capacity add up to 1, it is feasible for 100% of conventional electricity production to convert to electricity production with CCS. Note that in the early simulation years almost all of conventional CCS capacity is available at lower cost, more favourable sites (Step 1). In other words, of the 66% capacity in the first two steps, 65% is available for step 1. I assume that biomass CCS requires no fossil fuel inputs (coal, RPPs, and natural gas), because all the energy requirements of the sector are fulfilled by biofuel.

In the VERITAS representation of CCS, I attempt to represent two temporal processes, which have opposite effects on CCS uptake. The depletion of the most favourable storage sites over time inhibits future CCS uptake, yet decreasing start-up and operating costs due to economies of scale and learning promotes CCS uptake.

In order to model the depletion of storage sites over time, the availability of CCS capacity in step 1 decreases by 10% each decade after 2020, while the capacity in step 2 increases by 10%. As mentioned, almost all conventional CCS capacity is available in step 1 in “good” sites in 2010 and 2020 (Table 5). However by 2050, half of the capacity in step 1 is lost to less favourable sites in step 2, where each step now has 33% capacity of conventional electricity. Table 6 shows the parameter values for specifying CCS technology in the later simulation years of 2030-2050. The available capacity for biomass CCS remains constant through all simulation years.

Table 6 Characteristics of CCS steps in the alternative electricity sector for years 2030-2050

Ya step	Capital mark-up	Fuel mark-up	Land requirement	Capacity		
				2030	2040	2050
1: CCS	0.23	0.10	0	0.53	0.43	0.33
2: CCS	0.48	0.18	0	0.13	0.23	0.33
3: biomass CCS	0.96	--	0.19	0.33	0.33	0.33

In contrast to the uptake of storage sites, increasing economies of scale and learning over time with increased CCS implementation will tend to decrease CCS costs. According to Aljuaied and Whitmore (2009), the electricity costs of CCS will decrease around 40% by 2030 relative to the costs of conventional electricity production. Accounting for this, all capital and fuel mark-up values from 2030 on are 40% lower (Table 6) than in earlier simulation years (Table 5). IEA (2006) also purports decreased fuel input costs by a similar proportion in second-generation plants.

Steps 1 and 2 assume an 85% emissions capture rate, therefore only 15% of the sector's fuel inputs are subject to a carbon penalty. The net emissions for Step 3 are calculated using information on the amount of carbon sequestered in biomass CCS from Keith and Rhodes (2005), from which I calculated that 0.007 Mt (or 7 kt) of carbon dioxide is sequestered per dollar of electricity output from biomass CCS. This assumes that emissions from the harvest, processing and transport of the biomass are negligible. In other words, biomass is treated as carbon neutral before entering the CCS plant (Keith and Rhodes, 2005).

Fuel and capital mark-up information for non-biomass CCS was taken from the IPCC Report on Carbon Capture and Storage (IPCC, 2005). Steps 1 and 2 mark-ups are based on the respective lowest and highest mark-up values in the range of estimates provided in the report.

Limited information exists on the costs of biomass CCS, where lack of experience and substantial variability of cost estimates contribute to high cost uncertainty (IPCC, 2005). I assume that in terms of capital mark-up, biomass-

CCS requires double the capital compared to conventional CCS. According to IEA (2006), biomass CCS costs per kilowatt-hour are about double that of conventional CCS. Reilly and Paltsev (2007) estimate the mark-up for inputs into biomass electricity (without CCS) to be 1.4-2.0 times that of conventional electricity production. Although this estimate does not incorporate CCS, it reflects the mark-up required for converting from conventional fuel inputs to biomass inputs in electricity generation, which can be used to infer mark-ups in converting between these inputs with CCS.

The land requirement for biomass CCS helps represent land supply constraints, with competing demands on land for biomass as an energy source and for agricultural food production. The proportion of land required is based on Reilly and Paltsev (2007), who assume that land comprises 19% of all inputs into biomass electricity production. I also assume that non-biomass carbon capture and storage does not require additional land beyond conventional electricity production, therefore, this land requirement is applied only to biomass CCS.

In VERITAS, the value of the land factor, like all other inputs to production, is assumed to grow over time at a specified rate of economic growth. Although this may seem counterintuitive since land is generally a fixed input, I assume that the price of land increases. Therefore, although the quantity of available land may be fixed, it becomes more valuable over time consistent with the economic growth rate.

Land is a homogenous factor in VERITAS and this study uses a simple method of representing biomass fuels and the requirement for land in the biomass CCS process. Kretschmer and Peterson (2008) provide a survey of biofuel modelling techniques in CGE modelling, taking into account factors such as different land types and productivity, different biofuel types, and biofuel trade.

Storage of sequestered carbon is also an important issue to be considered, as the amount of CCS capacity available in each year may be limited due to storage availability. Estimates of storage capacity have been performed for Canada, the US, Europe, and Australia (IEA, 2006). However, estimates for

the Middle East, Latin America, Russia, and Africa are limited, although there is likely significant potential for storage in depleted oil and gas reservoirs in these areas (IPCC, 2005).

I determined using simple calculations that for each region for which storage capacity information is available, the capacity to store CO₂ is expected to last between one hundred and several hundred years for each region, based on business-as-usual emission levels. However, these estimates have a high level of uncertainty given the aggregation of regions and lack of spatial detail in VERITAS. For example, I aggregated estimates of underground storage capacity for Europe and Australia to calculate total capacity within the OECD region, though it is unlikely that carbon captured in Europe would be stored in Australia.

According to Dooley et al. (2006), the world has enough storage capacity to address storage needs for at least a century. According to IEA (2006), low-end estimates of storage capacity in geological formations are about 80 years of current emissions, while optimistic estimates give several hundred years of capacity. The above estimates do not include storage in oceans, which is thought to be much larger than the world's fossil fuel reserve (IPCC, 2005).

I assume that storage availability is not a significant constraint for CCS uptake, given that these estimates from the literature include emissions from all sources while the VERITAS model applies CCS only to emissions from the electricity sector and that low range storage estimates approximate a century's worth of storage capacity. Therefore, I assume in VERITAS that 100% of conventional electricity capacity is available for CCS in each simulation period.

2.2.4 Deriving Elasticities of Substitution

As mentioned, elasticities of substitution (ESUBs) are important parameters in computable general equilibrium modelling. This study incorporates some region-specific and sector-specific ESUB values. CIMS was used to derive ESUBs for certain sectors for the US and Canada regions. All

other values, including those for Canada and US not derived from CIMS and those for all other regions of VERITAS, are informed by values from both the literature and CIMS.

The ESUB values from CIMS were obtained by shocking the model with various prices for fuels and then deriving a relationship between the price changes and the response using a program described by Rivers (2009)² and based on a method developed by Bataille (2005). I generated ESUBs for each sector within CIMS. For use in VERITAS, the CIMS sectors were aggregated into VERITAS sectors and the ESUB values averaged within each new sector. Since ESUBs were derived for only Canada and the US, the Canadian ESUB values were assumed for all other world regions.

In order to provide more accurate regional differentiation, it would have been helpful to use region-specific ESUBs for all VERITAS regions. However, the global regions in CIMS are not adequately differentiated themselves and it is likely the ESUBs derived for each region would be quite similar to one another. It is otherwise difficult to infer region-specific ESUBs simply based on level of economic development; rather these values may be based on more complex structural characteristics of an economy (Serletis et al., 2009).

I did not derive certain ESUBs from CIMS including values relating to consumer demand as well as import/export activities. In addition, CIMS ESUBs were not available for all VERITAS sectors. I based these values on estimation from other sources, including the GTAP-E model,³ the DEEP model,⁴ and the MIT-EPPA model.⁵ Table 7 provides a description of each ESUB value used in

² Jotham Peters and Nic Rivers at the Energy and Materials Research Group at Simon Fraser University developed the program for deriving ESUBs from CIMS.

³ GTAP-E is an extension of the base GTAP computable general equilibrium model, tailored specifically to model greenhouse gas emissions policies (Burniaux and Truong, 2002).

⁴ The DEEP (Dynamic analysis of Economics of Environmental Policy) is a dynamic computable general equilibrium model developed at the Center for International Climate and Environmental Research in Norway (Kallbekken, 2004)

⁵ The MIT-EPPA (Emissions Prediction and Policy Analysis) Model is a recursive, dynamic general equilibrium model developed by the Massachusetts Institute of Technology Joint Program on the Science and Policy of Global Change (Paltsev et al., 2005; Babiker et al. 2003)

VERITAS, the range of values that each ESUB takes on depending on the sector or region, as well as the source used to derive the values.

Table 7 ESUB values and (ETRAN value for DOMEX) and sources used in VERITAS

ESUB	Description	Value	Source
<i>Sector production</i>			
σ_S	Between intermediate inputs and aggregate of value-added and energy	0	
σ_{VAE}	Between value-added (factors) and energy	0.42-1.26	CIMS-US, CIMS-Canada, Paltsev et al. (2005), Kalbekken (2004)
σ_{VA}	Between sluggish and mobile factors	0	
σ_{SLUG}	Between natural resources and land	0	
σ_{MOB}	Between capital and labour	0.2-1.7	CIMS-US, GTAP
σ_E	Between fuels and electricity	0-1.8	CIMS-US, CIMS-Canada, Burniaux and Trong (2002)
σ_{FUEL}	Between non-electric fuels	0.2-3.4	CIMS-US, CIMS-Canada, Kallbekken (2004), Paltsev et al. (2005), Bohringer and Rutherford (2002)
σ_{LQD}	Between liquid fuels	0.3-5.7	CIMS-US, CIMS-Canada, Kallbekken (2004), Paltsev et al. (2005), Bohringer and Rutherford (2002)
<i>Import and export</i>			
σ_{ARM}	Between foreign and domestically-produced goods	1.9-10	Burniaux and Trong (2002)
$\sigma_{DOMEX(ETRAN)}$	Between production for domestic or foreign markets	2	Bohringer and Rutherford (2002)
<i>Consumer demand</i>			
σ_S	Between energy and non-energy goods	0.50-0.52	CIMS-US, CIMS-Canada
σ_C	Between non-energy consumption goods	0.65-1	Kallbekken (2004), Paltsev et al. (2005), Rivers and Sawyer (2008)
σ_E	Between RPPs and household fuel aggregate (natural gas and electricity)	0.4-0.5	CIMS-US, Kallbekken (2004), Paltsev et al. (2005)
σ_{HOU}	Between natural gas and electricity	0.8-1.7	CIMS-US, CIMS-Canada

Recall that the only elasticity of transformation (ETRAN) value between two outputs is in the DOMEX production block. The full set of ESUBs for each sector and region are in Appendix C.

The figures that follow illustrate the nested constant elasticity of substitution (CES) structure for each production block in VERITAS. It may be useful to refer back to Table 7 for descriptions of the ESUBs shown in the following figures. As Figure 3 to Figure 6 show, the nested form is a hierarchical structure, where ESUBs are encapsulated, or nested, within progressively higher and more aggregated ESUB values. For example in the Y production block (Figure 3), the ESUB, σ_E , is defined between electricity and fuels inputs. Nested within the category of fuels, there is an ESUB, σ_{FUEL} , between coal and liquid fuels. Within liquid fuels, an ESUB, σ_{LQD} , is defined between natural gas and RPPs.

The Y production block has the most complex ESUB structure of all production activities in VERITAS. Recall that the Y block represents sector production using flexible capital (and therefore has substitution between inputs) and the X block represents production using only fixed capital (with inherently no substitution amongst inputs, thus all ESUB values are zero).

In order to represent increased capital flexibility over time, ESUBs apply to a greater proportion of total capital as a greater percentage of flexible capital becomes available to the Y production sector. In the 2004 base year, over 99% of capital is set as fixed, however, the proportion of fixed capital decreases according to an annual rate of capital depreciation of 4% (Center for Global Trade Analysis, 2001). By 2050, I allow 94% of total capital to be flexible. This refers back to the aforementioned putty-clay capital representation within VERITAS.

The Ya production sector is characterized by ESUB values set to zero, except for those defining inter-fuel substitution. I assume no substitutability amongst other inputs, because the required inputs for CCS and biomass-CCS are already defined exogenously (Table 5 and Table 6). Inter-fuel ESUBs are set

to those used in the conventional electricity production sector, as I wish to allow the same ease in switching amongst fuel inputs in electricity production with CCS, as without.

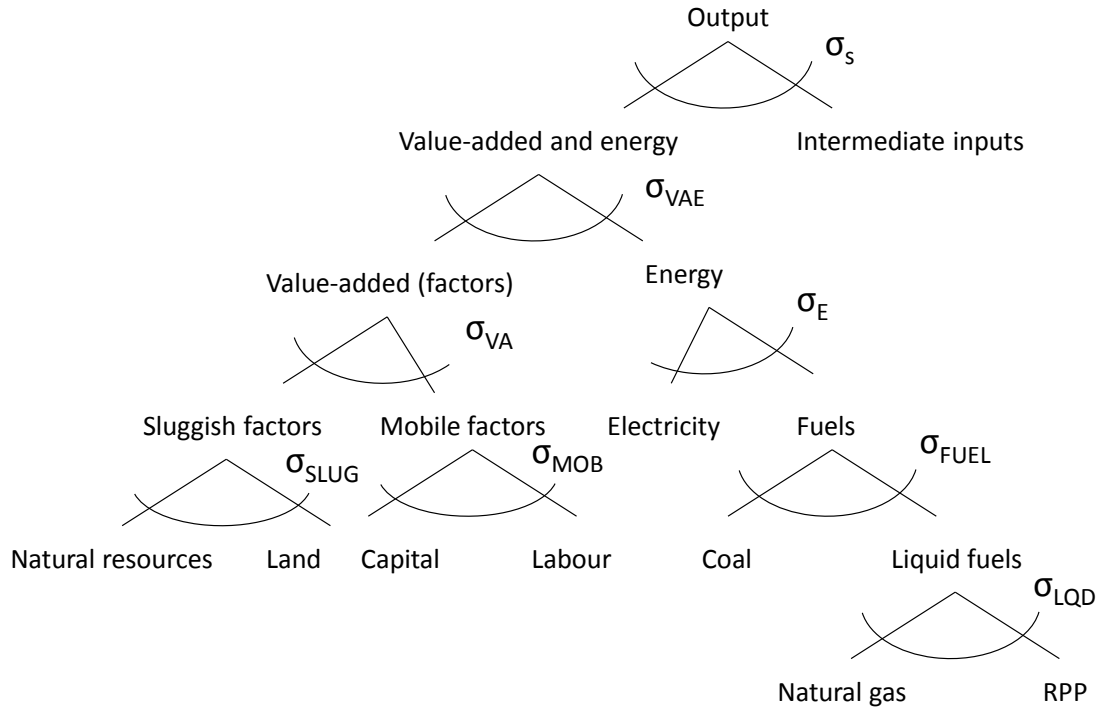


Figure 3 Nested CES structure for Y production block

In the Armington (AR) production block, commodities produced outside of the region are aggregated with domestically-produced commodities, to produce domestically-consumed commodities. The Armington elasticity describes the ease of substitution between a domestically-produced commodity and a foreign-produced one (Armington, 1969). This elasticity recognizes the differentiation of commodities based on geographic source, for example, Canadian firms and consumers differentiate to some extent between cars from Canada and cars from Japan. Figure 4 below shows the CES structure for the Armington production block in VERITAS.

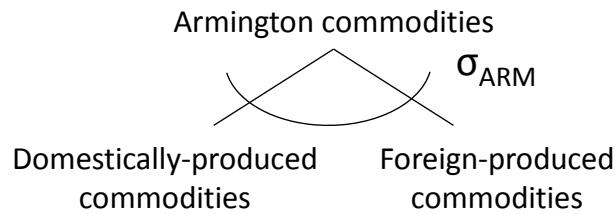


Figure 4 Nested CES structure for AR production block

Figure 5 shows the constant elasticity of transformation structure for the DOMEX production block, defining the elasticity between the two outputs: commodities for domestic use and commodities for export. As mentioned, this is the only elasticity of transformation in VERITAS.

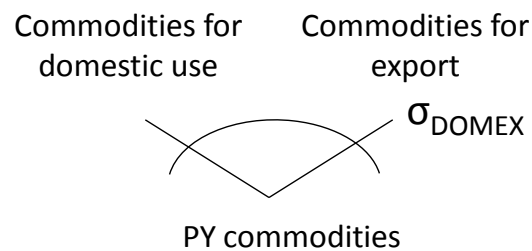


Figure 5 Nested CET structure for DOMEX production block

Households in VERITAS optimize utility by maximizing the value of commodities consumed. Figure 6 shows the nested ESUB structure for the production of an aggregate consumption commodity for the household.

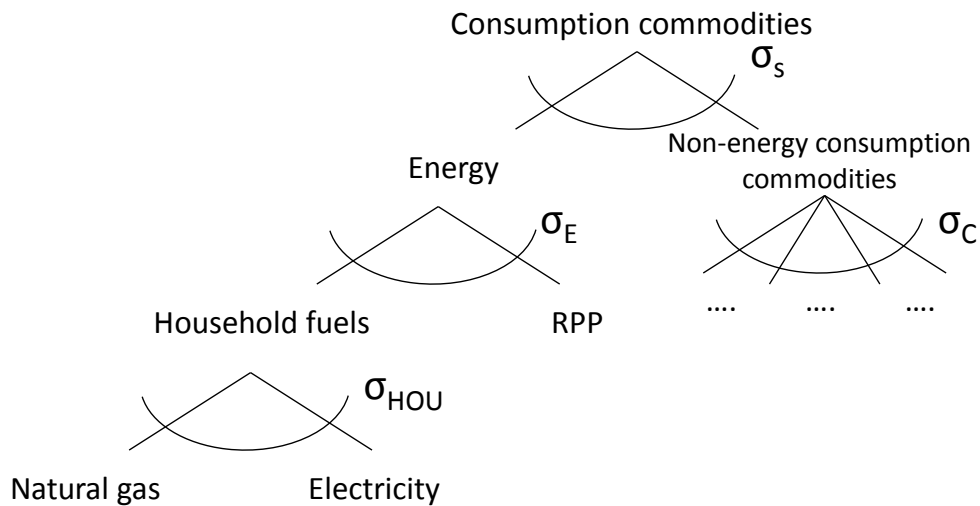


Figure 6 Nested CES structure for the C production block

There are two other production activity blocks in VERITAS. The IMP block does not have an ESUB structure because it transforms a single input into a single output. The CARB block has an ESUB value set to zero between its two inputs: PCARB (a carbon permit or tax) and PA (a non-carbon-priced commodity) because each fuel commodity input requires a price per unit of carbon emissions to be paid, and no substitution is permitted between these two inputs.

2.3 Data Management

In order to simulate counterfactual policy scenarios, an internally consistent dataset was required for the benchmark year of 2004. I constructed balanced social accounting matrices (SAMs) using GTAP-7 data. For each region, the set of SAMs includes: an intermediate input table, an output table, a final demand table, import and export tables (each at world price and market price) and a table on margins on international trade.

Each SAM reports the value of transactions between sectors in a method of double-bookkeeping, where tracking the use of commodity i for sector j also tracks the input into sector j for commodity i . Thus for example, one can track

what commodities and factors are being input into each sector's production, while also tracking to which sectors each commodity or factor is going. I formulated the SAMs to ensure the general equilibrium conditions are fulfilled, specifically:

1) the value of inputs into a sector (factors and intermediate inputs) equals the value of goods output by a sector;

2) the value of the output of a commodity, is equal to the inputs of that commodity into all sectors, plus final demand, plus exports, minus imports of that commodity; and

3) the value of total household endowments is equal to the value of total household expenditures, which is the value of final demand commodities, plus exported commodities, minus imported commodities.

Bilateral trade of each good is tracked between countries. I aggregated government activity with that of the household, since VERITAS does not represent government as an agent in the economy. Investments were incorporated into consumer final demand. Benchmark taxes are not represented in VERITAS, so I incorporated taxes as part of the inputs into production. All prices used to construct the SAMs for internal consistency are market prices.

In order to balance international trade, the SAMs were formulated so the value of imports (in world price) into region r from country rr , equals value of the exports from country rr to country r , plus margins on international trade for the exporting region, rr . On a separate note, the total value of exports for region r does not need to equal the total value of imports for region r . Only the sum of all imports to all regions must equal the total sum of exports by all regions, to ensure balance of global trade.

In VERITAS, a balance of trade parameter accounts for the trade imbalance (either surplus or deficit) that often exists, where value of imports to a region differs from the value of exports from that region. Balance of trade for region r is calculated as world price of imports to region r from region rr , minus world price of exports from region r to region rr , minus margins on international

trade of the exporting region rr summed over all trading partners. The balance of trade value of a region is endowed to the consumer.

2.3.1 Extrapolating SAMs to Future Years

In order to extrapolate the 2004 balanced SAMs to create benchmark or business-as-usual SAMs for 2010 to 2050, all values in each SAM were increased by a region-specific GDP forecast rate (Table 8). The growth rates for OECD, AMELA, ASIA, and EEU regions are from CIMS GDP forecasts (Melton, 2008; Goggins, 2008; Goldberg, 2009; Wolinetz, 2009). The Canada, China and US forecasts are derived from the US Energy Information Administration (EIA, 2009b).

Table 8 Annual GDP growth rates for each region

Region	US	CAN	OECD	TE	DA	AMELA	CHN
Annual GDP increase	2.4%	2.2%	2.0%	3.9%	5.0%	3.1%	6.4%

“Growing” each SAM independently in this manner, however, puts global trade out of balance in each year. Therefore, a balancing routine was used to balance each region’s SAMs internally by satisfying zero profit, market clearance, and income balance conditions, as well as to balance global trade by ensuring total global imports equal total global exports.⁶ Inputs and final demand for energy goods (natural gas, RPPs, coal, oil, and electricity) were set as fixed; therefore the balancing routine did not change these values

I also incorporated energy efficiency gains over time in the business-as-usual case for each region. The Autonomous Energy Efficiency Index (AEEI) is an exogenous parameter, which represents technological change in an economy, independent of price change (Löschel, 2002). It represents an economy’s

⁶ Acknowledgements, once again, to Jotham Peters and Nic Rivers for developing this method of balancing SAMs in GAMS

technological progressions in energy intensity occurring over time as a result of autonomous technology innovation, as opposed to being induced by energy price changes (Grubb et al., 2002). In order to represent this gain in energy efficiency, the fuel inputs into every sector within the SAMs for each period beyond the 2004 base year were decreased by the AEEI percentage. The AEEI values for each region were taken from the MIT-EPPA model and can be found in Appendix D.

2.4 Modelling Scenarios

The successor to the Kyoto Protocol will undoubtedly contain a diversity of targets and mechanisms. The aim of this research is not to model the complexities of a potential future framework, but rather to examine the effects of specific aspects of this architecture.

The scope of this project focuses on actions taken at the geographic scale of the seven world regions in VERITAS. While there has been a fair amount of discussion around more fragmented and disaggregated post-Kyoto systems (Aldy and Stavins, 2007; Barrett, 2008; Keohane and Victor, 2010; Dobriansky and Turekian, 2010), I will not assess them here.

Furthermore, this study focuses on the universal implementation of a price on carbon emissions, whether regions participate in a single global system or each region functions within its own pricing system. This study does not attempt to model policies such as prescriptive regulations, voluntary initiatives, or subsidies. It is assumed that these policies will simply be complementary to the primary pricing instrument. All policies modelled in this study are cap-and-trade systems, as this has emerged as a favoured policy instrument for reducing greenhouse gas emissions in numerous jurisdictions around the world (Stavins and Jaffe, 2009).

Unless otherwise indicated, the reduction targets in this study are based upon the stated goal of keeping cumulative greenhouse gas emissions between the years 2000-2050 under 1000 gigatonnes (Gt). According to Meinshausen (2009), this results in about a 75% chance of staying under the 2°C target. Measuring an emissions reduction target in terms of cumulative emissions

reflects a potentially more useful metric for measuring emissions reductions, as compared to greenhouse gas concentrations in parts per million (Meinhausen, 2009; Baer et al., 2009).

Table 9 summarizes the global reduction targets assumed for each year, indicating both the reductions below business-as-usual (BAU) and 1990 emissions. This reduction pathway fits within the range of those examined by the IPCC for keeping cumulative emissions under 1000 Gt (IPCC, 2007b). No reductions targets are set for 2010 and therefore business-as-usual emissions are assumed.

It is important to keep in mind that my calculations of cumulative emissions are approximate, given that I only have six points on a graph showing emissions in each year (2004, 2010, 2020, 2030, 2040, and 2050). An accurate calculation of cumulative emissions would require infinite points of emissions over time.

Table 9 Global emissions reductions pathway to reach 1000 Gt cumulative emissions target

	2010	2020	2030	2040	2050
Reduction from 1990	-29%	-21%	0%	28%	60%
Reduction from BAU	0%	21%	43%	64%	85%

In each scenario, I assume a certain percentage of permits is auctioned each year (Table 10). The economic efficiency of full permit auctioning compared to free allocation has been supported by numerous economic analyses due to the ability to use auction revenue to reduce distortionary taxes (Burtraw et al., 2001, Edenhofer et al., 2009; Cramton and Kerr, 1998). However, it is recognized that allocating allowances without charge to emitters has merits for increasing buy-in from large emitters, thereby increasing political acceptability of a cap-and-trade system.

Table 10 Schedule for percentage of permits auctioned in each year

Year	2020	2030	2040	2050
% Auctioned	40	80	100	100

In this study, the majority of permits are allocated for free to polluters in 2020, with the percentage of auctioned permits increasing over time. This broadly corresponds with the schedule established through the Waxman-Markey Bill in the United States, as well as the cap-and-trade systems of the European Union and Western Climate Initiative (Larsen et al., 2009; Tuerck et al., 2009).

2.4.1 Methods of Permit Allocation

One important characteristic of a cap-and-trade system examined in this study, which may pose substantial welfare implications for different regions is the method of emissions permit allocation. Different allocation methods can result in substantially different wealth transfers between regions.

Four methods of allocation, based on different principles of equity were assessed:

1. *Per-capita allocation*: each region receives permits proportional to its population in 2005. This follows the egalitarian principle. (*PerCap*)
2. *GDP-based allocation*: each region receives permits inversely proportional to its Gross Domestic Product (GDP) in 2004. This follows the capacity to pay principle, where regions with higher GDP receive fewer permits. (*PerGDP*)
3. *Allocation based on cumulative emissions*: each region receives permits inversely proportional to the amount of cumulative emissions (contributed between 1980-2006). This method follows the principle of *historical/cumulative responsibility*. (*Cumulative*)
4. *Grandfathering*: each region receives permits proportional to the amount emitted in 1990. This method follows the sovereignty principle. (*Grandfather*)

Reference years for calculating allocation were chosen based on available data. See Appendix E for specific calculations of regional allocations.

2.4.2 Permit Trading

The second characteristic of a global architecture examined is the extent of co-ordination amongst carbon pricing systems. I examine the following two scenarios:

1. all regions operate within a single global system, where permits are freely traded amongst regions (*TRADE*), and
2. regions do not trade with other regions and are therefore only able to re-distribute permits amongst their own sectors and consumers (*NO TRADE*).

For the *TRADE* scenario, I assume the grandfathering method of allocation. For the *NO TRADE* scenario, I assume that all regions categorized as Annex I (industrialized and transition economy) countries under the Kyoto Protocol, take on a reductions target consistent with what the IPCC calls for, which are 25-40% reductions below 1990 levels by 2020 (IPCC, 2007a). In VERITAS, the Annex I regions are CAN, OECD, EEU, and US.

I then calculate the percent reductions required to occur within the non-Annex I regions (AMELA, ASIA, and CHN) in order to reach the global emissions defined to reach 1000 Gt. Each group of regions has identical reductions targets measured from 1990 levels, but not below BAU (Table 11). The negative reduction values in the table signify an increase in emissions.

Table 11 Emissions reductions pathways for the *NO TRADE* scenario

Year		2010	2020	2030	2040	2050
Reductions below 1990	Annex I	0%	33%	45%	67%	85%
	non - Annex I	0%	(-130)%	(-91)%	(-51)%	9%

Next, I provide a comparison of regional abatement costs in the year 2050, where each region faces identical reduction targets in terms of percentage reductions below BAU. No permit trade is permitted amongst regions, in order to elucidate the abatement costs solely within each region.

2.4.3 Emissions Reduction Target

The third characteristic I examine is the global emissions reductions target. The goal of a temperature rise no greater than 2°C has been widely communicated as the target to achieve in order to “prevent dangerous anthropogenic interference with the climate system” (UN,1992). However, it is becoming increasingly recognized that the targets put forth by the IPCC for reaching reach greenhouse gas concentrations of 450ppm, or about 1500 Gt cumulative CO₂ emissions from 2000-2050, still results in a 50% chance of exceeding this 2°C rise (Wells, 2009; Hansen et al., 2008; Edenhofer et al., 2009). Low-lying states (including the Alliance of Small Island States AOSIS), certain developing nations, and environmental groups have recently begun to call for a more ambitious global target that gives a higher chance of staying within the 2°C limit.

This push for more aggressive emissions reductions has been popularized by being associated with a target of 350 ppm CO₂. According to Hansen et al. (2008), stabilizing at this concentration allows for 750 Gt CO₂ to be emitted in the first half of the century. This results in approximately 85% chance of staying within the 2°C limit (Baer et al., 2009; Meinshausen, 2009).

The Chair of the IPCC, Rajendra Pachauri, stated in August, 2009:

“As chairman of the Intergovernmental Panel on Climate Change, I cannot take a position because we do not make recommendations, but as a human being I am fully supportive of that [350 ppm] goal. What is happening, and what is likely to happen, convinces me that the world must be really ambitious and very determined at moving toward a 350 target.”

Although the achievability of this target is debatable, it is nonetheless worthwhile to examine the consequences of reaching this level of deep global reductions, which has received minimal attention in even the most recent IPCC Assessment Report. Thus, this scenario represents more emergent thinking on reductions targets.

I examine the following two scenarios, both with full international permit trading and a grandfathering method of permit allocation:

1. a reduction pathway to reach a maximum of 1000 Gt cumulative CO₂ emissions in the first half of the century (Table 9) (1000); and
2. a reduction pathway to reach a maximum of 750 Gt CO₂ cumulative emissions (Table 12) (750).

Table 12 Global emissions reductions pathway to reach 750 Gt cumulative emissions target

Year	2010`	2020	2030	2040	2050
Reduction from 1990	-29%	42%	70%	85%	100%
Reduction from BAU	0%	62%	83%	92%	100%

The 750 scenario follows the pathway defined by Baer et al. (2009) for achieving emissions stabilization at 350 ppm CO₂ and cumulative emissions of 750 Gt by mid-century. It is not linear, as it requires deep reductions in earlier simulation years in order to reach the target.

Figure 7 illustrates the mitigation pathways in terms of absolute emissions, for stabilizing emissions at 1000 Gt and 750 Gt CO₂ as compared to business-as-usual emissions.

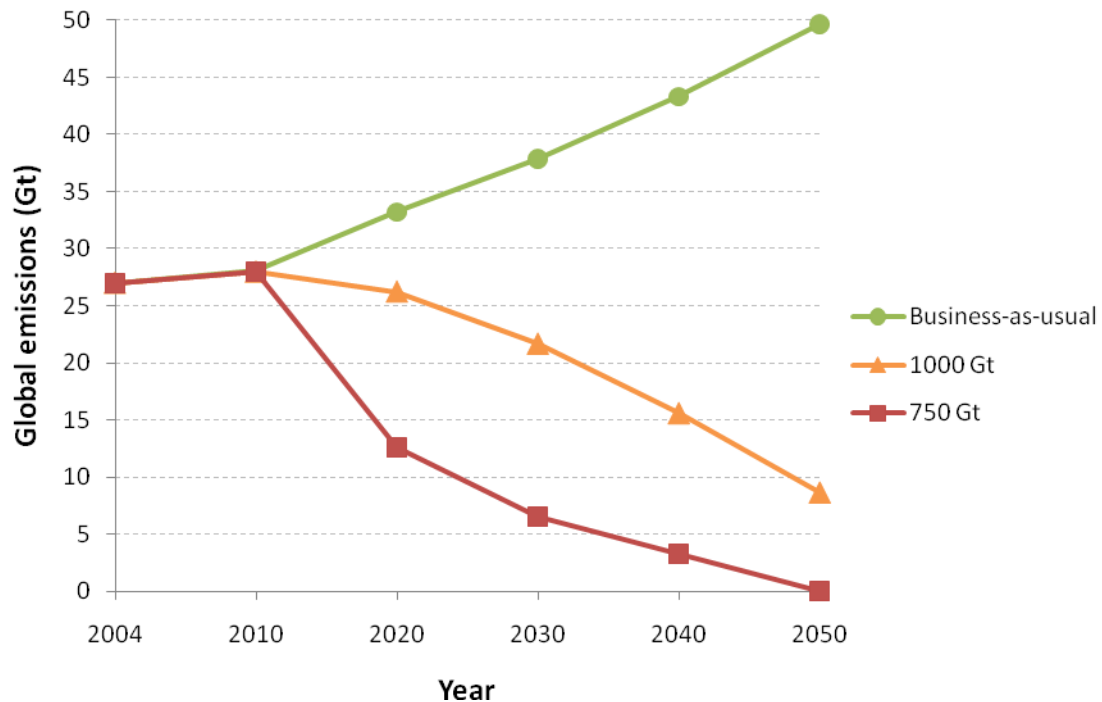


Figure 7 Assumed emissions pathways in VERITAS scenarios, for two reduction targets

2.5 Sensitivity Analyses

A number of major assumptions needed to be made in producing the simulation results for this study. There is a fair amount of uncertainty associated with some of the parameters used in VERITAS. In order to be transparent about the uncertainty that exists, I perform a sensitivity analysis on key parameters.

This involves testing a range of values for key parameters and noting the sensitivity of model output to these changes. This does not represent a comprehensive assessment of all the uncertainty that exists in this analysis. It does, however, provide some insight into the level of confidence that can be

placed on some results, given the sensitivity of output (or lack thereof) to key assumptions I have made.

I perform sensitivity analyses on three parameters in VERITAS: 1) the availability of CCS capacity, 2) the value of the ESUB, VAE , between energy and value-added (factor) inputs, and 3) the value of the ESUB, E , between inputs of electricity and carbon-emitting fuels. I deemed these three parameters to be of particular importance for sensitivity testing either because there has been little research performed on the value of the parameter (in the case of available CCS capacity), or because there is a substantial range in estimates of the parameter's value (in the case of the ESUB values).

For all three parameters, I test increases and decreases in the value by 1.5-fold and 2-fold. The exception is with a 2-fold decrease in CCS-capacity, which I do not report because it imposes substantial constraints on the uptake of CCS, thereby resulting in an unreasonably high global emissions price. I assume global permit trading and a grandfathering method of allocation for all sensitivity analysis simulations.

3: RESULTS AND ANALYSIS

I now present the VERITAS simulation results, in the form of carbon emissions price paths and regional welfare effects of different policy scenarios. Sections 3.1 to 3.3 summarize and provide analysis of the results of varying permit allocation, altering permit trading and changing the global emissions reduction target. Section 3.2 also includes relative marginal abatement cost curves for each region. Section 3.4 presents the results of the sensitivity analyses performed on three key assumptions made in VERITAS: CCS capacity and two ESUB values.

3.1 Methods of Permit Allocation

In the first policy scenarios, I assess the effects of various methods of allocating emissions permits on global emissions price and regional welfare. To refresh the reader, the VERITAS region abbreviations are as follows: US (United States), CAN (Canada), AMELA (Africa, Middle East, Latin America), OECD (OECD countries, including the Pacific and Mexico), ASIA (Developing Asia), EEU (Transition Economies), and CHN (China).

Grandfather tends to favour permit allocation to the industrialized and transition regions, while *PerCap*, *PerGDP*, and *Cumulative* tend to favour developing regions. In displaying results of multiple allocation schemes, the *Grandfather* method will often be compared to one of the methods in the latter group, as they all tend to produce similar results.

3.1.1 Carbon Emissions Price Paths

Figure 8 illustrates the global price on carbon dioxide emissions required to reach the specified reductions pathway using different permit allocation methods.

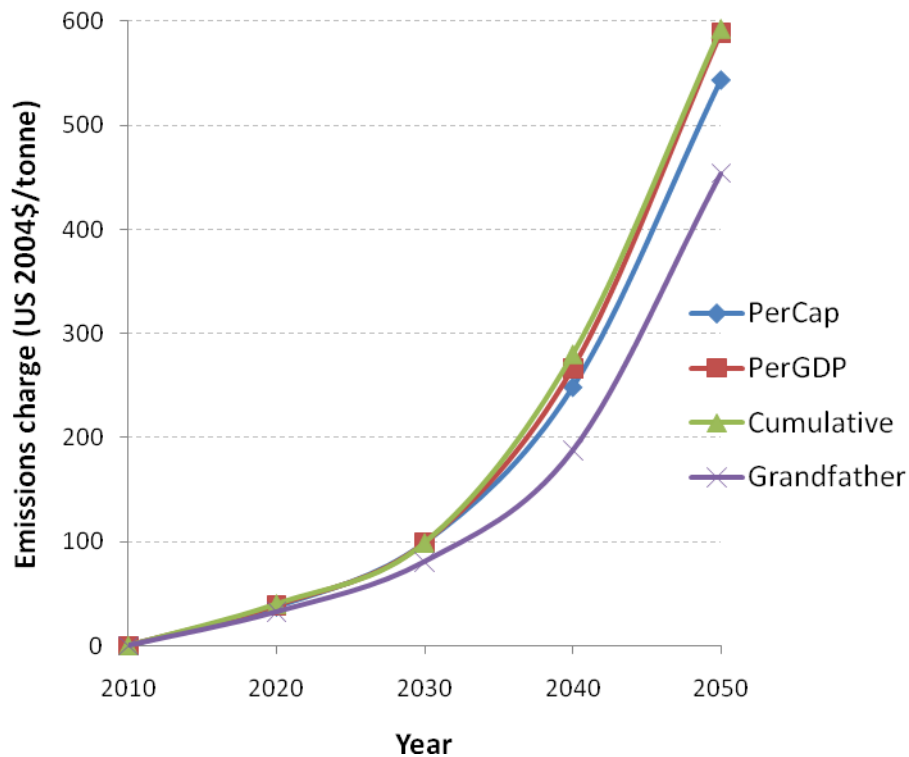


Figure 8 Global emissions price paths for four methods of permit allocation

The *Grandfather* method results in lower emissions charges for reaching the reduction target, requiring \$450/tonne by 2050. *PerCap*, *PerGDP*, and *Cumulative* allocation methods produce similar emission price paths, all higher than that for *Grandfather* by reaching close to \$600/tonne by 2050.

According to conventional economic wisdom, it may be expected that emissions prices should not vary across permit allocation methods. I attribute the difference in emissions charges to wealth effects, where allocating permits (or essentially wealth) to regions that demand more emissions-intensive goods

requires a higher emissions price to reach a certain level of reductions. This will be discussed in the next chapter.

3.1.2 Welfare Impacts

Equivalent Variation (EV) is the indicator used to determine welfare impacts of each policy scenario on each region. EV measures consumer welfare as the amount by which we can reduce a consumer's income in order to make her indifferent to a policy scenario. Where a policy makes the consumer better off, EV measures the income that the consumer must gain in order to make her just as well off. The EV metric takes on the assumption that consumers are optimizing their welfare in the BAU case to begin with and thus policy scenarios, which tend to restrict consumer choice, will reduce consumer welfare.

I present EV for each policy simulation as a proportion of EV in the BAU case. The EV trends for the *PerCap* method are similar to those from the *PerGDP* and *Cumulative* methods, therefore only one of the three is shown here (Figure 9).

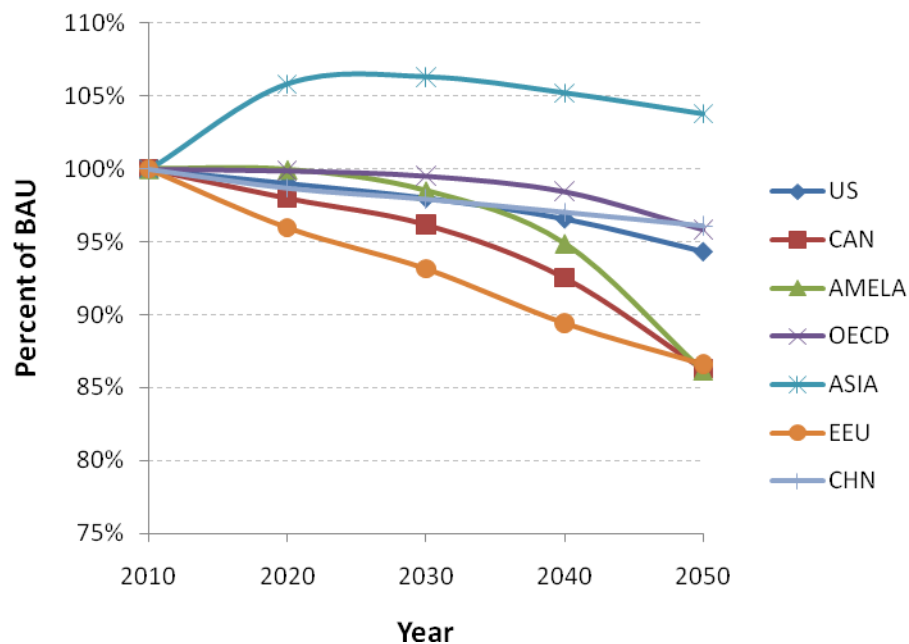


Figure 9 Change in equivalent variation for the *PerCap* allocation method

ASIA is the only region that experiences a growth in consumer welfare compared to the BAU scenario. All other regions experience a net decrease in welfare, where EEU and CAN have the greatest welfare losses. Welfare in the AMELA region decreases significantly in the last decade from 2040-2050.

In the *Grandfather* case as illustrated in Figure 10, both EEU and the US experience net increases in welfare until 2040. AMELA on the other hand, sees significant welfare declines. Between 2040 and 2050, welfare declines significantly for most regions, with the exception of ASIA, which experiences a welfare increase during this time.

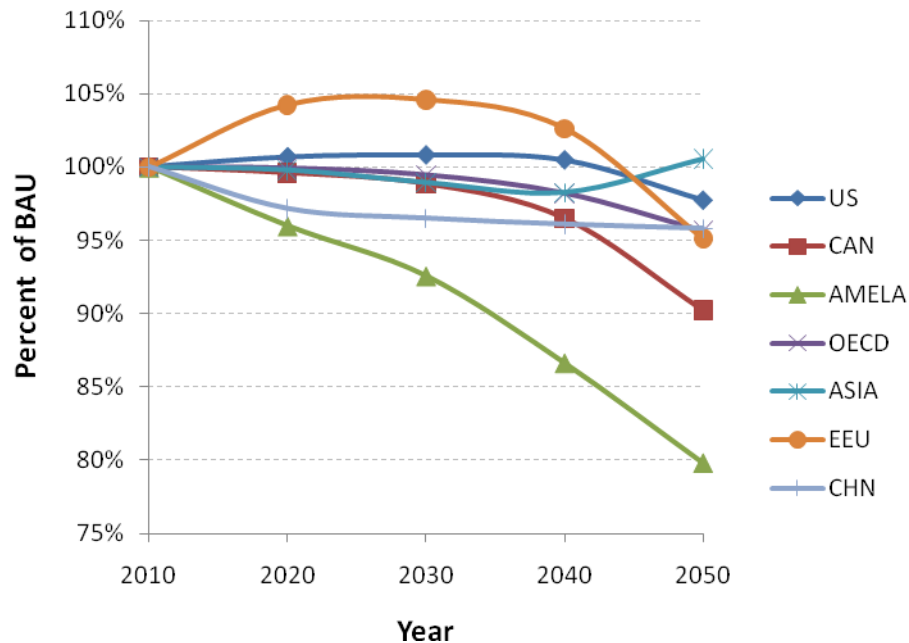


Figure 10 Change in equivalent variation for the *Grandfather* allocation method

Welfare impacts differ significantly for some regions between the two allocation methods and little for other regions. EEU in particular, experiences a significant positive welfare impact with *PerCap* allocation and a significant negative impact with *Grandfather* allocation. Similar patterns, though to a lesser

extent, are experienced by ASIA and AMELA regions, which both suffer more in the *Grandfather* case. Meanwhile, OECD and CHN experience similar moderate declines in welfare in both *PerCap* and *Grandfather* methods,

Grandfathering permits clearly benefits EEU because of the 1990 baseline year chosen for this allocation method. The collapse of the Soviet Union around this time resulted in significant deindustrialization of the EEU economy and large decreases in emissions in the early 1990s. Since the EEU region has yet to reach its 1990 emissions levels, allocating permits based on 1990 emissions results in a permit allocation to the region greater than its business-as-usual emissions - what is known as “hot air” (Aldy and Stavins, 2007).

On the other hand, in *PerCap* allocation, EEU suffers the greatest welfare losses of all regions because of its low population resulting in a relatively low allocation. As well, the EEU region is a net fossil fuel exporter and suffers as a result of decreasing global demand of its fossil fuel goods. These trade effects are an important determinant of a region’s welfare impacts in an emissions abatement scheme, as will be discussed in the next chapter in section 4.4.

The OECD region does not experience significantly different welfare effects as it is allocated a similar proportion of permits between the two methods. As compared to the other industrialized regions of US and CAN, OECD’s emissions in 1990 were approximately four times less on a per capita basis. Meanwhile, OECD has a large population. Therefore, as compared to the other industrialized regions that tend to prefer grandfathering, OECD is more indifferent as it receives fewer permits in the *Grandfather* method but more permits in the *PerCap* method.

For the US and CAN regions, welfare impacts end up being similar by 2050 in both allocation scenarios. In the *PerCap* method, regions experience a gradual decline, while in the *Grandfather* method, welfare loss is delayed until it drops substantially between 2040 and 2050. This may mean that regardless of the allocation of permits, emissions reduction opportunities have reached the same limits by 2050 in these two regions, resulting in welfare losses that permit

allocation cannot compensate for. The US does, however, experience net welfare gains in the *Grandfather* method until 2040, reflecting the generous allocation to the region in this scheme due to high historical emissions.

AMELA and ASIA both experience much more favourable welfare effects in the *PerCap* allocation method, because they have the lowest emissions per capita of all regions. AMELA, however, experiences substantial net welfare declines in both cases, while ASIA experiences net welfare increases in the *PerCap* method.

AMELA's welfare declines are not surprising, given the presence of energy-exporting countries within the AMELA region (most notably those in the Middle East), which would be expected to suffer from an emissions pricing policy due to decreased demand for the region's exports. The AMELA region is highly dependent on fossil fuel exports, exporting 68% of the region's primary energy production, half of which comes from the Middle East. All members of the Organization of the Petroleum Exporting Countries (OPEC) are in this region, except for Indonesia (Melton, 2008).

In attempting to identify the reasons for AMELA's welfare declines, I examine the prices of certain commodities and activity levels of key sectors in the region. Reflecting the dependence on fossil fuel exports, AMELA is the only region that experiences a decline in its value of total exports in 2050 with an emissions pricing scheme, reflecting primarily the decrease in the prices of its exported goods (as opposed to a decrease in quantity of exports). The crude oil sector experiences the greatest declines in export value, followed by the coal and natural gas sectors; these declines reflect decreasing global demand of fossil fuels and AMELA's worsening global trade position in these markets.

In AMELA, the prices of fossil fuels (including their emissions charge) increase the most of all regions. Note that these price increases are for fossil fuels with the carbon emissions price paid, thus although lower global demand for fuels results in lower prices, it is the emissions pricing requirement that increases the price of each unit of fuel purchased by consumers and firms. Even

with *PerCap* allocation, in which the AMELA is better off compared to *Grandfather*, the final price for coal rises to 74 times the BAU price. Electricity prices also see the greatest increase of all regions. In both *PerCap* and *Grandfather* scenarios, AMELA's conventional electricity sector (without CCS) becomes inactive, while the region fully employs its CCS capacity by 2050. Therefore, it cannot make any further emissions reductions through CCS.

It is important to note that aggregation of the Middle Eastern countries with Africa and Latin America masks important sub-regional differences. For example, although it appears that the AMELA region would suffer significantly from a *PerCap* method of allocation, the African sub-region (with substantially lower per-capita emissions) may not. As suggested by Melton (2008), increasing regional disaggregation, particularly in the AMELA region which contains countries of significantly variable income level and economic structure, may help increase model accuracy. These disparities are particularly pronounced between the Middle Eastern and African countries within the region.

The welfare impacts on the AMELA region are supported by Peterson and Klepper (2007), who find that the Middle East and Africa suffer the greatest welfare losses where permits are allocated based on grandfathering. Peterson and Klepper (2007) also find that where a contraction and convergence⁷ style of permit allocation is followed (which can be compared to *PerCap* allocation in this study), the African region experiences net welfare gains. While these gains may be masked by the much larger welfare losses experienced in the Middle East region, this may be a reason why the AMELA region as a whole has fewer losses in the *PerCap* method.

ASIA is another region which experiences more favourable welfare impacts from the *PerCap* method compared to *Grandfather*. It is the most populous region in VERITAS and therefore receives the greatest proportion of permits in the *PerCap* method. Peterson and Klepper (2007) also find that in a

⁷ The contraction and convergence framework 'contracts' global emissions by first allocating emissions rights based on grandfathering and over time, 'converges' the distribution of emission rights, eventually resulting in equal per-capita emissions allocations.

per-capita allocation scheme similar to that of *PerCap*, India, a country within the ASIA region, is one of two regions experiencing net welfare gains due to generous permit allocations.

Like AMELA, ASIA fully employs its CCS capacity in all three steps for both *Grandfather* and *PerCap* methods, although its conventional electricity sector remains active (albeit at a substantially lower activity level compared to BAU). The abatement costs in ASIA also tend to be low, so ASIA reduces emissions significantly and in fact produces net negative emissions by 2050 by employing biomass CCS. Therefore, ASIA is able to gain from generating surplus permits.

In contrast to AMELA, ASIA is much less economically reliant on fossil fuel production and is able to decrease emissions significantly without experiencing substantial welfare loss, while in some instances, even gaining welfare. Its fuel prices (including emissions charge) increase only moderately compared to increases in other regions. ASIA increases substantially the value of its exports, notably in the crude oil sector, where the price of crude for export increases 4.5-fold in a *PerCap* allocation method. Recall that crude oil does not incur any carbon penalties in this modeling approach as it is used primarily as a feedstock for RPP production, so the ASIA region is not penalized by emissions pricing for maintaining a strong crude oil sector.

It is notable that ASIA is the only region for which the price of crude oil exports increases. It appears that ASIA's crude oil is highly demanded by other regions, thus driving up the export price of the commodity, because of the low emissions intensity of the crude oil sector in ASIA compared to other regions. However, I express caution in interpreting this result, as I have not incorporated any constraints to the availability of any inputs to sectors over time, including fossil fuels. For example, Indonesia, the only country in the ASIA region in the Organization of Oil Exporting Countries, is set to decline its output of crude oil due to maturation of oil fields (EIA, 2010). Therefore, I may have overestimated the availability of certain inputs, particularly those in essentially finite quantities

such as crude oil. Also the Armington elasticities of substitution for the crude oil sector may be set too high, indicating that crude oil from the ASIA region can displace too readily crude oil from any other region.

3.2 Permit Trading

3.2.1 Carbon Emissions Price Paths

Next, I examine the results of restricting global permit trading. Figure 11 below shows the regional emissions price paths in the *NO TRADE* scenario. Recall that in this scenario, industrialized and transition regions face different emission reduction targets from the developing regions. The black line shows the emissions price path in the *TRADE* scenario for comparison, where permits are allocated through grandfathering. Until 2030, CAN, OECD, and US have a higher carbon emissions price than in the *TRADE* case. In 2040 and 2050, EEU also has higher emissions prices. AMELA, ASIA, and CHN all have lower emissions charges than the global price path in the *TRADE* scenario.

It is important to note that I needed to place constraints on the increase in land price, for each simulation year. Otherwise, the price of land would skyrocket, significantly restricting uptake of biomass CCS. This would result in extremely high emissions charges (on the order of thousands of US\$2004), particularly around 2040 and 2050 for regions with already high costs, specifically OECD and CAN.

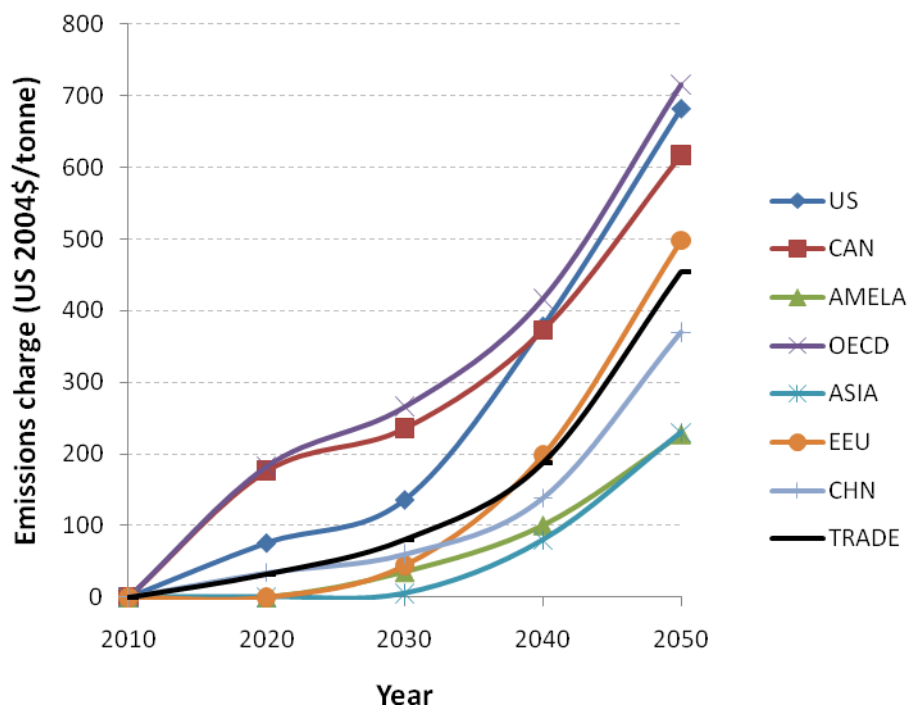


Figure 11 Carbon emissions price paths for all regions, in the *NO TRADE* scenario, compared to the *TRADE* scenario

In scenarios where regions are not permitted to trade permits, it is the industrialized and transition economy regions of OECD, CAN, US, and EEU that have higher emissions charges than the global emissions price path in the *TRADE* scenario. This pattern is supported by other studies, including Bohringer and Rutherford (2002), Tulpulé et al., (1999), Kainuma et al. (1999) and Ellerman and Decaux (1998), which find that the emissions permit price in Annex I (industrialized) countries is lowered where permits are traded with other regions. Thus, in a scenario with permit trading, industrialized regions tend to be able to emit more (due to access to lower-cost abatement opportunities), while developing nations tend to emit less (because they sell their emission rights to industrialized regions), as compared to a *NO TRADE* scenario.

It is important to keep in mind that in the *NO TRADE* case, percentage emissions reductions below 1990 levels are the same for all industrialized and transition regions (85% reduction by 2050) and all developing nations (9%

reduction by 2050). However, percentage reductions from BAU levels vary for each region because of different projected growth rates. Table 13 elaborates upon specific emissions reductions achieved in the *NO TRADE* case.

Table 13 Emissions reductions below 1999 and BAU levels in 2050 in the *NO TRADE* scenario

Region	US	CAN	OECD	TE	AMELA	DA	CHN
Reduction from BAU	89%	93%	93%	80%	80%	70%	82%

This table helps explain the pattern of some of the emissions charges in Figure 11. Where ASIA reduces the least below BAU, it also has the lowest emissions charges. Both OECD and CAN have the highest emissions reductions and they have the steepest emissions price paths until 2040, after which the US price path becomes steeper than CAN's. However, although EEU, AMELA, and CHN achieve similar percentage reductions in 2050, it is apparent that their emissions charges differ significantly: they are lowest in AMELA and highest in EEU.

3.2.2 Relative Marginal Abatement Cost Curves

Marginal abatement cost (MAC) refers to the cost of reducing an additional unit of emissions. Plotting MACs on a graph generates MAC curves, which tend to slope upwards as the incremental cost of reducing more emissions increases. MAC curves are useful in visualizing the cost of reducing the last unit of emissions (which is equal to the permit price determined by the market), relative to a level of emissions reductions. MAC curves help visualize the minimum emissions price required to achieve a certain level of reductions.

I now present results of simulating harmonized reduction targets from the BAU baseline for more appropriate comparison of regional MACs. I do not

differentiate reduction targets between industrialized and developing regions, as I did in the *NO TRADE* case. Figure 12 shows the MAC curves for each region in the year 2050, based on relative emissions reductions measured in percent reductions from BAU.

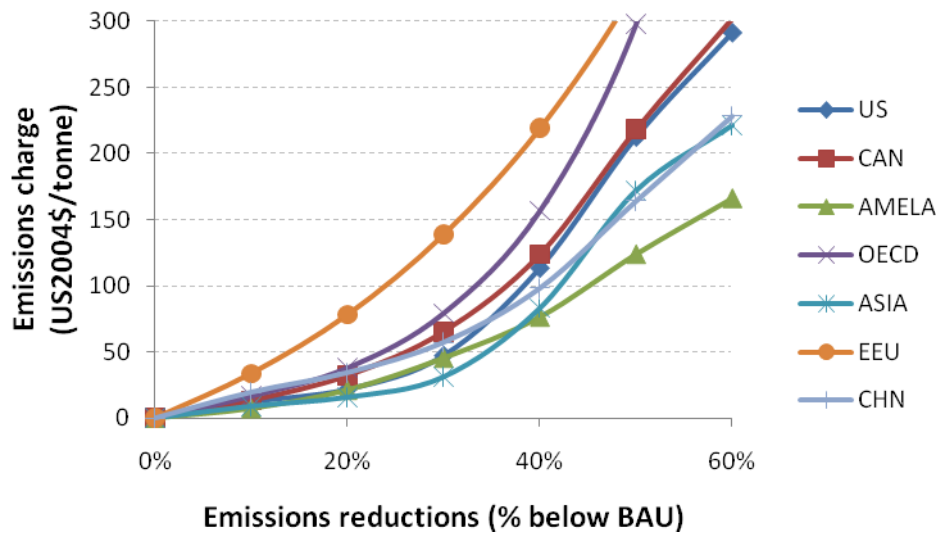


Figure 12 Marginal abatement cost curves for each region in 2050, in terms of percent reductions from BAU

The general trend can be observed that industrialized and transition economies experience higher MACs than developing regions. Overall, the MACs in EEU are the highest, while those in ASIA are the lowest up to the level of 40% reductions, after which those in AMELA are the lowest and ASIA's MAC curve converges with that of CHN. Of the industrialized regions, OECD has higher MACs than the US and CAN, which have very similar curves.

Overall, EEU has the highest MACs. According to Wolinetz (2009), the EEU region has relatively few inexpensive options for abatement, as many production processes already use natural gas. Intuitively, given the similarities in economic structure, US and CAN have similar MAC curves, while ASIA and CHN also have similar curves, particularly at reductions over 40% below BAU.

Developing regions tend to have lower MACs, since there is a fair amount of energy efficiency to be gained as well as fuel switching away from emissions-

intensive fuels, especially coal. This pattern of differentiation of relative MAC curves between industrialized and developing regions is supported by other studies, including Ellerman and Decaux (1998), Sands (2004), den Elzen et al. (2005), and McKibbin et al. (1998), which find that in general, MACs for Japan and Europe are the highest and those in Asia and Africa are the lowest.

It is interesting to note the comparison of Figure 12 with Figure 13 below, which shows the emissions reductions in each region in a global trade scenario. There is a clear relationship between marginal abatement costs and level of emissions reductions, where those regions with highest MACs tend to reduce least, while regions with low MACs reduce the most.

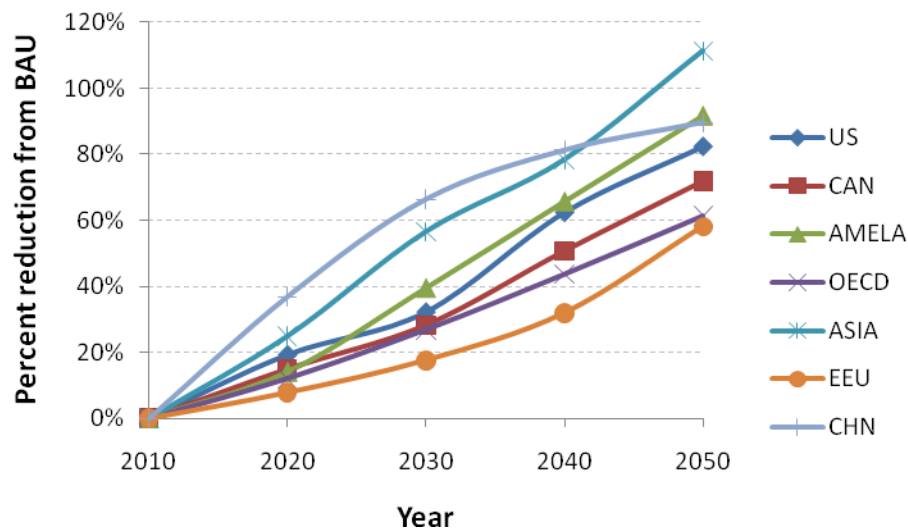


Figure 13 Emissions reductions in each region where permits are traded globally and allocated according to *Grandfather*

The regional reductions vary only slightly with each method of allocation, therefore only those for *Grandfather* are shown here. It is interesting to note that ASIA reaches net negative emissions in 2050, due to full uptake of both conventional and biomass-CCS in the electricity sector. The ASIA and CHN regions undertake the greatest total reductions of all regions.

3.2.3 Welfare Impacts

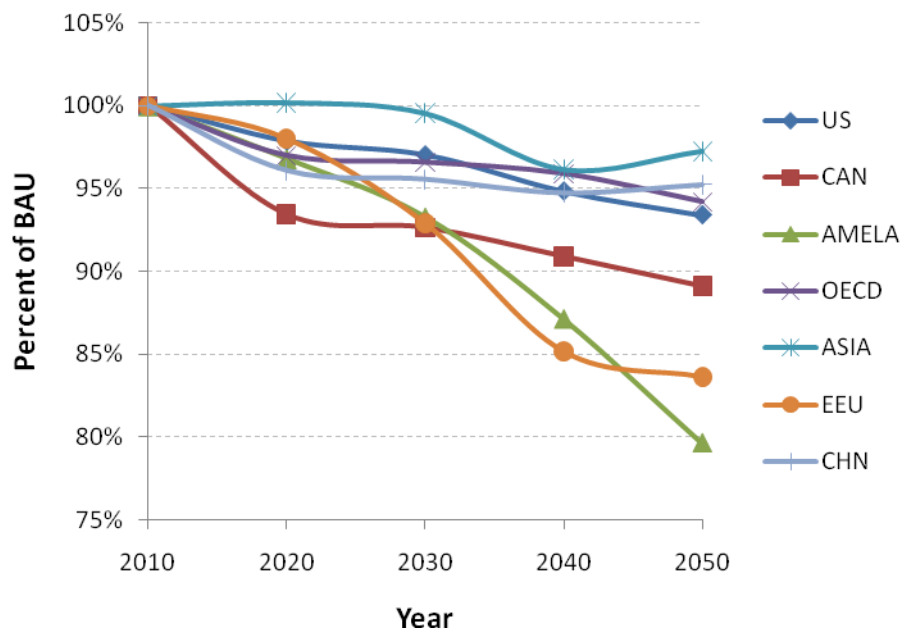
The effects on consumer welfare in each region are shown in Figure 14, which compares the *NO TRADE* and *TRADE* cases. Overall, regions benefit from global permit trading. In the *TRADE* scenario, regions generally have smaller declines in welfare in the years leading up to 2040, then experience steeper losses by 2050.

For most regions in the *TRADE* scenario, welfare may decrease to a similar extent by 2050 compared to the *NO TRADE* case, but significant welfare declines seem to be held off until about 2040, after which welfare decreases significantly for some regions. In both scenarios, a jump in welfare of the ASIA region is observed between 2040 to 2050. EEU experiences the greatest difference between the trading scenarios benefitting greatly from permit trading, while AMELA sees similarly large welfare declines in both cases.

The EEU region benefits the most from trading permits given that in the *Grandfather* method, it is allocated a surplus of “hot air” emissions permits. Otherwise, EEU suffers from declines in the value of its fossil fuel exports and experiences the greatest welfare losses in the *NO TRADE* scenario.

EEU and the industrialized regions tend to benefit more from trade than the developing regions, implying that access to low-cost abatement opportunities for industrialized regions results in greater welfare gains than the increased revenue to developing regions from selling lower-cost emissions permits. McKibbin et al. (1998) also find greatest welfare gains from permit trading for OECD countries (which includes Canada and the US). It is also possible, however, that welfare gains could change with differing permit allocation; for example, developing regions may benefit more from trade in a *PerCap* allocation scheme. However, these alternative allocation scenarios were not assessed.

NO TRADE



TRADE

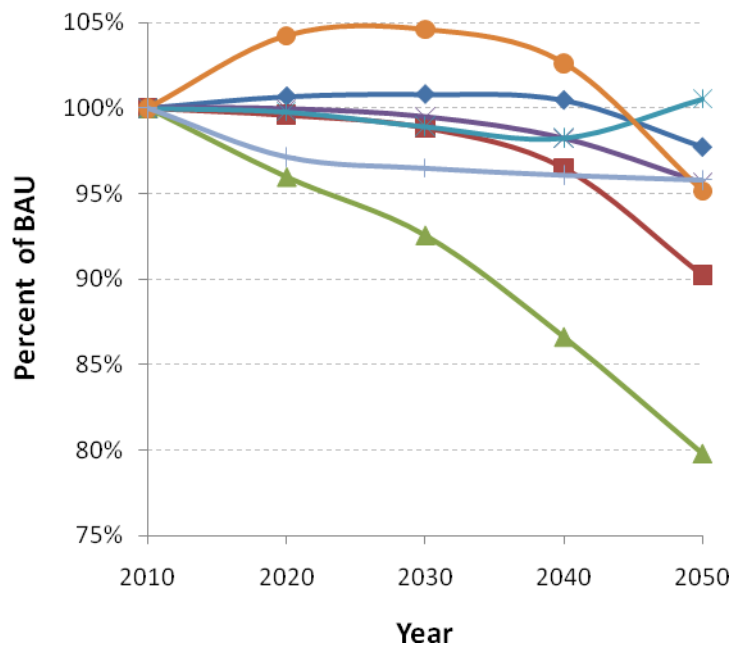


Figure 14 Changes in equivalent variation in two trading scenarios

CHN is the least affected by the change in permit trading. I suggest that this is because CHN's MAC curve in the *NO TRADE* scenario is only slightly lower than the global MAC curve in the *TRADE* case (Figure 11). In 2050, CHN abates less in the *NO TRADE* scenario thus incurring fewer total abatement costs. In the *TRADE* scenario, however, although the region abates slightly more, it receives just enough revenue in terms of permit allocation to make it relatively indifferent between the two scenarios. In other words, it incurs approximately the same total costs in both cases.

AMELA continues to experience the greatest welfare losses in general. Meanwhile, ASIA suffers relatively few welfare losses in both cases. A comparison between the AMELA and ASIA regions may be useful at this point, where the two regions have the lowest MACs (Figure 12) but generate very different welfare results.

Since the reductions in both regions are relatively cheap, they both incur high total emissions reductions for any given price on carbon emissions. Thus, both regions have low *marginal* abatement costs, but incur high *total* abatement costs. In order to achieve these reductions, both regions depend heavily on CCS technology. The dependence of emissions abatement on CCS in the AMELA and ASIA regions is supported by the findings of Melton (2008) and Goggins (2008). In a *TRADE* scenario, both regions receive similarly meager permit allocations.

It appears that the difference in observed welfare effects between the two regions is due to their differential vulnerability to international trade effects within fossil fuel markets, as mentioned previously. AMELA suffers significantly, whether permits are traded globally or not, due to the significant decline in the price of its fossil fuel exports resulting from decreased demand.

Alternatively, ASIA as a net fossil fuel-importer benefits from lower prices of imported fuels. This is consistent with Bohringer and Rutherford (2002) who find that economic gains can be realized by fuel-importing regions in a carbon abatement scheme, where global fuel prices drop due to decreased demand thus

making imports to these regions cheaper. ASIA derives wealth from other sectors, notably crude oil production. The region also appears to benefit from permit trading, by profiting significantly from the deployment of its CCS technologies, including biomass-CCS and generating substantial negative emissions. The ASIA CCS sector is less dependent on fossil fuels than AMELA and therefore less emissions-intensive and more profitable in a carbon-constrained world. These advantages for the ASIA region appear to grow significantly between 2040 and 2050, which accounts for the jump in welfare for the region during this period.

Overall, these patterns of regional welfare effects are consistent with Kainuma et al. (1999), who also find the largest GDP gains in the former Soviet Union in a scenario with permit trading and the largest GDP losses in the Middle East in a no-trading scenario. Similarly, Bohringer and Rutherford (2002) also find that the former Soviet Union experiences greatest welfare gains with permit trading, and without permit trading, both this region and oil-exporting countries experience the greatest welfare losses.

3.3 Emissions Reduction Target

3.3.1 Carbon Emissions Price Paths

I will now summarize the results of achieving a more aggressive emissions reductions target. Figure 15 shows the carbon emissions price paths for the two reduction pathways examined. Intuitively, reaching the more ambitious target in the 750 scenario requires a higher emissions charge. By 2050, an emissions charge close to \$700/tonne is required to reach this level of reductions, compared to \$450/tonne price for the less stringent target. The increase in price requirement differs over each simulation year, peaking around 2040 where an emissions charge of \$400 more per tonne is required to reach the more aggressive target.

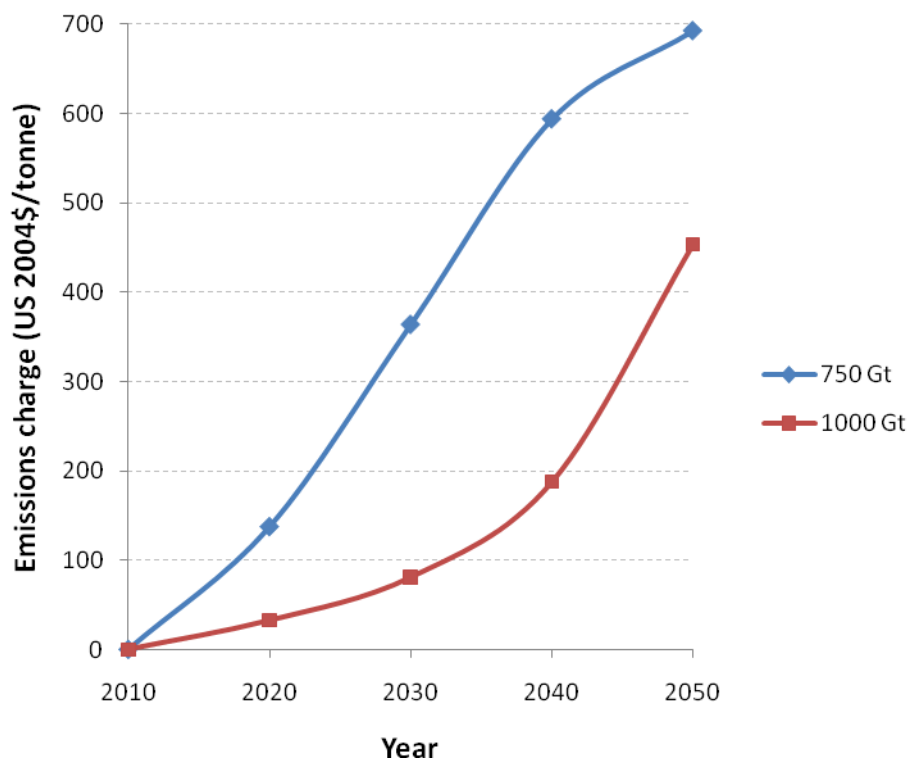


Figure 15 Carbon emissions price paths for 750 and 1000 emissions reduction targets with a *Grandfather* method of allocation

The shape of each price path is determined by the specified emissions reduction pathway. For the 1000 case, I specify linear reductions below BAU and thus the emissions charge is shown to increase exponentially with increased emissions reductions.

The curve for the 750 case does not follow the shape of the other emissions price trajectories in this study. This is because I specify significant emissions earlier in the simulation years and proportionately few between 2040 and 2050 (refer back to Figure 7 for reduction pathways). Thus, the 750 MAC curve becomes less steep in these later simulation years, as increasing reductions from 92% below BAU in 2040 to 100% in 2050 takes place with relative ease. By 2040, the emissions charge has risen high enough in order to activate both conventional and biomass CCS in all regions. Reaching a few

more reductions in the decade between 2040-2050 thus only requires small increases in CCS activity in a few regions.

However, I must caution that I may have overestimated the ease with which CCS can be taken up. Since VERITAS is a static model, I determine exogenously the amount of CCS capacity available in each simulation year regardless of the amount of CCS taken up in previous years. In other words, if CCS uptake is high in 2040 and most of the “good” storage sites are used, I still assume only a 10% decrease in CCS capacity in these favourable sites in 2050. Converting VERITAS to a dynamic model would address this problem, as is discussed in the next chapter.

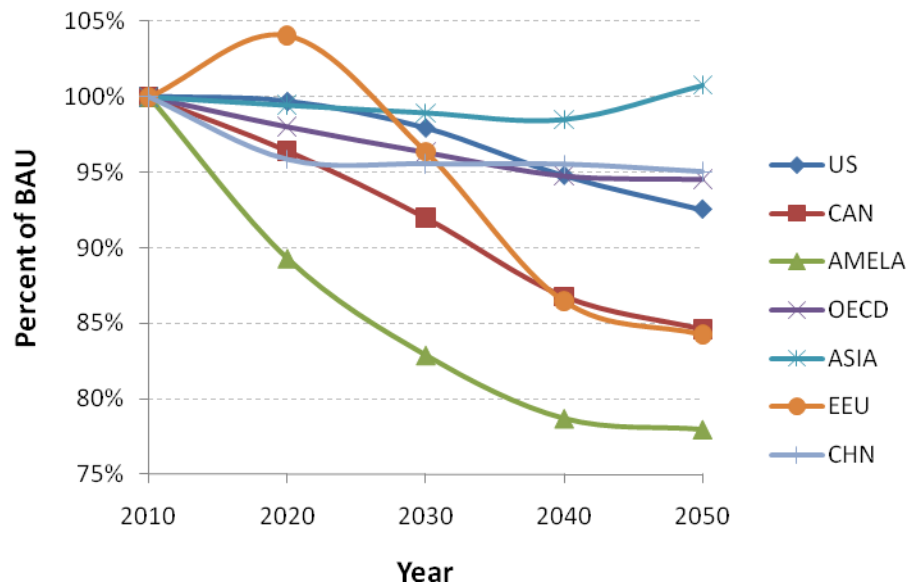
3.3.2 Welfare Impacts

Figure 16 shows the regional welfare effects for two global emissions reduction scenarios. Achieving the more ambitious target generally results in 5-10% greater welfare losses than in the *1000* scenario for any given region. In both scenarios, AMELA again experiences the greatest welfare decreases, while EEU experiences net welfare gains followed by steep declines.

Recall that I assume a grandfathering method of permit allocation in these scenarios, which explains the general welfare trends observed in each region (for example, the net gains for EEU). The welfare in ASIA increases from 2040 to 2050 and is the only region experiencing net welfare gains by 2050 in both reduction scenarios.

The pattern of welfare impacts is also reflective of the assumed emissions reduction pathways. Similar to the pattern seen in the emissions price path for the *750* case, welfare declines are high in earlier simulation years and tend to flatten out after 2040. In the *750* case, the welfare decline EEU experiences after 2020 may signify that the benefits accrued from the sale of “hot air” permits become exhausted. This decline occurs later in the *1000* scenario, where surplus permits provide net welfare gains to EEU until 2040.

750 Gt



1000 Gt

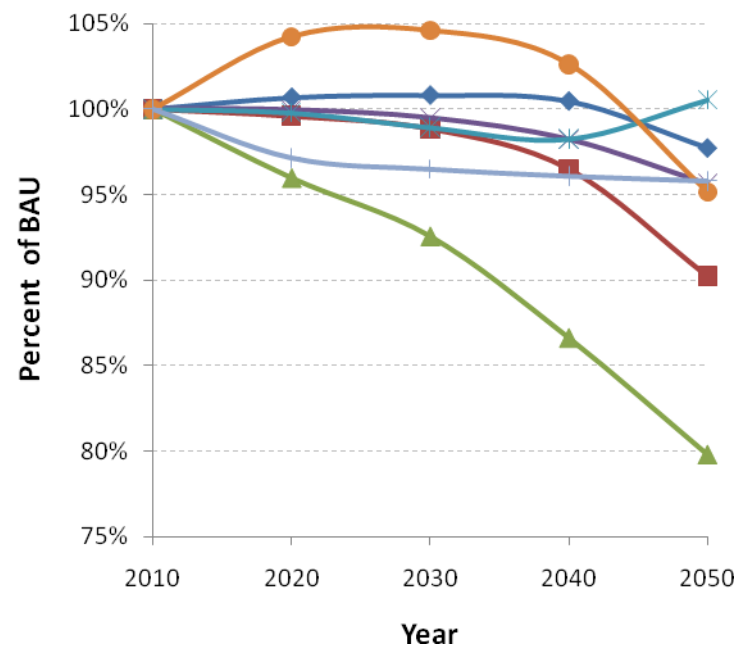


Figure 16 Changes in equivalent variation for two emissions reduction targets

Both OECD and ASIA experience similar welfare declines in both target scenarios. In other words, reaching a global 750 target does not result in much lower welfare in these regions.

I suggest three potential reasons for ASIA's resilience. Firstly, this region has low marginal abatement costs and is able to undertake significant emissions reductions at relatively low cost, including producing negative emissions through the full employment of biomass CCS. Conventional electricity production in the ASIA region is second largest in terms of output value, after CHN. This means that there is high capacity for CCS, given that CCS capacity is proportional to capacity of the conventional electricity sector. Thus, ASIA has the potential to accrue many benefits from CCS in both reduction scenarios. The value of land also increases the least in ASIA out of all regions, facilitating the uptake of biomass CCS. Secondly, when the reduction target is higher, ASIA receives a substantially higher price for its crude oil exports as demand for the commodity from this region increases significantly. As previously discussed, caution is merited in interpreting this rapid increase in value of these exports. Thirdly, the value of output in a number of ASIA sectors remains relatively stable in both reduction scenarios, signifying that ASIA's sectors exhibit a fair amount of resiliency by fuel-switching (primarily to electricity) and efficiency with greater carbon constraints.

The stability of welfare changes in OECD may be due to substantial increases in CCS activity. In making the leap between the 1000 and 750 target in 2050, this region sees the greatest increase in CCS uptake of all regions. In the 1000 target, OECD only employs about 10% of its biomass CCS capacity and no conventional CCS. In the 750 target, the first step of conventional CCS capacity becomes fully activated and the second step is 22% employed. This rapid onset of CCS in the 750 case may imply that CCS in the OECD region was just below the threshold of being economical in the 1000 scenario. With the increasing emissions price with a more ambitious reductions target, OECD finds an easy way of significantly reducing its emissions and joining all the other regions in producing net negative emissions from the electricity sector.

Furthermore, the OECD is able to switch with relative ease away from fossil fuels to electricity, where its electricity generation sector is already quite efficient. This is consistent with the findings of Goldberg (2009), where in an emissions pricing policy, GDP in the OECD region either declines slightly or even increases slightly over the simulation period, benefitting partly from increased demand of electricity in the region.

Overall, it appears that the ambitious 750 target is achievable, albeit with a significantly higher emissions charge, greater welfare declines for all regions, and high dependence on CCS. Conventional CCS capacity is fully employed in all regions except OECD. Biomass-CCS is also fully employed in the ASIA and AMELA regions for the 2050 simulation year.

In order to properly assess whether reaching an aggressive reduction target is worthwhile, the estimates of abatement cost and welfare losses from this study should be weighed against the benefits of averting climate change damages. These benefits would be substantially greater in this scenario where very deep reductions are achieved.

There remains, of course, uncertainty in natural sink capacities and in the level of emissions reductions that will ensure a cumulative 750 Gt or 350 ppm CO₂ target is reached. Given that this ambitious target is somewhat new to the climate literature, a relatively few number of studies provide quantitative information on required emissions reductions to reach this target. I simply chose reductions consistent with some of the few studies in existence, which include Baer et al. (2009) and Hansen et al. (2008).

3.4 Sensitivity Analysis

I tested three uncertain parameters in VERITAS. The first parameter is that of available CCS capacity. In the VERITAS simulations, I assume that 100% of conventional electricity can be converted to CCS. However, this is likely a low value, since storage capacity estimates range much higher, thus allowing greater amounts of carbon to be stored than I assume. Also, since CCS capacity is

based on that of conventional electricity in the business-as-usual case, I am potentially limiting CCS uptake since I do not assume any increased electrification in the future.

Figure 17 shows the results of varying percentages of CCS capacity in proportion to the conventional electricity capacity in the reference case. The price on carbon emissions is moderately responsive to decreases in CCS capacity, becoming more sensitive to these decreases over time. By 2050, a 1.5-fold decrease in CCS capacity results in a 62% increase in emissions charge.

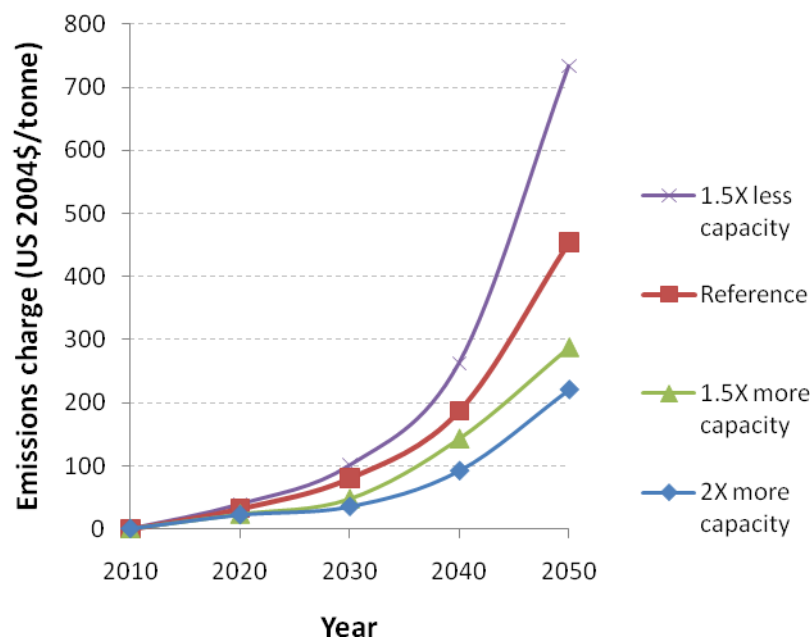


Figure 17 Sensitivity of varying available CCS capacity on global emissions price paths

The decrease in capacity has a greater proportional effect in later years, where there is greater dependence on CCS for carbon abatement. In earlier simulation years, the effects of decreasing CCS capacity are smaller because less CCS is being used and therefore changing specifications for this technology is less meaningful for changing simulation results.

Meanwhile, increasing CCS capacity has a relatively consistent proportional effect on the emissions charge over time. Doubling available capacity approximately halves the emissions charge in any given year. This indicates that the strength of constraint of this parameter remains generally consistent over any level of reductions, where if the constraint is relaxed (ie. more capacity is available), the emissions charge lowers accordingly by a certain proportion.

On the other hand, increasing this constraint (ie. decreasing capacity) produces increasingly higher demands on the model to find abatement options as more reductions are required over time, thus producing greater proportional increases in the emissions charge. As mentioned, this is likely because the default estimates of CCS capacity are conservative. Decreasing capacity even more results in significant CCS constraints, making it that much more difficult to reach a certain level of emissions reductions.

I now present the sensitivity analysis results on two ESUB values. Figure 18 first shows the sensitivity of global emissions charge to changes in VAE, the elasticity of substitution between value-added (factor) inputs and energy inputs.

The emissions charge appears to be sensitive to increases in VAE up to a certain point, after which incremental increases produce minimal emissions price reductions. This may reflect a situation where this constraint has been relaxed to the point where other constraints become more important. In other words, no matter how much easier the substitution between factors and energy becomes, limits on CCS uptake or other rigidities in the economy may not make abatement cheaper. Decreasing VAE results in a more steady increase of the emissions charge, which may indicate that VAE continues to be an important constraint as it decreases.

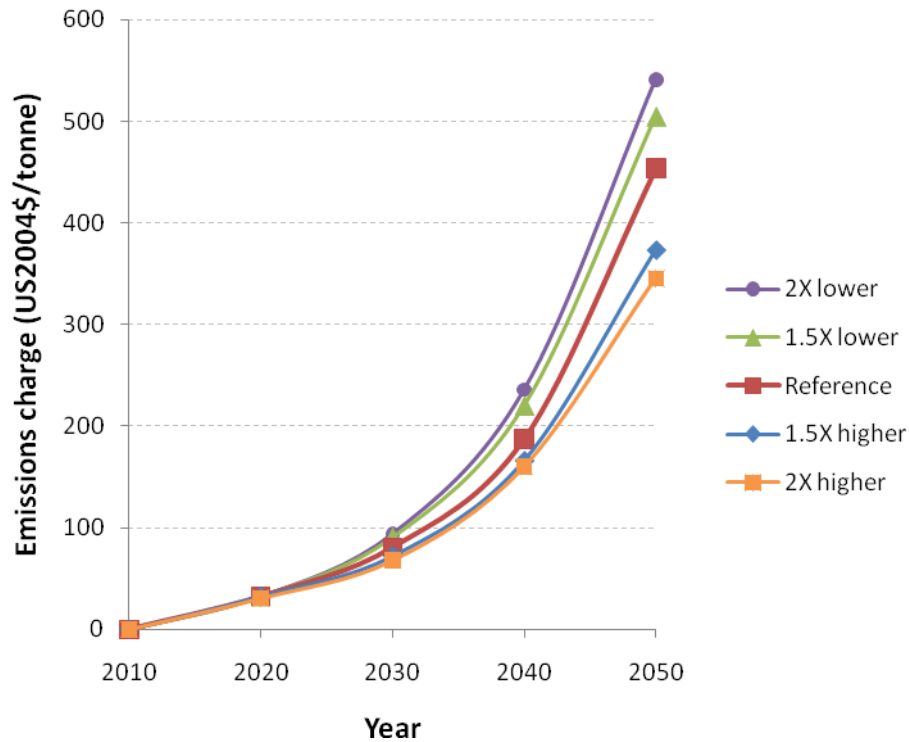


Figure 18 Sensitivity of varying the VAE elasticity of substitution value on global emissions price paths

Figure 19 shows the response of global emissions charge to changes in E , the elasticity of substitution between electricity and fossil fuels. Similar to the responsiveness of the emissions charge to VAE changes, increasing the E value results in significant emissions charge decreases until a certain point, after which it may no longer be an important constraining parameter. In contrast to VAE however, incremental lowering of the E value also appears to approach more quickly a limit of its effects on the emissions charge. Thus, at a certain point even if the E value was lowered to zero it may no longer act as an important model constraint.

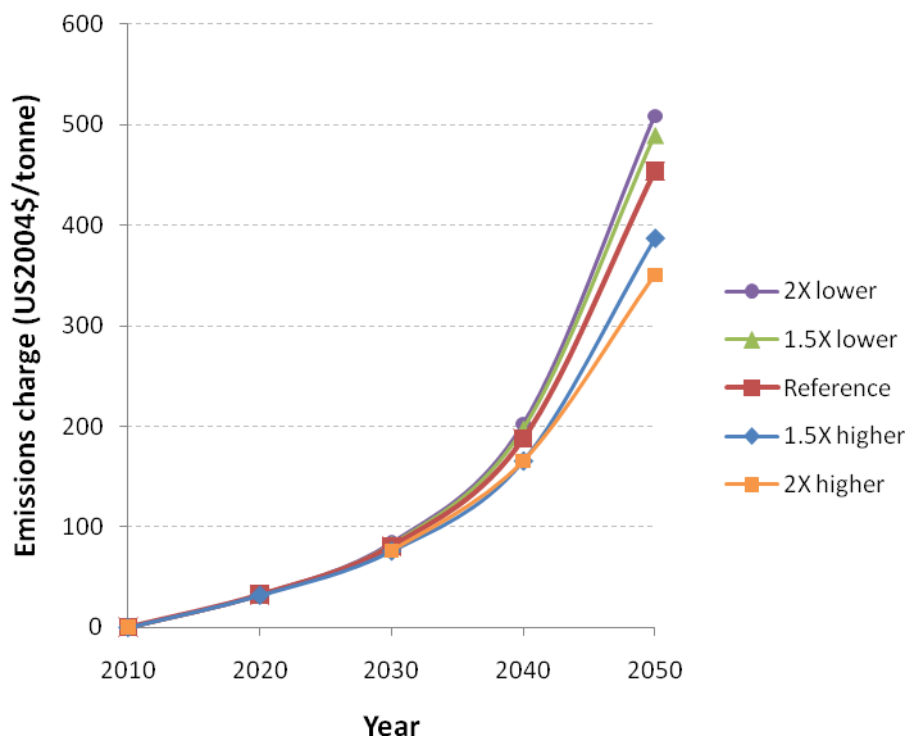


Figure 19 Sensitivity of varying the E elasticity of substitution value on global emissions price paths

This may reflect a situation where the model has shifted focus to find substitutions elsewhere to produce emissions reductions. For instance, instead of pursuing electrification by substituting fossil fuels for electricity, VERITAS may achieve emissions reductions by substituting between different fossil fuels (such as switching from coal to natural gas) or between factors and energy (ie. energy efficiency).

The sensitivity of the global emissions charge in 2050 to the change in each of the three parameters is summarized in Figure 20. The change in global emissions charge is plotted over change in the parameter value, thus a steeper slope indicates greater emissions charge changes, or greater sensitivity, to changes in the parameter. Overall, the model is very sensitive in 2050 to changes in available CCS capacity, particularly to decreases in this value. The model's output of emissions charge is also moderately sensitive to ESUB

changes where the magnitude and pattern of changes for both ESUB values are similar.

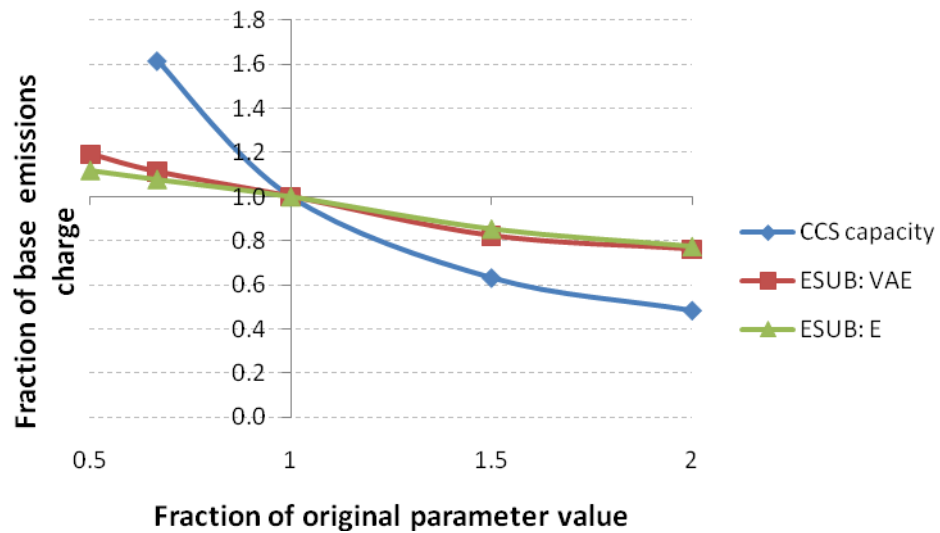


Figure 20 Sensitivity of 2050 global emissions charge to changes in three key parameters in VERITAS

4: DISCUSSION

The aim of the previous section was to display results and provide analysis of VERITAS model simulations, evaluating various components of an international climate change architecture. This section aims to provide a deeper discussion of some results and general trends, including comparisons with findings from other studies.

Firstly, I compare my business-as-usual projections of emissions and GDP with those from other sources in section 4.1. In section 4.2, I compare the carbon emissions price paths generated by other studies assessing similar emissions reduction schemes. In section 4.3, I discuss wealth effects in the context of changing permit allocation, then in section 4.4, I examine the importance of international trade effects in determining regional welfare effects. This chapter concludes with a description of study limitations and recommendations for improvement in future work in section 4.5.

4.1 Business-as-Usual Forecast Comparisons

Business-as-usual (BAU) forecasts define scenarios where an emissions pricing policy is absent. These assumptions are key for providing the reference from which to base impacts of various policy scenarios.

The BAU emissions forecasts used in this study are based upon fuel use projections, derived from previous analyses using the CIMS model. Delineating a BAU emissions pathway is important for determining the emissions reductions that must take place in order to reach a specified reductions target. A higher emissions forecast results in greater required reductions.

The VERITAS BAU emissions projections correspond broadly with those from other forecasts. Figure 21 shows the comparison of VERITAS emissions

projections with those of the United States Energy Information Agency (EIA) International Energy Outlook (EIA, 2007), the MESSAGE⁸ model, the DART⁹ model, and the International Energy Agency (IEA) World Energy Outlook 2002 (IEA, 2003). The IEA and the EIA produce forecasts only to 2030.

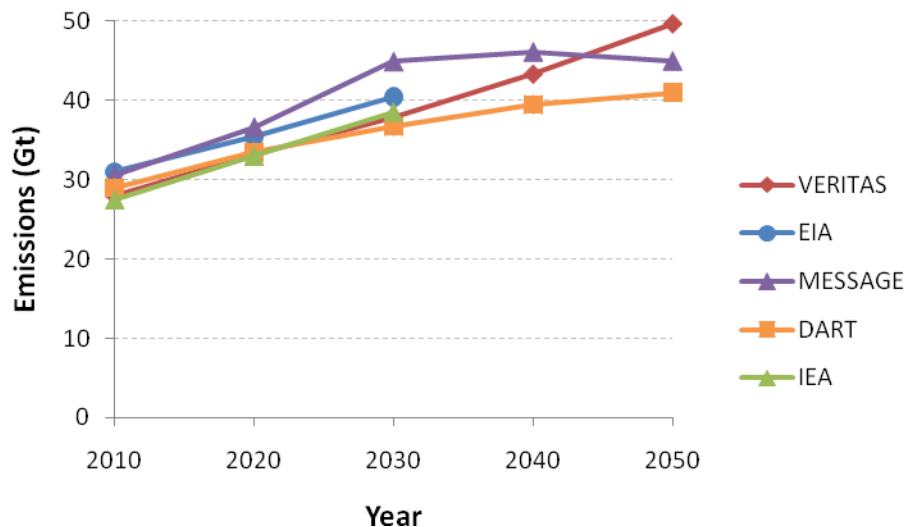


Figure 21 Global business-as-usual emissions from VERITAS, compared to other projections

VERITAS projections are relatively consistent with those from other sources. I do not, however, make regional comparisons of emissions forecasts, which is beyond the scope of this study. This could help elucidate any inconsistencies in projected emissions at a more disaggregated level.

The BAU forecast for GDP defines a reference for measuring effects on economic activity. Although this study uses equivalent variation rather than GDP to track welfare impacts, comparing VERITAS GDP projections with other

⁸ The MESSAGE model was developed by the International Institute for Applied Systems Analysis (also known as IIASA). It is a regional, bottom-up systems engineering model. It optimizes for a portfolio of least-cost technologies in each time period. The model can, however, also be linked to MACRO, a top-down macroeconomic equilibrium model and has both dynamic and static versions (Rao et al., 2006)

⁹ The DART (Dynamic Applied Regional Trade) model was developed by the Kiel Institute for the World Economy. It is a CGE model representing multiple regions and sectors, developed specifically for the purpose of assessing international climate policy (Peterson and Klepper, 2007; Klepper et al., 2003).

forecasts allows for comparison of baseline economic activity, reflecting other assumptions made in the model. Therefore, ensuring consistency with other GDP forecasts can produce greater confidence in VERITAS simulations.

GDP projections vary substantially, particularly at the global scale where differing assumptions about regional GDP growth are aggregated in producing a single global value. Figure 22 illustrates the global GDP forecast used in VERITAS, as compared to projections from the IEA World Energy Outlook (IEA, 2003), EIA International Energy Outlook 2009 (EIA, 2009b), the MESSAGE model, a framework developed for the OECD Project on the Economics of Climate Change Mitigation (Duval and de la Maisonnette, 2009), and the WITCH¹⁰ model.

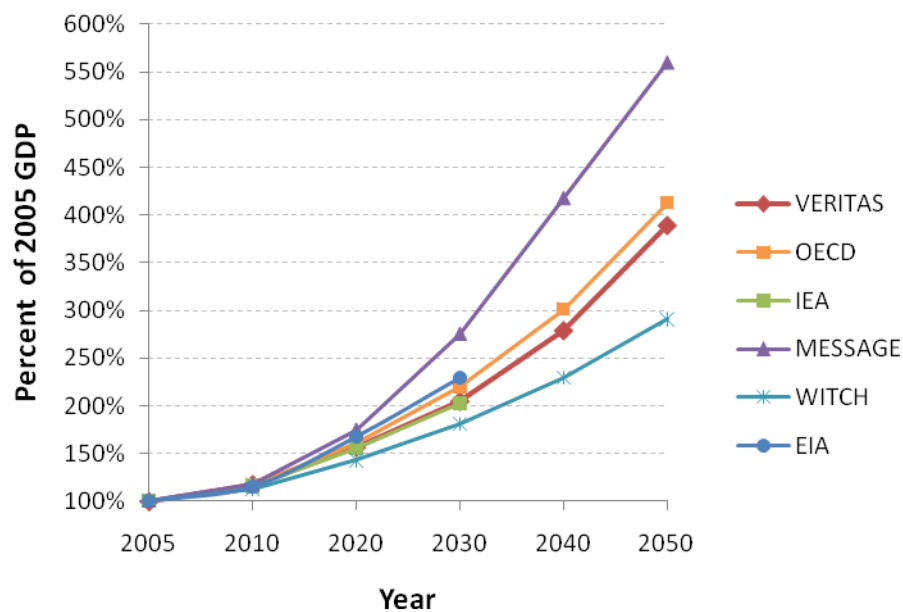


Figure 22 Global business-as-usual GDP forecasts in VERITAS, compared to other projections

At the low end of the forecasts I reviewed, the WITCH model assumes an average annual GDP increase of 2.4%. Meanwhile at the other end of the

¹⁰ The WITCH model was developed by the climate group at Fondazione Eni Enrico Mattei (also known as FEEM) in Italy. It is a regional optimal growth model, with perfect foresight and an emphasis on inertias within the energy-economy system (Edenhofer et al., 2009).

spectrum, the MESSAGE model assumes an annual increase of 3.2% to 2040, then 2.9% to 2050. In VERITAS, I assume an average global GDP growth rate of approximately 3.0%, which is within the range of these projections. To further demonstrate the ranges of forecasted wealth increases, average per capita incomes in the IEA case increase about 77% from 2000 to 2030, while in the MESSAGE model they grow 120% over the same period (IEA, 2003).

It is important to note the increasing uncertainty in GDP forecasting, particularly past 2030. From 2010-2030, the majority of projections examined fall within a similar range but diverge rather significantly by 2040. Forecasting farther into the future inherently results in greater uncertainty and it is important to keep this in mind when interpreting results from later simulation years.

4.2 Comparison of Carbon Emissions Price Paths

Figure 23 shows the emissions price paths generated by VERITAS in a global trading scenario, with 1000 Gt cumulative emissions and grandfathered permits. Comparisons are made with the DART model, the WITCH model, and the IMACLIM¹¹ model.

There are a few differences in the policy scenarios for each model that should first be noted. Both WITCH and IMACLIM reach higher cumulative emissions of about 1500 Gt and follow a contraction and convergence method of permit allocation, which is similar to the *PerCap* method used in this study. It is difficult to say whether the difference in these two assumptions would result in a higher or lower emissions charge compared to VERITAS, since the reduction target is less stringent thus resulting in a lower emissions price, while the *PerCap* allocation method may increase the price as was seen in Figure 8. DART follows very closely to the stabilization pathway used in this study, with a grandfathering method of allocation based on 1990 emissions.

¹¹ The IMACLIM model is a recursive CGE model developed by the Centre International de Recherche sur l'Environnement et le Développement. It represents semi-perfect foresight in the power sector, with no foresight in the others (Edenhofer et al., 2009).

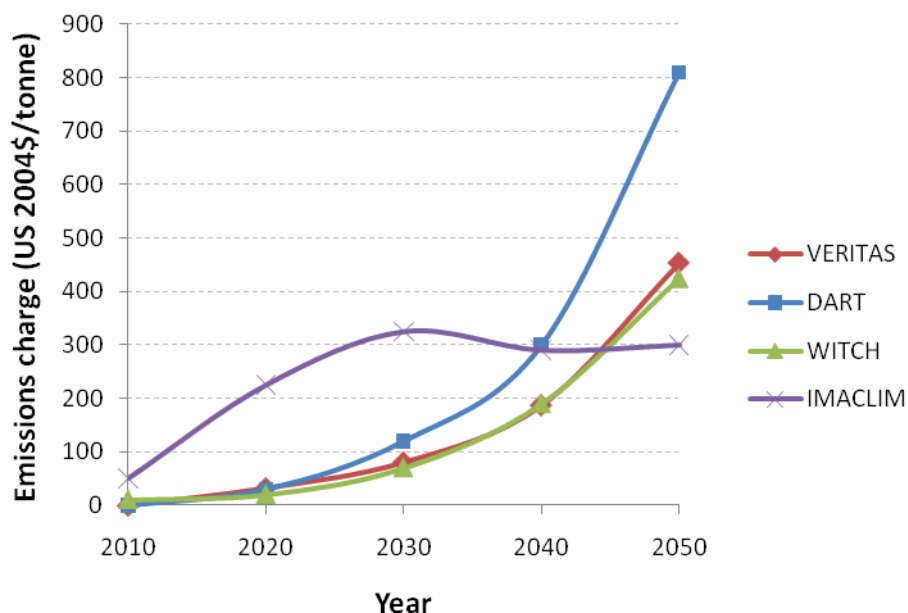


Figure 23 Comparison of VERITAS emissions price paths with those from the DART, WITCH, and IMACLIM models

The WITCH model generates an emissions price path almost indiscernible from that of VERITAS. The IMACLIM model displays an unconventional MAC curve shape, for which Edenhofer et al. (2009) provide an explanation. Due to a combination of imperfect foresight and capital inertia represented in IMACLIM, the model agents make sub-optimal investment decisions in the baseline through the underuse of production factors, and a relatively high price signal is required to catalyze the transition to low carbon technologies. Once the economy has made this transition, however, a relatively low price signal is required to stay on this path. This is because uptake of low carbon technology is deemed to be profitable in the long-run in IMACLIM, where these measures were simply not undertaken in the BAU case due to myopic agent behaviour. As a result, IMACLIM generates relatively high emission prices in early simulation years and low prices in later years (Edenhofer et al., 2009).

The reason for a significantly higher emissions price path from the DART model may be explained by the presence of lower ESUB values in certain

sectors, signifying lower substitutability between certain inputs and therefore a higher required emissions charge to reach a reductions target. For example, inter-fuel substitution in DART is lower in the ELEC, RPP, NMET, and OMAN sectors (Klepper et al., 2003). There may be other key assumptions that differ between DART and VERITAS.

The wide variation in the emissions price projections I assessed reflects the high level of uncertainty around the required price on carbon emissions for achieving a given emissions target. These reflect the myriad of important assumptions made in each model, including assumptions about structural rigidities (as reflected by ESUB values), business as usual emissions, the extent of agent foresight, and the availability and cost of climate-friendly technologies, such as conventional and biomass CCS.

4.3 Wealth Effects

Figure 8 showed that in a global permit trading scheme, the *Grandfather* method of allocating permits results in lower emissions charges than all the other permit allocation methods, which tend to produce similar emissions price paths. Economists suggest that the economically efficient outcome will result regardless of the allocation of atmospheric property rights to emit greenhouse gases. However, this assertion depends on the absence of income or wealth effects, which I suggest are the reason in this study for differing emissions charges resulting from different methods of permit allocation.

As explained earlier, emissions permits allocated to a region are modelled as an endowment to the consumer in that region, acting as a lump sum wealth transfer. In other words, allocating permits to a region essentially equates to making the consumer in that region richer. In turn, this increased wealth results directly in increased consumption. Allocating wealth to a consumer with emissions-intensive demand for goods and services (high emissions/\$ of consumption) means the consumer places greater output demands on the firms

producing these emissions-intensive commodities. Thus, a higher emissions charge is required to achieve a given level of emission reductions.

The opposite is true of allocating wealth to a consumer in a region with low-emissions final demand (low emissions/\$ of consumption). In this region, the consumer places fewer demands on high-emitting firms, and therefore, a lower emissions charge is required to reach the same level of emissions reductions. Different emissions intensities of consumption may result from a number of region-specific factors, including technology efficiency, fuel choice in production, or simply demand preferences.

The emissions intensity of final demand for each region is shown in Figure 24. Although the consumer emissions intensity in the EEU region is quite high, the trend remains that developing regions tend to produce greater emissions per dollar of consumption than industrialized regions in any given year.

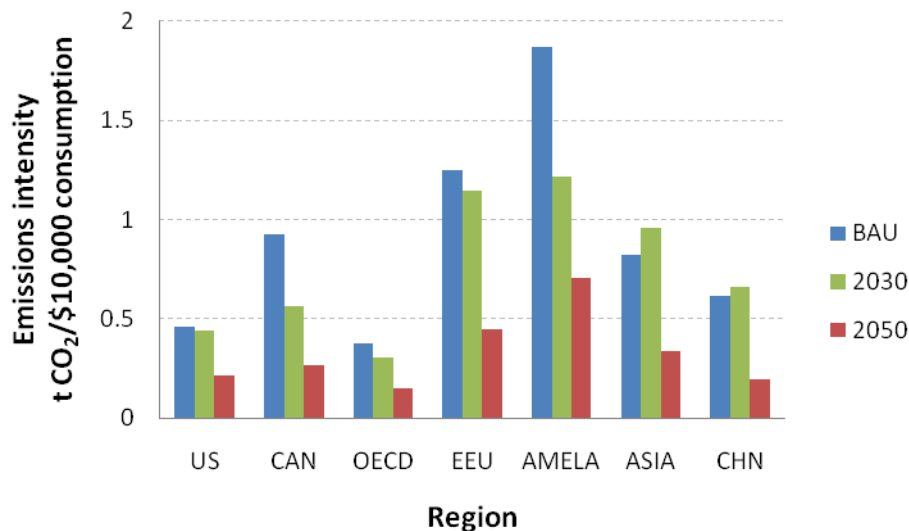


Figure 24 Emissions intensity of consumption in each region, over time with *Grandfather* permit allocation

In the *PerCap*, *PerGDP*, and *Cumulative* allocation methods, the developing regions are favoured (specifically AMELA, ASIA, and CHN). Since these regions have higher emissions intensity, a higher global emissions price is

required to reach a given level of reductions. In the *Grandfather* permit allocation method, consumers in the industrialized and transition economy regions tend to be favoured, specifically US, CAN, and EEU. Therefore, this allocation method results in a lower emissions charge.

Other factors may also contribute differing carbon emissions prices arising from different permit allocation methods. Peterson and Klepper (2007) find that in a scenario where permits are grandfathered, emissions permit prices are 20% lower than in a scenario similar to the *PerCap* allocation method. One reason provided is that transfers to fast-growing developing nations result in greater capital accumulation, making it more difficult to transition to a lower-emission economy. VERITAS, however, is not a dynamic model; therefore capital accumulation over time is not tracked. Furthermore, Olmstead and Stavins (2009) assert that other factors, including a region's ability to assert market power, may produce differing global emissions prices resulting from different methods of allocating permits.

Meanwhile, other economic analyses have generated results consistent with the theory that allocation of emission rights does not change the emissions price (Rose et al., 1998; Kvendokk, 1993; Rose and Zhang, 2004). However, consumer wealth effects are not represented in these analyses, as firm and consumer behaviour are not distinguished within a region.

Overall, there does appear to be a trade-off between economic efficiency and equity in choosing a permit allocation scheme, where wealth transfers to developing regions tend to result in a higher overall societal cost. In maximizing economic efficiency, it appears that emissions rights should be allocated to those with an already efficient consumption lifestyle, which tend to be industrialized regions, thus reinforcing the current distribution of emissions. In turn, this places a larger financial burden on developing nations to purchase emissions rights.

This modeling analysis, however, may have exaggerated the influence of wealth effects. VERITAS simplifies representation of the economy by excluding government. As such, emissions permit allocation is modeled as a lump sum wealth transfer to the consumer, resulting in a direct increased consumption of

commodities. In reality, it is more likely that an intermediate government body would receive the allocated permits and distribute welfare in another way, by reducing income tax or by diverting revenue to a technology development fund, for instance. Permit allocation may not lead to such a direct increase in final consumption as is modelled in VERITAS.

Furthermore, I assume a linear increase in the pattern of goods consumed over time for each region. Therefore, as regions become richer over time, they do not change the proportion of goods consumed, other than decreasing fossil fuel consumption by the AEEI rate. It is more likely that as the wealth of developing regions converges with that of industrialized regions, the emissions intensity of consumers will also decrease as preferences change. I do not account for this process, which is a consequence of increases in income rather than in the price of emissions as seen in Figure 24. I note this as a study limitation in section 4.5.

This analysis therefore may exacerbate the wealth effects experienced by consumers, resulting in a significant difference in emissions charge required to reach a given level of reductions (particularly in later simulation years), amongst different allocation methods. However, this study has elucidated the role wealth effects may play in a future allocation scheme. This reflects an important trade-off between wealth distribution and economic efficiency of a permit trading system that participants in a future climate framework will need to assess and negotiate.

4.4 International Spillover Effects

I now turn to further examination of regional welfare trends observed across a number of policy scenarios. It appears that the pattern of welfare effects observed for each region is closely linked to its position in the global trade of fossil fuels commodities. Specifically, the trend appears to be that the greater the regional dependence on fossil fuel exports, the greater the welfare losses in an emissions pricing scheme.

Bohringer and Rutherford (2002) divide the impacts of an emissions pricing policy into domestic market effects and international fossil fuel market effects. The former comprise effects from changes in domestic markets and consumption. Thus in a region's efforts to reduce emissions, these impacts relate to domestic actions to improve energy efficiency, undertake fuel switching, reduce output or invest in CCS technology. The latter group of effects encompasses secondary impacts from changes in international fuel prices and demand, thus affecting a region's exports and imports. Specifically, as demand for fossil fuel goods decreases so do their prices, thereby reducing the gains accrued by fossil fuel exporting regions. These international spillovers can be an important determinant of a region's overall welfare impact from an emissions abatement scheme (Bohringer and Rutherford, 2002).

These international trade effects can be elucidated by examining terms of trade for a region. Terms of trade indicates the trading "clout" of a region, measured as the ratio of an index of prices for exported goods to an index of import prices. Improving terms of trade indicates that a region can purchase more imports with each unit of its exports, while deteriorating terms of trade means that a region must export more in order to import the same value of goods.

According to Bohringer and Rutherford (2002) and Backus and Crucini (1998), a major determinant of the overall trade effects a region experiences is the price of crude oil. This study does not have an international oil price (rather crude oil is regionally-distinct), thus the price of crude oil in each region is different. I therefore examine the relative price of each region's crude oil exports to an aggregate price index of its imports, as compared to BAU (Figure 25).¹² This value serves as an indicator of the change in each region's trade position in the international crude oil market, where a percentage over 100% indicates that the region can purchase more imports from its revenue from crude oil exports.

¹² The aggregate price of imports was calculated using the Laspeyres price index.

Alternatively, a percentage lower than 100% indicates that the region can purchase fewer imports with its crude oil export revenue.

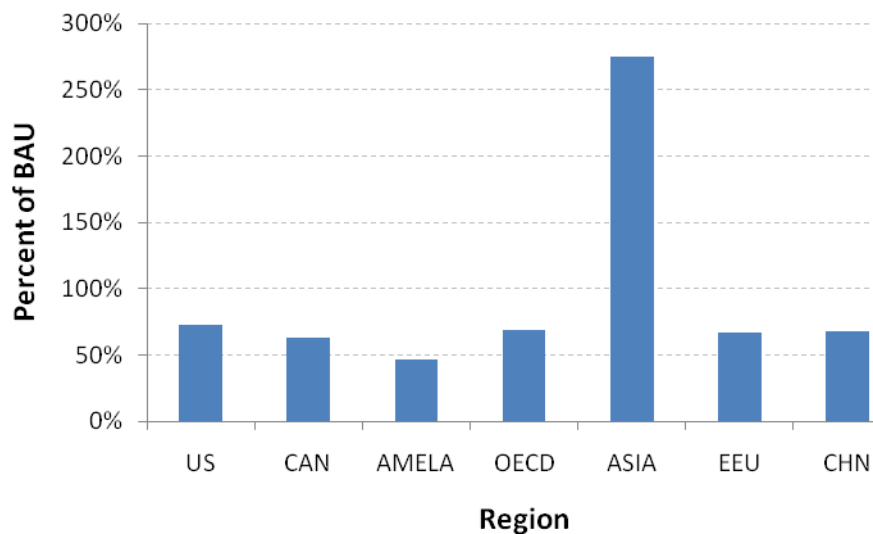


Figure 25 Ratio of crude oil export price to an aggregate price index of imports for each region in 2050 with *Grandfather* allocation

As is apparent, ASIA is the only region for which the price of crude oil exports increases compared to the price of its imports. This occurs as ASIA's crude oil becomes increasingly demanded due to its low emissions intensity compared to other regions. All other regions experience significant declines in the relative price of crude exports. Thus at least in the global crude oil market, ASIA becomes the clear winner.

These values provide some insight into the overall welfare impacts experienced by different regions. Although this ratio of crude exports to total imports decreases substantially for all regions, losses are greater for some than others.

AMELA experiences significant welfare declines across all policy scenarios and also sees the greatest deterioration in its trade position for crude oil of all regions. CAN experiences the second greatest declines in the relative price of its crude oil exports. These reflect the relatively high welfare losses and

vulnerability to an emissions pricing scheme experienced by these fossil fuel-exporting regions. EEU is another region that sees significant welfare losses across numerous emissions abatement scenarios, however, its trade position in the crude oil market does not decrease as much as other regions in Figure 25. This is because a *Grandfather* allocation method is assumed, which provides significant revenues to EEU.

In this study, the fossil fuel-exporting regions of AMELA, CAN, and EEU are most sensitive to an emissions pricing scheme and experience greater welfare losses as compared to the fossil fuel-importing regions of ASIA, US, OECD, and CHN, which exhibit greater resilience. Thus overall, it may be that a more important determinant of regional welfare effects of an emissions pricing policy is the position a region occupies in the global trade of fossil fuel goods, rather than the specific characteristics of the emissions abatement policy.

These findings are consistent with those from other studies. Bohringer and Rutherford (2002) find that a “major determinant” of regional trade effects in a multi-lateral emissions abatement scheme is the region’s role in the global trade of crude oil and coal commodities in particular. Decreased demand for fossil fuels can offer gains for fuel importers but losses for fuel exporters.

Peterson and Klepper (2007) also find that the fossil fuel-exporting characteristic of a region is a key determinant of welfare effects in an emissions pricing policy. Welfare decreases in these regions as they lose their comparative advantage due to decreases in demand for their exports. Fossil fuel-importing regions are more resilient to the implementation of carbon emission prices. Peterson and Klepper (2007) state that “the internal economic structure and the degree to which an economy relies on energy inputs and on the sale of energy and energy intensive products are important determinants for the overall welfare effect.”

Den Elzen et al. (2008) also emphasize the importance of trade effects and find similar welfare implications across emission allowance schemes, with

high costs for the Middle East, North Africa, and the former Soviet Union, medium costs for the OECD, and low costs or gains for Asian regions.

4.5 Study Limitations and Directions for Future Research

The modelling approach taken in this study has helped provide insight into the macroeconomic effects of international climate change architectures. Using ESUB values derived from the CIMS hybrid energy-economy model has helped shift away from the traditional methods of econometrically and/or judgmentally deriving estimates of these parameter values. This has helped incorporate some of the unique attributes of CIMS and hybrid energy-economy modelling to this study. There are, of course, a number of limitations in this study.

I first discuss certain limitations, from which I do not necessarily recommend future changes. I then outline potential improvements for any future expansion of this work.

4.5.1 Study Caveats

This study focused solely on the costs of emissions mitigation. As a result, two important factors were excluded from a full assessment of climate policy costs and benefits: costs of adaptation and the benefits of climate change mitigation. Thus, this study is not a full cost-benefit analysis of climate policy – it considers only the component of mitigation costs.

Meanwhile, costs of adaptation are understood to be a significant part of addressing climate change. The UNFCCC estimates adaptation costs to be 49-171 billion US dollars each year until 2030, about half of which will be required for developing nations (UNFCCC, 2007)¹³. This amounts to less than 0.2% of

¹³ It is important to keep in mind that adaptation costs will vary as a function of emissions mitigation. Higher mitigation will result in fewer adaptation costs due to greater avoided emissions. The application of an integrated assessment model (IAM), which links the biophysical climate with the economy, would allow for the definition of this relationship between carbon abatement and adaptation costs. Examples of IAMs include the RICE model (Yang and Nordhaus, 2006), DICE model (Nordhaus, 2007), and MiniCAM model (Smith and Wigley, 2006)

global GDP, although the costs would be proportionately higher for industrialized nations, who would be expected to pay much of this bill.

Paying for the full costs of adaptation would require substantial wealth transfers, specifically from industrialized Annex I nations to developing non-Annex I nations. Regardless of the permit allocation scheme, industrialized nations have already committed to providing some financial support to developing nations. If permits are grandfathered, lump sum financial contributions will simply be higher. This is because it is likely that an international emissions permit trading system resulting in significantly greater welfare losses for developing regions compared to industrialized regions (such as grandfathering emissions permits) would not be politically feasible, thus it would include greater transfers from developed to developing nations.

Furthermore, in order to undertake a comprehensive cost-benefit evaluation, one must include a quantification of the value of benefits of emissions mitigation. VERITAS does not quantify benefits beyond those resulting from market processes, including gains from efficiency, allocation of surplus permits (“hot air”) and positive trade effects. Numerous studies have attempted to quantify benefits from climate policies, including Stern (2008), Azar and Lindgren (2003), and Nordaus and Zang (1996). The application of an integrated assessment model (see footnote 13) would also help in quantifying benefits of reducing emissions. Valuation of benefits is associated with high levels of uncertainty and was left outside the scope of this study.

There are also challenges inherent in using a static CGE model to simulate scenarios in the long term. With a static model, it is difficult to account for factors such as the decrease over time in storage capacity for CCS and the possible foresight of investors in response to expected future emissions prices.

Lastly, for all scenarios explored in this study, I assumed a certain emissions reduction pathway. The reductions pathway chosen likely has significant implications for the emissions price required to reach a certain reduction target. In the extreme example, requiring significant net negative emissions in the next decade, with few emissions reductions farther in the future

will likely result in higher overall costs due to premature retirement of capital stock in the short-term. Weighing emissions reductions differently over time will certainly result in varying emissions prices as well as welfare effects. It is therefore important to recognize the dependence of the study results to assumptions of the emissions reduction pathway.

I now provide a list of potential improvements for future work. Some of these can be done rather easily in the short-term, while others require more extensive work over a longer period. I have ordered them roughly according to this characteristic, starting with potential improvements in the short-term. An important note must be made that this is a substantial list of recommendations and I do not advocate the complete implementation of this list. Rather they are simply suggestions that a modeller building on this work may wish to consider. In fact, some of these potential improvements involve simply waiting for research to be published in an emerging area. A balance must, of course, be struck between increasing model complexity, as most of the recommendations would do this, and managing the increasing uncertainty resulting from increased complexity.

Include government and benchmark taxes

This analysis has shown the potential for wealth effects to change the economic efficiency of a cap-and-trade system through varying permit allocation methods. However, this study may have overestimated this wealth effect due to the absence of an intermediary government body. The addition of a government agent, along with benchmark taxes, would allow more accurate representation of permit allocation to a region. Rather than allocation directly resulting in increased consumption, one could model the reduction of benchmark taxes or diversion of revenue to a separate fund for technology development. This would represent more indirect, and more realistic, added benefits to the region. Related to this, a demand for consumer leisure could also be added so that consumer welfare is optimized by balancing commodity consumption with leisure time, rather than being solely dependent on consumption.

Expand representation of technologies

VERITAS represents carbon capture and storage technology (conventional and biomass) but there are other important technologies that a modeller may wish to track. Particularly, in reaching aggressive reductions into the future, emissions abatement will likely depend on an array of renewable energy, CCS, and/or geoengineering technologies.

In VERITAS, the production of renewable energy is represented implicitly through the substitution of inputs in the production of electricity, by favouring greater capital but fewer fuel inputs. In switching to explicit representation of renewable energy technologies, ESUBs would be derived from CIMS without the availability of these technologies in reducing emissions. Thus, for example, if the modeller wishes to track the uptake of wind power, she would de-activate wind power electricity generation in CIMS so that the ESUB would reflect sector substitutions without the availability of this technology. In the CGE model, wind power (which would be represented separately) would enter endogenously if it became economically viable. This is the same method used to represent CCS in VERITAS.

With this recommendation in particular, however, the modeller must strike a careful balance between the desire to track certain technologies, on one hand, and, on the other, increasing technological complexity, data requirements and uncertainty.

Expand emissions accounting

Only carbon dioxide emissions from fossil fuel combustion, also called energy-related CO₂ emissions, were accounted for in this analysis. Therefore, other greenhouse gases, including methane were excluded, as were non-combustion emissions from manufacturing, agriculture, and land-use change. The World Resources Institute estimated that in 2000, 35% of global emissions were those other than CO₂ combustion emissions (WRI, 2006).

Expanding greenhouse gas accounting beyond carbon dioxide would provide a more comprehensive analysis of emissions reduction strategies, including examining effects on regions and sectors with high agricultural and process emissions. An example includes China, which produces half of the global cement supply (the production of which has non-combustion CO₂ emissions) and generates significant agricultural emissions. Africa and Latin America also contribute substantial agricultural emissions, which are projected to increase at greater rates in the next few decades (Worrell et al., 2001; World Resources Institute, 2006).

Further address uncertain assumptions

Beyond the sensitivity analysis performed in this study, there would be merit in 1) identifying more assumptions and parameters in VERITAS to which the model output is sensitive and 2) further addressing the identified uncertainties in the model, including a wider range of ESUB parameters, CCS costs and capacity, and business-as-usual projections. This may be undertaken with a more comprehensive sensitivity analysis of a greater range of values, as well as quantification of probability attached to each parameter's range of values.

In addition to performing sensitivity analyses, the robustness of certain model assumptions could be increased in order to address uncertainty. I discuss two below: improving SAM extrapolation into future years and deriving region-specific values of key parameters.

Improve technique of SAM extrapolation

In this study, I assume a constant rate of business-as-usual growth for economies. This is represented by the increase in value of inputs and outputs for sectors as well as household consumption, by a single annual rate of economic growth. Although an AEEI parameter is incorporated in order to reduce the input of fuels over time, firm and consumer preferences remain the same. That means that if agricultural goods comprise 40% of ASIA's consumer's demand in 2004,

this will generally remain true in 2050 in a business-as-usual case.¹⁴ However, as ASIA consumers become richer over time, they may use a smaller proportion of their income to purchase agricultural goods. More realistic assumptions regarding changing firm and consumer preferences over time (particularly when moving from low-income to higher income) may generate more accurate BAU assumptions.

Furthermore, it has been mentioned numerous times that the availability of certain inputs (particularly crude oil in the ASIA region) has not been adequately limited. As a result, ASIA's crude oil becomes increasingly demanded over time (the availability of which simply increases at a constant rate), thus substantially improving the region's trade position in the crude oil market. By incorporating region-specific constraints on the availability over time of fossil fuels in particular, VERITAS could provide more accurate simulations of the changing dynamics in global fossil fuel markets.

Derive region-specific parameters

Deriving ESUBs from CIMS has provided a unique method of extracting these key values for use in VERITAS. Region-specific ESUBs from CIMS would help in defining the relationships amongst inputs in each region, to more accurately represent regional character. This would require better differentiation of regional characteristics amongst the CIMS regions. Further regional disaggregation would also help provide more accurate regional differentiation, which is a common recommendation made by the researchers who expanded CIMS to have global coverage (Melton, 2008; Goggins, 2008, Goldberg, 2009; Wolinetz, 2009).

There would also be merit in seeking out region-specific CCS information. As an example, this study may overestimate the uptake of CCS in the ASIA region. As Goggins (2008) notes, the presence of higher cost coal-CCS

¹⁴ VERITAS does not specifically track agricultural goods as a commodity

technologies, potential storage limitations, and political reservations with respect to CCS may limit CCS uptake. In VERITAS simulations, I make uniform CCS cost and capacity assumptions across regions and exclude any consideration of political constraints. Thus, the limiting factors specific to this region were ignored. Geographically explicit information on CCS storage capacity would also be useful in providing more robust, regionally-differentiated output, given that VERITAS output was shown to be sensitive to estimates of regional storage capacity.

Improve representation of biomass

In this study, the requirement for land in biomass-CCS is used as a proxy to represent constraints that demands for biomass may place on production of other agricultural goods. Since the agricultural sector is aggregated with the Rest of Economy sector, I have been unable to model the direct competition between land demands of the agricultural sector and of biomass for energy. I recommend disaggregating the agricultural sector in future work.

Better information on the required inputs into biomass CCS, as well as the emissions benefits, would improve representation of this important technology. Research in this area, however, is just emerging, and improving biomass-CCS representation may take time.

Convert VERITAS to a dynamic model

While running a static CGE model has benefits of computational ease and greater simplicity (thus greater transparency), there are various limitations of analyzing long-term climate policies within a static model. Since endogenous changes over time are not represented, static models depend on exogenous parameters specifying characteristics of future simulation periods, which can add to model uncertainty. For instance, capital stock accumulation cannot be represented, which relates to the inability for investment decisions to be made with foresight into future emissions prices. Rather, the availability of fixed or flexible capital in any time period is determined exogenously in VERITAS.

Although it is clear that agents in the real world do not exhibit the perfect foresight represented in dynamic models, representation of endogenous changes over time can offer certain benefits in modelling long-term climate policies. In addition to capital stock accumulation, a second example is CCS technology, where the gradual uptake of favourable CCS sites cannot be represented endogenously over a temporal scale in VERITAS. In other words, how much a region uses of “good sites” in 2030 has no bearing on how many “good” sites remain available in 2040; this is determined exogenously.

Another consideration is that permits cannot be banked from past years or borrowed from future years. This is an important characteristic in the existing European Union and proposed US permit systems and would be a useful process to model for any future cap-and-trade systems. Converting VERITAS to a dynamic model would help simulate endogenous responses to climate policy over time and allow the modeller to overcome the limitations of myopic agents.

5: CONCLUSION

5.1 Overall Findings

There are a number of key themes that have emerged from the results of this study. I discuss these general findings for each region in turn.

Firstly, in almost every policy simulation, the AMELA region experiences the greatest welfare harms of all regions. This is due to high dependence on fossil fuel production and export. It is therefore of little surprise that in the international forum, nations of the Middle East in particular are championing the creation of adaptation funds to climate change *policy*, rather than climate change *effects*, to be allocated to regions adversely affected by emissions mitigation measures.

The EEU region is another region that suffers significant welfare losses from emissions pricing. Russia and other EEU countries are expected to increase their exports of oil and natural gas over the simulation period, thus EEU suffers from the reduction in price of its fossil fuel exports due to decreased demand. The *Grandfather* allocation method was used as the default in numerous policies, where EEU experiences welfare gains due to allocation of surplus permits. However without these generous allocations, the EEU region has few inexpensive abatement opportunities in VERITAS and experiences substantial welfare declines. A similar trend is seen in the CAN region, which is also an energy-exporting region.

The ASIA region fares relatively well in most policy scenarios, even gaining welfare compared to the BAU in some cases, particularly between 2040 and 2050. I suggest a few reasons for this. Firstly, ASIA is a fossil fuel-importing region and less economically vulnerable to decreases in fuel prices. Secondly, ASIA appears to gain an advantage by generating large amounts of negative-

emissions electricity while other regions start to exhaust abatement options. One must be cautious with this result, however, as it is possible I did not account for other CCS constraints in this region thus overestimating the potential for CCS uptake. Thirdly, the value of crude oil exports by ASIA increases substantially. The region's crude oil sector remains strong while the price of crude oil exports from the region rises, thus generating significant export revenue. This occurs because the ASIA crude oil sector is the least emissions-intensive of all regions and demand of this commodity by other regions increases substantially. However, caution must also be taken in interpreting this finding, as I likely do not adequately constrain the availability of natural resources, including crude oil, to each region.

Welfare in OECD and CHN is the most robust across scenarios. The US also displays a relative level of resiliency, given that it is a net fossil fuel importer and less reliant on fossil fuel production for its economic welfare. CHN, like the ASIA region, is able to achieve significant negative emissions from the electricity sector from biomass-CCS while receiving a fair amount of permit revenue in each policy with a global permit trading scheme.

The OECD undergoes electrification of its energy sources with relative ease. In fact, it is the only region that increases the activity of its conventional electricity sector (without CCS) with an emissions pricing policy. Increasing demands for electricity provide revenue for this region. Also, the OECD economy has low projected emissions increases, thus it requires fewer reductions from BAU to reach a specified target.

Regions tend to experience their most substantial welfare losses later in the simulation years, particularly from 2040-2050. This may indicate an exhaustion of lower cost abatement opportunities, potentially reflecting inadequate representation of abatement options far into the future within VERITAS. One reason for this is that technological innovation is not an endogenous process in this analysis since VERITAS it is a static model. Therefore, anticipation of future increases in emissions price does not catalyze

technological innovation, which would help reduce marginal abatement costs particularly in achieving aggressive reduction targets in later simulation years.

5.2 Research Questions

I now summarize the key findings with respect to the key research questions outlined at the start of this report.

What are the global and regional effects of varying methods of emissions permits allocation in a global permit trading system?

Allocating permits in a method favouring industrialized nations (grandfathering-*Grandfather*), compared to methods favouring developing nations (based on population-*PerCap*, cumulative emissions-*Cumulative*, or *PerGDP*), results in a lower global emissions price. The existence of wealth effects is an explanation for the generation of differing permit prices, where allocating permits essentially translates to increased household consumption. As a result, favouring permit allocation to developing regions where consumers have higher emissions intensity (emissions/unit of final consumption), results in greater demand of emissions-intensive commodities and a higher emissions charge to reach a specific reduction target.

In terms of welfare impacts, *Grandfather* benefits the EEU region the most, due to the allocation of surplus “hot air” emissions permits. Otherwise, this region suffers the greatest welfare losses in a *PerCap* allocation scheme. In general, developing regions (AMELA, ASIA, CHN) experience fewer welfare declines in the *PerCap* method compared to *Grandfather*, while the opposite is true for the industrialized and transition economy regions (OECD, CAN, US, and EEU).

What are the regional effects of varying coordination of regional permits systems (ie. global trading versus regional trading of permits)?

Higher prices on carbon emissions are required in industrialized and transition economy regions, as compared to the global emissions price path in a scenario where all regions trade permits. The emissions charges in developing regions are lower than this global price.

All regions appear to benefit from global permit trading as evidenced by the increase in welfare in all regions in a trading scenario. Industrialized and transition regions with high marginal abatement costs are provided the opportunity to reduce more at the same emissions price by exploiting lower cost abatement options in developing regions. On the other hand, developing regions are provided the opportunity to sell excess permits, given that their own marginal abatement costs are lower than the global permit price. However, the industrialized regions tend to experience greater welfare gains with trade, implying that access to lower-cost abatement opportunities translates to higher gains in welfare.

What are the relative marginal abatement costs in each region?

I rank the regions from those with highest to lowest abatement costs: EEU, OECD, CAN, US, CHN, ASIA, and AMELA. There are, however, slight variations in this order depending on the percentage of emissions reductions required. Up until 40% reductions below BAU, the ASIA region has the lowest MACs. This ranking of MAC curves is consistent with the findings of other studies, where the industrialized and transition economy regions have steeper MAC curves than those in developing regions.

What are the global and regional effects of achieving a more ambitious emissions reduction target?

Achieving a more aggressive global reductions target requires a substantially higher emissions charge. The increase in this required charge ranges from US\$100-\$400/tonne in any given year for reaching an aggressive 750 Gt target, which is consistent with stabilizing CO₂ concentrations at 350 ppm. It is important to recognize, however, that the shape of the emissions price path in each reduction scenario is dependent on the emissions reduction pathway.

Achieving greater global reductions also results in higher welfare losses on the order of 5-10% in any given year. With higher global reductions, the ASIA region sees welfare gains by profiting from production of substantial negative emissions and increased value of crude oil exports, a commodity that is not emissions-priced in this study. However, I likely do not account fully for specific production constraints in each region, including in the ASIA crude oil sector. AMELA experiences the greatest welfare losses in both reduction scenarios due to its dependence on fossil fuel exports and vulnerability to international trade effects from decreased demand for fossil fuels. Net fossil fuel importing regions, particularly OECD and CHN, display greater resiliency with a more stringent reduction target and increasing price on carbon emissions.

What are some key uncertainties in the assumptions made in this analysis?

Sensitivity analyses were performed on three key assumptions: the capacity of CCS available in each year and two elasticity of substitution values: VAE between the input of energy and value-added (factors), and E between the input of electricity and carbon-emitting fuels.

The global price on carbon emissions is sensitive to the available CCS capacity, particularly to decreases in this value (because default capacity estimates are low) and particularly in later simulation years (where CCS is more important in achieving substantial emissions reductions). The global emissions

price is moderately sensitive to changes in each of the two ESUB values assessed as well.

With the aggregation of small changes in values of important parameters, significant changes in the global emissions price could result. It is important, therefore, to recognize the sensitivity of the results presented here to the assumptions I have made.

APPENDICES

Appendix A: List of Countries Within Each Region

OECD: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey and the United Kingdom, Australia, Japan, Korea and New Zealand, Mexico

ASIA: Afghanistan, Bangladesh, Bhutan, Brunei, Cambodia, Chinese Taipei, Fiji, French Polynesia, India, Indonesia, Kiribati, Democratic People's Republic of Korea, Laos, Macau, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, Tonga, Vietnam, Vanuatu

AMELA:

Africa - Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Congo, Democratic Republic of Congo, Côte d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, United Republic of Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe

Middle East - Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq

Latin America - Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St. Kitts and Nevis, Saint Lucia, St. Vincent and Grenadines, Suriname, Trinidad and Tobago, Uruguay and Venezuela

EEU: Albania, Armenia, Azerbaijan, Belarus, Bosnia-Herzegovina, Bulgaria, Croatia, Cyprus, Estonia, Serbia and Montenegro, the former Yugoslav Republic of Macedonia, Malta, Georgia, Gibraltar, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Romania, Russia, Slovenia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan.

US: United States

CAN: Canada

CHN: China

Appendix B: Model Code in GAMS and MPS/GE

* Modeller notes outside of the model code are indicated by *

SETS

a Commodities /OIL, ELEC, GAS, COAL, RPP, MET, NMET, OMAN, TRANS, ROE, L, K, LN, NR/
j Industries /OILJ, ELECJ, GASJ, COALJ, RPPJ, METJ, NMETJ, OMANJ, TRANJ, ROEJ/
fd Final demand categories /FDEM, INV/
r Regions /US, CAN, AMELA, OECD, ASIA, EEU, CHN/
f(a) factors /L, K, LN, NR/
i(a) commodities only /OIL, ELEC, GAS, COAL, RPP, MET, NMET, OMAN, TRANS, ROE/
e(i) energy goods only /COAL, ELEC, GAS, RPP/
ele(i) electricity only /ELEC/
fe(i) energy goods with emissions /COAL, GAS, RPP/
nce(i) non carbon emitting goods only / OIL, MET, NMET, OMAN, TRANS, ROE, ELEC/
ne(i) non energy goods only / OIL, MET, NMET, OMAN, TRANS, ROE/
lfe(i) liquid final energy goods that emit carbon only / GAS, RPP /
sf(f) sluggish factors ie sector-specific / NR /
mf(f) mobile factors ie not sector specific / K, L, LN /
ALIAS (r,rr);

PARAMETER

OPT Defines regional or global abatement option, where 1 signifies global permit trading and
2 is where regions act alone;
OPT = 1;

*The list of sets is included at the end of model code

\$INCLUDE Sets.txt

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

SCALAR YEAR Simulation year;
\$set year 2050
Year = 2050;

* Name of policy for output file
\$SET POLICY_Description "Grandfather"

*Permit allocation to different regions
PARAMETER allo allocation of revenue to regions ;

*Per capita allocation
allo("US")\$(opt=1) = 0.040832666;
allo("CAN")\$(opt=1) = 0.004963971;
allo("OECD")\$(opt=1) = 0.13498799;
allo("AMELA")\$(opt=1) = 0.244995997;


```

allo("EEU")$(opt=1)    = 0.055084067;
allo("ASIA")$(opt=1)   = 0.336269015;
allo("CHN")$(opt=1)    = 0.182866293;

```

*GDP-based allocation

```

allo("US")$(opt=1)     = 0;
allo("CAN")$(opt=1)    = 0;
allo("OECD")$(opt=1)   = 0;
allo("AMELA")$(opt=1)  = 0.329405928;
allo("EEU")$(opt=1)    = 0;
allo("ASIA")$(opt=1)   = 0.421882343;
allo("CHN")$(opt=1)    = 0.248711729;

```

*CE

```

allo("US")$(opt=1)     = 0;
allo("CAN")$(opt=1)    = 0;
allo("OECD")$(opt=1)   = 0;
allo("AMELA")$(opt=1)  = 0.250860517;
allo("EEU")$(opt=1)    = 0;
allo("ASIA")$(opt=1)   = 0.373286414;
allo("CHN")$(opt=1)    = 0.375853069;

```

*grandfathering

```

allo("US")$(opt=1)     = 0.231970401;
allo("CAN")$(opt=1)    = 0.021904676;
allo("OECD")$(opt=1)   = 0.164441028;
allo("AMELA")$(opt=1)  = 0.100336209;
allo("EEU")$(opt=1)    = 0.250660414;
allo("ASIA")$(opt=1)   = 0.124889772;
allo("CHN")$(opt=1)    = 0.1057975;

```

```
$INCLUDE    Atech %year%.txt
```

PARAMETERS

```

inputTable(r,a,j)
outputTable(r,a,j)
fdTable(r,a,fd)
importTable(r,rr,i)
importmTable(r,rr,i)
exportTable(r,rr,i)
exportmTable(r,rr,i)
VTWRTable(r,rr,i)

```

```
$GDXIN './EXCELINPUT/balsam_%year%.GDX'
```

```
$LOAD inputTable, outputTable, fdTable, importTable, importmTable, exportTable,
exportmTable, VTWRTable
```

PARAMETERS

XO(r,i,j)	Benchmark intermediate inputs,
YO(r,i,j)	Benchmark outputs,
FO(r,f,j)	Benchmark factors,
FDEM0(r,i)	Benchmark final demand,
IMO(r,rr,i)	Benchmark import world price,
IMMO(r,rr,i)	Benchmark import market price,
EXO(r,rr,i)	Benchmark export world price,
EXMO(r,rr,i)	Benchmark export market price,
VTWR(r,rr,i)	Benchmark trade margins;

XO(r,i,j)	= inputTable(r,i,j);
YO(r,i,j)	= outputTable(r,i,j);
FO(r,f,j)	= inputTable(r,f,j);
FDEM0(r,i)	= (sum (fd, fdTable(r,i,fd)));
IMO(r,rr,i)	= importTable(r,rr,i);
IMMO(r,rr,i)	= importmTable(r,rr,i);
EXO(r,rr,i)	= exportTable(r,rr,i);
EXMO(r,rr,i)	= exportmTable(r,rr,i);
VTWR(r,rr,i)	= VTWRTable(r,rr,i);

PARAMETERS

TCO(r)	Total consumption for each country,
EO(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,
USEO(r,i)	Benchmark domestic use of each commodity (including intermediate use),
SECUSE(r,i)	Benchmark domestic use of each commodity by sectors only,
BOTDEF(r)	Benchmark balance of trade deficit,
totalexm(r)	total exports market price,
totalimm(r)	total imports market price;

EO(r,f)	= SUM(j, FO(r,f,j));
TCO(r)	= SUM(i, FDEM0(r,i));
COMPROD(r,i)	= SUM(j, YO(r,i,j));
SECPROD(r,j)	= SUM(i, YO(r,i,j));
USEO(r,i)	= SUM(j, XO(r,i,j)) + FDEM0(r,i);
SECUSE(r,i)	= SUM(j, XO(r,i,j));
BOTDEF(r)	= (SUM(rr, (SUM(i, (IMO(r,rr,i) - EXO(r,rr,i) - VTWR(rr,r,i))))));
totalexm(r)	= sum(i, (sum(rr, EXMO(r,rr,i))));
totalimm(r)	= sum(i, (sum(rr, IMMO(r,rr,i))));

* Capital stock split over time

PARAMETERS

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;

```
If (year = 2004,
    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;
```

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 intensity for each fuel
 *Taken from NGGIF for Energy Industries
 CARB_INT_GJ(r,"COAL") = 0.0983;
 CARB_INT_GJ(r,"GAS") = 0.0561;
 CARB_INT_GJ(r,"RPP") = 0.0730;

* From EIA

CARB_INT_GJ("US","COAL") = 0.09240;

CARB_INT_GJ("US","GAS") = 0.05029;

CARB_INT_GJ("US","RPP") = 0.06883;

*NRCAN Energy Handbook

CARB_INT_GJ("CAN","COAL") = 0.0901;

CARB_INT_GJ("CAN","GAS") = 0.0513;

CARB_INT_GJ("CAN","RPP") = 0.0718;

\$INCLUDE Fuel consumption forecast.gms

*Emission of CO2 if there is a carbon intensity value (aka if it is a fossil fuel)

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 sequestration (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)	Alternative sector production;

altsec(r,j) =0;

altsec(r,"ELECJ") =1;

*Including file to read in information about the alternative CCS sector

\$INCLUDE Atech reading global.gms

XAO(r,j,s,fe)\$altsec(r,j)	= (XO(r,fe,j) * (ATechfe(r,j,s,fe))*Atechq(r,j,s));
SUMXAO(r,j)	= sum(fe,(sum(s,(XAO(r,j,s,fe)))));
YAO(r,j,s,i)\$altsec(r,j)	= (YO(r,i,j) * (Atechq(r,j,s)));
ASECPROD(r,j,s)\$altsec(r,j)	= sum(i,YAO(r,j,s,i));
FAO(r,j,s,f)\$altsec(r,j)	= (FO(r,f,j) * (1+Atechf(r,j,s,f))*Atechq(r,j,s));
FAO(r,j,s,"LN")\$altsec(r,j)	= (Atechf(r,j,s,"LN") * YAO(r,"ELECJ","3","ELEC"));
EAO(r,j,s)\$altsec(r,j)	= (SECPROD(r,j)*Atechq(r,j,s));
CSO(r,j,s)\$altsec(r,j)	= (sum(fe,(CARBONCOEF(r,fe)*(XAO(r,j,s,fe))* ATechcs(r,j,s)));
CSO(r,j,"3")\$altsec(r,j)	= (Atechcs(r,j,"3") * YAO(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;

*Load elasticities of substitution from a separate file

\$INCLUDE "Read elasticities.txt"

*This is the MPS/GE portion of the model code

\$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 (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
PfIK(r)	!Price index for flexible capital (flexible)
PfixK(r,j)\$FixCap(r,j)	!Price index for fixed capital (sector-specific) ie. indexed over j
PSF(r,sf,j)\$FO(r,sf,j)	!Price index for natural resources (sector-specific) ie. indexed over j
PLN(r)	!Price index for land (flexible)
PA(r,i)	!Price index for Armington good
PerCap(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)\$IMO(r,rr,i) !Price index for imports
 PAC(r,fe) !Price index for Armington goods with a carbon permit
 PerCapARB(r)\$ (ABATE(r) AND (opt=2)) !Price index of carbon permits
 PerCapARBGLOBE\$(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

*Output-based subsidy in the form of a negative tax
 \$AUXILIARY:

LS(r,j)\$ (ABATE(r) and PR(r,j)) !Lump sum transfer rate for regional permit method
 LS(r,j)\$ (GLOBALABATE and PR(r,j)) !Lump sum transfer rate for global permit method

\$CONSUMERS:

CON(r) !Representative agent

*Sector using flexible capital

\$PROD:Y(r,j) S:ESUB_S(r,j) vae(s):ESUB_VAE(r,j) ii(s):0 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:PfIK(r) Q:F0(r,"K",j) mob:
 I:PSF(r,sf,j) Q:F0(r,sf,j) slug:
 I:PLN(r) Q:F0(r,"LN",j) slug:
 I:PA(r,nce) Q:X0(r,nce,j) 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))

*Sector using fixed capital

\$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:PSF(r,sf,j) Q:F0(r,sf,j)
 I:PLN(r) Q:F0(r,"LN",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))

*Alternative sector representing CCS for electricity generation

\$PROD:Ya(r,j,s)\$altsec(r,j) cs1:0 cs(cs1):0 cvae(s):0 cva(cvae):0.2 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:FAO(r,j,s,"L")	cmob:
I:PflK(r)	Q:FAO(r,j,s,"K")	cmob:
I:PSF(r,sf,j)	Q:FAO(r,j,s,sf)	cslu:
I:PLN(r)	Q:FAO(r,j,s,"LN")	cslu:
I:PA(r,ele)	Q:XO(r,ele,j)	ce:
I:PA(r,ne)	Q:XO(r,ne,j)	cs1:
I:PAC(r,"COAL")	Q:XAO(r,j,s,"COAL")	cfue:
I:PAC(r,lfe)	Q:XAO(r,j,s,lfe)	clqd:
I:PQ(r,j,s)\$altsec(r,j)	Q:ASECPROD(r,j,s)	
O:PY(r,i)	Q:YAO(r,j,s,i)	
O:PerCapARB(r)\$ (ABATE(r) AND (opt=2))		Q:CSO(r,j,s)
O:PerCapARBGLOBE\$(GLOBALABATE AND (opt=1))		Q:CSO(r,j,s)

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

I:PA(r,fe)	Q:USEO(r,fe)
I:PerCapARB(r)\$ (ABATE(r) AND (opt=2))	Q:((CARBONCOEF(r,fe)*USEO(r,fe)))
I:PerCapARBGLOBE\$(GLOBALABATE AND (opt=1))	Q:((CARBONCOEF(r,fe)*USEO(r,fe)))
O:PAC(r,fe)	Q:USEO(r,fe)

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

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

\$PROD:IMP(r,rr,i)\$IMO(r,rr,i)

I:PX(rr,r,i)\$EXO(rr,r,i)	Q:(EXO(rr,r,i)+ VTWR(r,rr,i))
O:PM(r,rr,i)	Q:IMO(r,rr,i)

\$PROD:Ar(r,i)\$USEO(r,i) S:ESUB_ARM(r,i)

I:PD(r,i)	Q:(COMPROD(r,i)-(sum(rr,EXMO(r,rr,i))))
I:PM(r,rr,i)	Q:IMMO(r,rr,i)
O:PA(r,i)	Q:(COMPROD(r,i)-(sum(rr,EXMO(r,rr,i))) + (sum(rr,IMMO(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:PerCap(r)	Q:TCO(r)	

\$DEMAND: CON(r)

D:PerCap(r)	Q:(TC0(r))
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:PLab(r)	Q:E0(r,"L")
E:PfIK(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:PerCapARBGLOBE\$(GLOBALABATE AND (opt=1))	
Q:((1-GLOBALABATE)*(SUM(rr,(SUM(fe,(CARBONCOEF(rr,fe)*USE0(rr,fe))))))*allo(r))	
E:PerCapARB(r)\$ABATE(r) AND (opt=2)	
Q:((1-ABATE(r))*(sum(fe,(CARBONCOEF(r,fe)*USE0(r,fe))))))	
E:PerCap("US")\$(BOTDEF(r))	Q:(BOTDEF(r))
E:PQ(r,j,s)\$altsec(r,j)	Q:(EA0(r,j,s))

\$REPORT:

V:TotalFuelDemand(r,fe)	O:PAC(r,fe)	PROD:CARB(r,fe)
V:NumberofGlobalPermits(r,fe)\$opt=1	I:PerCapARBGLOBE	
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:PfIK(r)	PROD:Y(r,j)
V:FlexCapDemYa(r,j,s)\$altsec(r,j)	I:PfIK(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: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: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: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)	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:SectorPerCaparb(r,j,s)\$opt=2	O:PerCapARB(r)	PROD:Ya(r,j,s)
V:SectorPerCaparbGlobe(r,j,s)\$opt=1	O:PerCapARBGLOBE	
PROD:Ya(r,j,s)		

V:PerCaplevel(r)
 PROD:C(r)
 V:EqVar(r)

O:PerCap(r)
 W:CON(r)

\$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=
 PerCapARB(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=
 PerCapARBGLOBE*(SUM(rr,(SUM(fe,(CARBONCOEF(rr,fe)*USE0(rr,fe))))))* (1-
 GLOBALABATE)*allo(r)*PR(r,j);

\$OFFTEXT
 *End of MPS/GE code

\$SYSINCLUDE MPSGESET TRADE

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

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

*Running the benchmark
 PerCapARBGLOBE.L = 0;
 Ya.l(r,"ELECJ",s) = 0;
 altsec(r,j) = 0;
 GLOBALABATE = 0;
 Ya.l(r,j,s)\$altsec(r,j) = (FlexCapPer*atechq(r,j,s));
 Y.l(r,j) = FlexCapPer;
 X.L(r,j)\$FixCap(r,j) = FixCapPer;
 PR(r,j) = 0;
 PLN.lo(r) = 0.1;
 TRADE.ITERLIM = 10000000;
 \$INCLUDE TRADE.GEN
 SOLVE TRADE USING MCP;

Appendix C: Sector- and Region-Specific Elasticities of Substitution

The following ESUBs were derived from CIMS:

US										
Sector production										
	OIL	ELEC	GAS	COAL	RPP	MET	NMET	OMAN	TRAN	ROE
σ_s										
σ_{VAE}	0.45	0.45	0.53	0.60	0.45	0.52	0.48	0.49	0.45	0.42
σ_{VA}										
σ_{MOB}	0.20	1.30	0.70	0.20	1.30	1.30	1.30	1.20	1.70	1.20
σ_{SLUG}										
σ_E	0.75		1.01	0.10		0.28	0.21	0.48	0.25	0.58
σ_{FUEL}	0.64	3.95		0.40		0.21	1.06	3.38		
σ_{LQD}	1.23	5.85	0.85	0.28	2.75	0.93	1.40	5.66	1.00	1.95
Consumption										
σ_s	0.52									
σ_E	0.527									
σ_{HOU}	1.66									

Canada										
Sector production (assumed for all other regions)										
	OIL	ELEC	GAS	COAL	RPP	MET	NMET	OMAN	TRAN	ROE
σ_s										
σ_{VAE}	0.40	0.18	0.84	0.40	1.26	0.25	0.19		0.27	0.33
σ_{VA}										
σ_{MOB}										
σ_{SLUG}										
σ_E				1.20		0.90	0.31	0.28	0.25	1.80
σ_{FUEL}		2.17	1.00			0.42	1.93			0.80
σ_{LQD}	1.01	1.00		0.99	2.75	1.33	2.57	2.99	1.00	1.24
Consumption										
σ_s	0.5									
σ_E	0.5									
σ_{HOU}	0.8									

If ESUBs were not derived from CIMS, they took on the following default values as informed by literature or subjective judgments:

Sector production										
	OIL	ELEC	GAS	COAL	RPP	MET	NMET	OMAN	TRAN	ROE
σ_s	0	0	0	0	0	0	0	0	0	0
σ_{VAE}	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
σ_{VA}	0	0	0	0	0	0	0	0	0	0
σ_{MOB}	0.20	1.30	0.70	0.20	1.30	1.30	1.30	1.20	1.70	1.20
σ_{SLUG}	0	0	0	0	0	0	0	0	0	0
σ_E	0	1	0	0	0	1	1	1	1	1
σ_{FUEL}	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
σ_{LQD}	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66

Sources:

S: common assumption that the top-level substitution between intermediate inputs and the energy – value-added aggregate is zero

VAE: MIT-EPPA model (Paltsev et al., 2005) and DEEP model (Kalbekken, 2004)

VA: assumption that land and natural resources (sluggish factors) cannot substitute capital and labour, given the fixed nature of these sluggish factors

MOB: GTAP-7 database (Center for Global Trade Analysis, 2001)

SLUG: assumption that natural resources and land cannot be substituted given their fixed quantities

E: GTAP-E model (Burniaux and Trong, 2002)

FUEL: DEEP model (Kalbekken, 2004), Bohringer and Rutherford (2002), and EPPA model (Paltsev et al., 2005)

LQD: DEEP model (Kalbekken, 2004), Bohringer and Rutherford (2002), and EPPA model (Paltsev et al., 2005)

Imports and exports										
	OIL	ELEC	GAS	COAL	RPP	MET	NMET	OMAN	TRAN	ROE
σ_{ARM}	10	2.8	2.8	2.8	1.9	2.8	0.45	2.59	2.59	2.59
σ_{DOMEX}	2	2	2	2	2	2	2	2	2	2

Sources:

ARM: GTAP-E model (Burniaux and Trong, 2002)

DOMEX: Bohringer and Rutherford (2002)

Consumption			
	US	CAN	Others
σ_s			0.5
σ_c	1	0.95	0.65
σ_E			0.409
σ_{HOU}			1.23

Sources:

S: CAN value assumed for other regions

C: US value from DEEP model (Kalbekken, 2004), CAN value from Rivers and Sawyer (2008), value for other regions from EPPA model (Paltsev et al., 2005)

E: From MIT-EPPA model (Paltsev et al., 2005), DEEP model (Kalbekken, 2004), and CIMS-US

HOU: Average of CAN and US values assumed for other regions

Appendix D: Autonomous Energy Efficiency Index Values

Region	AEEI value
US	1.3%
CAN	1.21%
OECD	1.21%
AMELA	1.1%
EEU	1.1%
ASIA	1.27%
CHN	1.98%

Sources: Bataille et al. (2006), Babiker et al., (2001), McFarland et al., (2004)

Appendix E: Permit Allocation Calculations

1. Per-capita (*PerCap*)

Allocation equals the population a region comprised in 2004, as proportion of global population according to the World Population Prospects (UN, 2008).

2. GDP (*perGDP*)

Take the difference of the average global GDP/capita in 2004¹⁵ subtracted by GDP/capita of the region. If this difference is negative, allocation to the region is zero. If the difference is positive, multiply this difference by the population. Allocation to a region equals this value as a proportion of the global sum of these values for all regions.

3. Grandfathering (*Grandfather*)

Allocation equals the emissions of a region in 1990, as a proportion of total global emissions according to EIA (2006).

4. Cumulative emissions (*Cumulative*)

As with GDP, take the difference of average cumulative emissions per capita for all regions subtracted by the cumulative emissions per capita of the region. Negative values equal zero allocation to a region. Multiply positive differences by the population of the region. Allocation equals this value for each region, as a proportion of the global sum of these values for all regions. Cumulative emissions from 1980 to 2004 were used. Data on total historical emissions (from the 1600s) were unavailable for the VERITAS regions, though percentage of cumulative emissions of specific countries were verified to be similar to the percentages used in this study.

¹⁵ It should be noted that selection of a year on which to base emissions for grandfathering emissions or GDP is contentious. The selection of a given base year may result in a significantly different allocation of permits than another year. This is particularly true of non Annex I countries (of which China and India are the most poignant examples), which have experienced a larger rate of GDP and emissions growth than Annex I countries in recent years. Selection of a base year closer to present will generally result in fewer permits allocated to non Annex I countries. However, this issue will not be examined further here, and I have chosen base years based on available data.

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