Quantifying the Cost Uncertainty of Climate Stabilization Policies

by

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Abstract

Climate change researchers are often asked to evaluate potential economic effects of climate stabilization policies. Policy costs are particularly important because policymakers use a cost/benefit framework to analyze policy options. Many different models have been developed to estimate economic costs and to inform cost/benefit decisions.

This thesis examines what impact modelers' assumptions have on a model's results. Specifically, MIT's Emissions Prediction and Policy Analysis (EPPA) model is examined to understand how uncertainty in input parameters affect economic predictions of long-term climate stabilization policies. Eleven different categories of parameters were varied in a Monte Carlo simulation to understand their effect on two different climate stabilization policies.

The Monte Carlo simulation results show that the structure of stabilization policy regulations has regional economic welfare effects. Carbon permits allocated by a tax-based emissions path favored energy importers with developed economies (e.g., the US and the EU). Countries with energy-intensive economies (e.g., China) will likely have negative welfare changes because of strict carbon policy constraints. Oil exporters (e.g., the Middle East) will also be negatively impacted because of terms of trade fluxes.

These insights have implications for stabilization policy design. The uncertainty surrounding economic projections expose some countries to larger economic risks. Policies could be designed to share risks by implementing different permit allocation methods. Direct payments are another means to compensate countries disproportionately disadvantaged by a stabilization policy.

Thesis Supervisor: Dr. Henry Jacoby
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I would also like to thank my family, Greg, Jan, and Wade, and Lucia for supporting me and encouraging over the last two years. Life at MIT has its ups and its downs; you guys were always there for me.

> *"Decision making has to deal with uncertainties including the risk of non-linear and/or irreversible changes and entails balancing the risks of either insufficient or excessive action, and involves careful consideration of the consequences (both environmental and economic), their likelihood, and society's attitude towards risk."*
>
> Intergovernmental Panel on Climate Change (IPCC, 2001b)

1 – Introduction

With ever-increasing technological improvements, society has broadly written its signature across the Earth. Before the industrial revolution, environmental impacts caused by a society and its activities were contained to the society's immediate environs. Cutting and burning wood for cooking did not have a noticeable impact on their neighbors or the health of the planet. Today, the scale of industrial operations and the sheer volume of economic activity are impacting those we cannot see. Specifically, the increased burning of fossil fuels over the last 150 years is resulting in climate change (IPCC, 2001b).

Climate change is a phrase that describes the warming and cooling of various world regions over a long timeframe. Climate change is a complex issue because almost any energy-consuming activity in our modern economy contributes to the problem. For example, fossil fuels are typically consumed when producing electricity for households and industry. Additionally, oil powers the vast majority of transportation worldwide. Electricity production and transportation, along with other industrial and agricultural activities, have dramatically increased atmospheric concentrations of worldwide greenhouse gas (GHG) emissions. These GHGs are responsible for increasing Earth's global mean temperature (GMT). Impacts of a higher GMT include an increase in vector-borne diseases, rising sea level, changes in agricultural regions (i.e., shifts in crop locations), and decreased economic prosperity in many countries. Some countries and regions may be impacted disproportionately. For instance, some South Pacific island states may be inundated as sea levels rise; the polar regions are expected to warm substantially more than equatorial regions.

Impacts on the scale threatened by climate change have caught the attention of scientists and policymakers worldwide. In 1992, political leaders from 172 nations met in Rio de Janeiro for the United Nations Conference on Environment and Development, commonly referred to as The Earth Summit. From this important and historical summit came several important agreements, including Agenda 21 and the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992a; United Nations, 1992b). Agenda 21 presented a platform of guiding principles for the twenty-first century, including sustainable development goals. The UNFCCC is a separate agreement that formally acknowledged the climate change problem, created a common set of goals, and organized meetings for future negotiations.

Chapter 1

1.1 – Quantifying economic cost uncertainty of climate mitigation policy

Article 2 of the UNFCCC agreement states that nation members should stabilize “greenhouse gas concentrations … at a level that would prevent dangerous anthropogenic interference with the climate system.” This agreed upon wording defines a goal of climate mitigation policy. The subsequent principle, Article 3, states that a policy “should be cost-effective so as to ensure global benefits at the lowest possible cost.” Together these articles direct policymakers to design climate mitigation legislation that stabilizes the Earth’s atmosphere at safe concentrations of GHGs by cost-effective means.

This thesis explores the uncertainty in implementing the UNFCCC policy directives. Many predictions of climate policy costs are stated in definitive terms: a single number denoting the forecast carbon price or economic welfare loss. These single-estimate predictions are based on experts’ best guesses, which were codified into modeling assumptions. The following research tests these underlying modeling assumptions by varying key parameter values such that the output is not a single number, but rather probability density functions of carbon dioxide emissions, carbon prices, and welfare losses. The uncertainty surrounding these three model outputs exposes economic and environmental risks that need to be considered when designing legislation to meet the Article 2 and Article 3 principles.

Chapter 2 leads the reader through the climate change problem and some of the associated literature. The climate causal chain is described to highlight how uncertainty propagates from an economic or policy action to its resulting climate impact. In addition, Chapter 2 explains how policymakers require economic estimates when debating the costs and benefits of policy options. Past uncertainty studies are discussed and compared in order to put this research into context.

Chapter 3 describes the research methodology used to analyze the uncertainty associated with stabilization policies. MIT’s Integrated Global System Model (IGSM) and the associated EPPA4 economics model are introduced to the reader. The IGSM was used to design two different climate stabilization policies. The stabilization policies were run 250 times each in a Monte Carlo simulation. Each run varied key uncertain input parameters.

The results of the Monte Carlo simulations are presented in Chapter 4. Carbon dioxide emissions, carbon permit prices, and welfare changes are examined in both the near- and long-term. Economic welfare is broken down further into sample of four different regions: China, the European Union, the Middle East, and the United States. The results for these regions vary considerably under uncertainty. Policy implications of this uncertainty research are discussed in

Chapter 5. Finally, Chapter 6 concludes with some final comments and suggestions for further research.

2 – Defining the Climate Change Problem

2.1 – The climate change causal chain

When studying climate change, researchers should have a solid conceptual model of cause and effect. There are many different causes, effects, and feedbacks loops in the climate system. Figure 1 shows a simplified version that is important for this thesis. Energy production, industrial activity, crop and livestock production, and waste management release GHG emissions, such as carbon dioxide, methane and nitrous oxide. These emissions cause a buildup of greenhouse gas concentrations, which leads to an increase in global mean temperature. As the Earth's climate changes, a variety of economic and environmental impacts will occur.

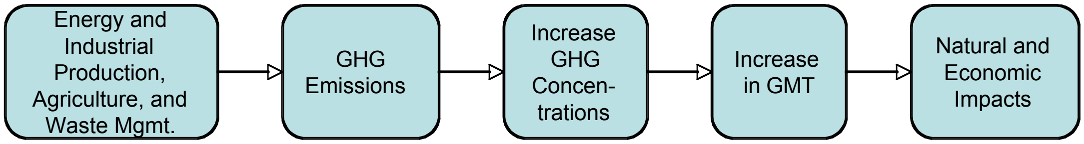


Figure 1 – A simplified climate change causal chain.

In order to model this causal chain, key parameters are estimated at each transition. Researchers must predict the size of the world economy in order to estimate the volume of emissions. Additional assumptions include how the Earth's natural systems will respond to increased atmospheric concentrations, how much temperature will rise, and how ecosystems will react to the GMT change.

Each estimated parameter could be a source of error. For example, estimates of economic growth could be wrong but economic activity is a vital input into the model. Parameters can only be estimated with limited confidence over the modeling timeframe (i.e., through 2100). Furthermore, parameter uncertainties are propagated through the causal chain (i.e., the uncertainty in economy activity is compounded by the uncertainty of Earth's ecosystems).

The uncertainties associated with each step of the causal chain have climate policy cost implications. Policymakers cannot be reasonably sure their mitigation regulations would be successful. Their intentions may be to implement a low cost policy, but the system uncertainty poses risks for any intervention. The objective of this thesis is to describe probability density functions that characterize the associated risks of two climate stabilization policies.

2.2 – Discussion of uncertainty surrounding mitigation policy

There are many uncertainties in when trying to predict the outcome of human interactions with the Earth's climate system. In a simple world of certainty, policymakers would legislate stabilization policy knowing exactly what "policies and measures" would be sufficient. One sample policy that would guarantee stabilization in this "certain world" would be to regulate greenhouse gases by assigning emissions quotas over time. In response to the policy, industry and the society would react accordinglyby reducing emissions. The ecosystems and physical Earth systems would behave as predicted by scientists, and the ultimate stabilization target would be reached while incurring only the predicted environmental impacts.

Unfortunately, each step of the mitigation process is laden with unknowns. If policymakers decided on an emissions pathway, there is no certainty that the quotas would be honored. Measuring GHG emissions from the countless sources is a daunting task. Also, non-point sources, such as agricultural fields, are difficult to measure and control. Once GHGs are released into the atmosphere, scientists cannot predict the exact environmental impact. While some physical systems are reasonably well understood (i.e., the atmospheric chemistry), Earth system interactions and feedbacks are still being actively researched.

When narrowing the uncertainty lens to examine economic consequences, there are many economic variables that influence the cost of a mitigation policy. For example, if economic growth is assumed to be a constant 2% when designing a climate change policy, the policy may have unintended consequences. If the rate is higher, the industry will have to make deeper emission reductions to reach fixed emissions quotas. These deeper reductions would become increasingly expensive as firms move up their marginal cost abatement curves. Conversely, if the growth rate is lower than 2%, the cost of complying with the mitigation policy will be lower than estimated. The economic growth rate is one uncertain parameter that directly influences the economic costs of enacting climate change legislation. When additional economic variables are considered, the uncertainties compound causing even further difficulties in predicting changes to economic welfare.

2.3 – Significance of impacts is causing concern

Climate change is a problem worth further research because its environmental and economic impacts will be felt for centuries. Many individuals have researched a range of possible environmental impacts including global sea level rise, the spread of vector-borne diseases and regional ecosystem and agricultural changes. While some of these impacts are based on a chain of future events (i.e., first temperature rises, then icecaps melt, and then the sea level rises), other environmental impacts can already be studied today. Researchers have found that natural systems display trends consistent with climate change theory (Parmesan and Yohe, 2003). One study by Root *et al.* (2003) concludes that, after controlling for local variation, ecosystem shifts of 6.1 km per decade (toward the higher latitudes) have occurred. The researchers believe with “very high confidence” that climate change is already changing natural systems.

Climate change will not only have environmental effects but will also impact the economy. The agriculture sector might have to change dramatically. Part of this impact may be a pole-ward shift of crop growing regions. This will mean that distribution centers may have to relocate (before they would otherwise have to be replaced), livestock production may change (due to feed and transportation costs), and increased crop pest damage because of milder frosts (IPCC, 2001a).

For the both the environmental and economic reasons, leaders worldwide are concerned about human-induced climate change. Though their policy responses have varied, many countries are beginning to act. One key policy step was the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992b). With almost every country a signatory of the Convention, it provides an international forum for policy debates and coordinated actions. Even without policy actions, the UNFCCC is an agreed-upon set of principles that provide guidance to policymakers and frame much of the global debate. Important for this research, the Convention has two different passages, Article 2 and Article 3, which set a policy goal and a policy metric, respectively.

This research helps concerned policymakers understand uncertainty of economic projections. Hypothetical stabilization policies are tested to expose uncertain economic impacts. These policies demonstrate possible pitfalls when implementing GHG controls to avoid climate change impacts.

2.4 – UNFCCC Article 2 calls for stabilization at “safe” levels

“The ultimate objective… [is the] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

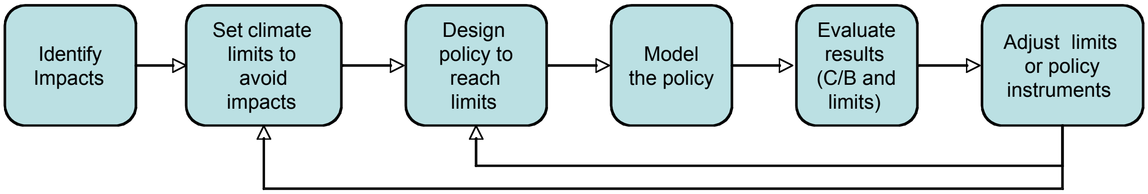
(United Nations, 1992b)

2.4.1 – Interpreting Article 2 of the UNFCCC

Article 2 of the UNFCCC states a metric for measuring successful mitigation policy as “preventing dangerous […] interference”. This metric is important because political leaders worldwide supported the UNFCCC agreement. Article 2 provides a target that many nations have pledged to meet.

Even with agreed-upon wording, policymakers have been debating how to interpret Article 2 for more than a decade. Different interpretations have led groups to focused on atmospheric concentrations of carbon dioxide (e.g., 450ppmv, 550pmmv, etc.), absolute global mean temperature increase (GMTI) (e.g., the European goal of stabilization at 2ºC GMTI), the height of sea level rise, preventing the collapse of the thermohaline circulation, and the severity of local climate impacts such as coral reef bleaching (Parry *et al.*, 1996; O'Neill and Oppenheimer, 2002; Corfee-Morlot and Hohne, 2003; Leemans and Eickhout, 2004).

Policy design should follow a general cyclical flow of decisions, as shown in Figure 2. With the help of climate scientists, possible impacts should be identified. Limits or thresholds could be identified that would avoid the impact of concern. With the environmental limits/threshold in mind, policymakers could design a public policy using regulatory instruments of their choosing. The policy could then be modeled in order to understand its relative effectiveness in meeting the limit and also its potential costs. At this point, the familiar cost/benefit framework could be used to evaluate the policy. If the policy fails by some measure, the process could start over by either redefining the environmental target or redesigning the public policy.



(Adapted from Parry *et al.*, 1996)

Figure 2 – Diagram of steps involved in stabilization policy analysis.

2.4.2 – Alternative climate targets to reduce risks

The process outlined in Figure 2 requires a climate threshold to be identified in order to avoid an impact. The nature of the threshold is actively being debated. Historically, atmospheric concentrations of carbon dioxide (e.g., 450 ppmv, 550 ppmv, 650 ppmv) were used to describe different levels of allowed climate change. Critics have argued that concentrations are too early in the causal chain (see Figure 1) to sufficiently reduce impact risks. They suggest that GMTI or radiative forcing should instead be used because these metrics are farther down the causal chain, thereby providing more certainty that reaching the threshold would avoid the impact of concern. Stated another way, the risk of the impact will be reduced if these alternative thresholds were used. A common alternative threshold in the literature is the European Union's 2 ºC GMTI target.

For this research, the historical carbon dioxide concentration targets used. While CO_2 concentrations maybe lacking in some regards, they are still the most often discussed measure in policy circles and provide a rich context for the results of this study.

2.5 – Policymakers use a cost/benefit decision framework

> *"The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."*
>
> (Article 3 of the UNFCCC, United Nations, 1992b)

Article 3 of the UNFCC states that any policy or measure enacted to respond to climate change "should be cost-effective so as to ensure global benefits at the lowest possible cost." This directs policymakers to make decisions using a cost/benefit framework. Cost/benefit analysis involves weighing the costs of a legislative action against the benefits of that action. In a strict sense, no policy should be implemented if the costs outweigh the benefits. However, in practice societal mores prevent this strict interpretation.

When measuring the economic costs of climate change policies, the term "economic welfare" is used. Economic welfare is a measure of the utility that society gets from the economy. Sometimes this is measured in GDP or GDP per capita, but many economists measure welfare using total economic consumption. This measure gives some indication of utility and overall size of the economy. For this thesis, economic welfare and economic consumption are used interchangeably.

This thesis provides policymakers with more information for cost/benefit analysis. Specifically, it to exposes uncertainties in economic cost projections so that better policies could be designed. Benefits of climate policies are not in the scope of this study but other groups are leading new research to answer key cost/benefit analysis questions (Corfee-Morlot and Agrawala, 2004).

2.6 – Previous economic studies of climate policies lack uncertainty

Policymakers have evaluated climate policies using a cost/benefit framework in the past. During the congressional debates over the Kyoto Protocol and the more recent McCain-Lieberman Climate Stewardship Act, climate researchers provided economic projections of policy impacts (Reilly *et al.*, 2000; Paltsev *et al.*, 2003). Many previous economic studies do not address the uncertainties associated with the modeling process.

Climate researchers have studied how the choice of the stabilization target affects the mitigation policy cost. When comparing the "least-cost" policy options for two different climate targets, the more stringent target (e.g., 550 ppmv) will likely cost more than a less stringent target (e.g., 650 ppmv). The climate target choice directly affects the cost of action. More stringent policies require tighter controls on emissions and, hence, the overall economy (Manne and Richels, 1990; Nordhaus, 1998).

While there have been a significant number of studies on the uncertainty surrounding climate predictions, there have been relatively few studies regarding mitigation cost uncertainty. Some efforts have explored uncertainty by coordinating several research teams to study a similar set of policies (e.g., the Energy Modeling Forum (Beaver, 1992) and the US Climate Change Science Program Product 2.1 (CCSP, 2005)). The end result is a range of policy costs. These coordinated studies capture the differences between models, which is termed structural uncertainty. Structural uncertainty describes the uncertain associated with choices made when abstracting economic processes and how those choices affect model output (Lucarini, 2002).

2.7 – Framing this research

When examining the cost uncertainty of climate change policy, the implications of the causal chain must be understood. For this thesis, some simplifications were made to narrow the scope of research. Instead of looking at the complete causal chain, uncertainty in the climate system was not explored. This removes significant steps from the causal chain and allows this thesis to focus on the economic cost uncertainty.

Instead of studying structural uncertainty using multiple models, this research focuses of parametric uncertainty of a single model. Input parameters of this economics model are varied to produce a range of probabilities. This method systematically explores parameter uncertainty is due to the lack of knowledge. This thesis builds of previous parametric uncertainty studies (Webster, 1997; Forest *et al.*, 2002; Webster *et al.*, 2002; Cossa, 2004) but provides new insight into cost uncertainty and its implication for climate policy.

3 – Uncertainty analysis of stabilization costs

A study to understand the effects of parametric uncertainty on the cost of climate stabilization consists of several steps. This chapter starts with an overview of MIT's climate change modeling system and then discusses the methodological process. Broadly, the first step was to identify uncertain parameters and perform a sensitivity analysis to see their affect on policy costs. Next, probability density functions (PDFs) were constructed for the eleven most sensitive parameter categories. These first two steps were based on previous work (Cossa, 2004). All of previously constructed PDFs were reviewed for this research. With PDFs defined, 250 parameter sets (i.e., combinations of initial values for the 11 parameter categories) were generated using the Latin Hypercube sampling method. The EPPA4 model was modified and updated for an ensemble run on a computer cluster. Separately, a climate stabilization policy was developed. Using the computer cluster, the 250 parameter sets were run in a two-step process. First a reference or business-as-usual case was run. This was followed by a stabilization policy run using the same parameter set. Output from 250 parameter sets was then analyzed and combined to explore the uncertainty associated with the predictions. (Figure 3 diagrams the steps of this thesis.) The specific output analyzed includes carbon emissions, economic consumption by region, and carbon permit prices.

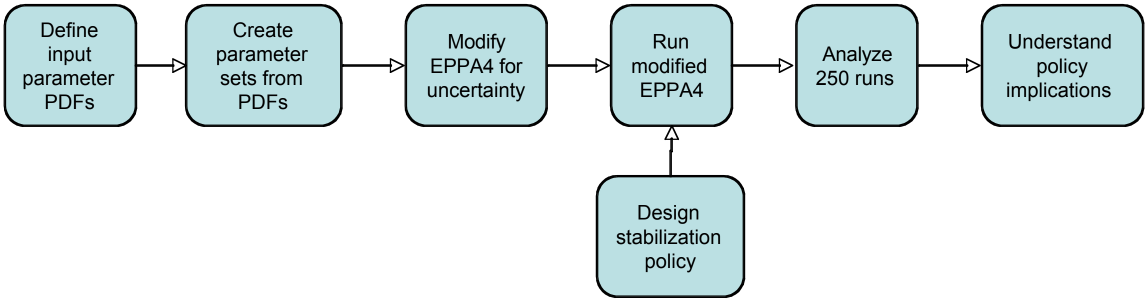
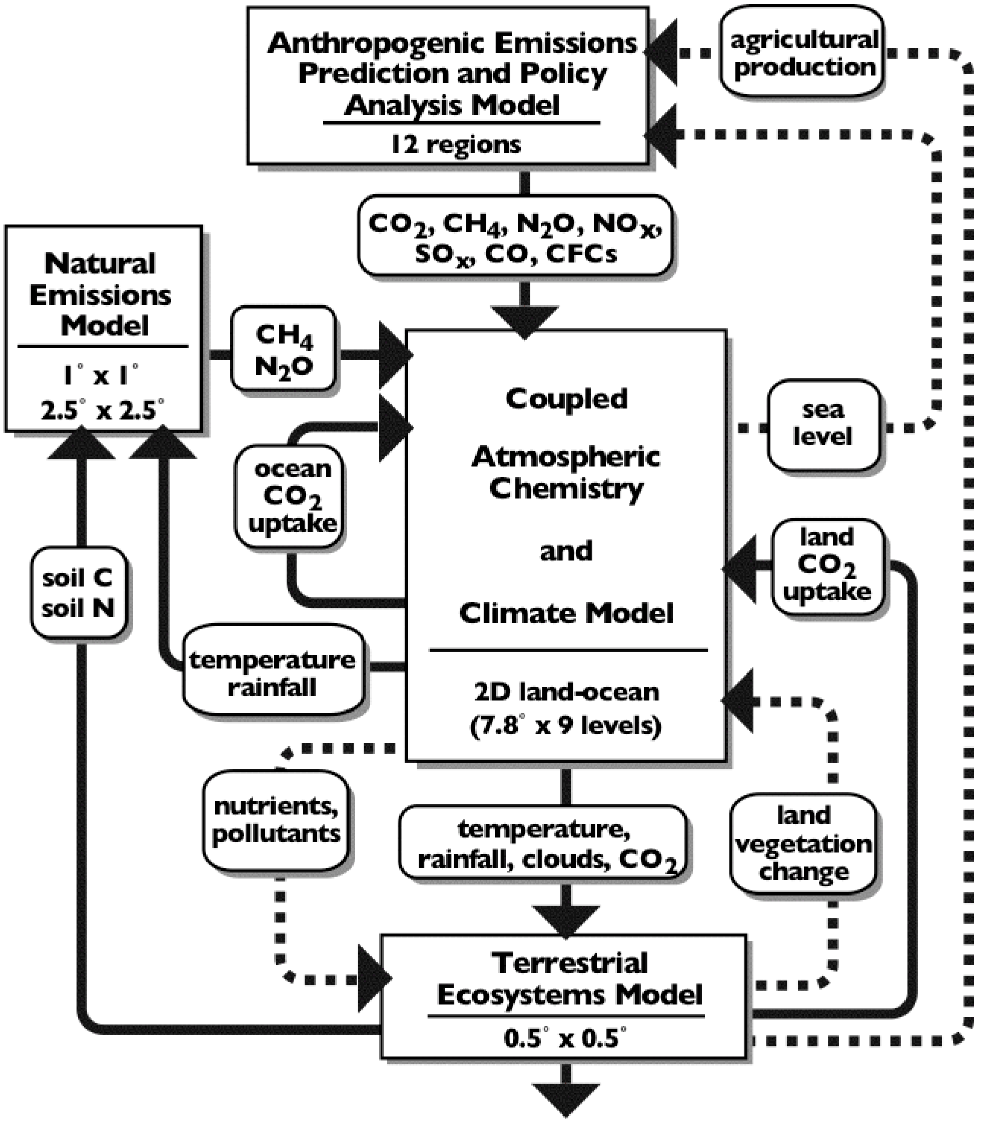


Figure 3 – Diagram of the research steps for this thesis.

3.1 – The Integrated Global System Model

For this research, every component of MIT's Integrated Global System Model (IGSM) (Prinn *et al.*, 1999) was utilized. The most heavily utilized IGSM component was the economic model: the Emissions Prediction and Policy Analysis (EPPA) model (Babiker *et al.*, 2001). In particular, research was conducted with EPPA4, the fourth major revision, with modification to allow for uncertainty analysis.

The IGSM consists of several sub-models that focus on different steps in the climate change causal chain. Figure 4 shows the flows and feedback between the components. Typically a policy is designed and run through the EPPA model. The emissions output is processed through an coupled atmospheric chemistry, 2-D land and 2-D ocean model that predict climate impacts such as atmospheric concentrations and temperature change. This coupled climate model was used to verify the stabilization policies for this research.



(Source: Prinn *et al.*, 1999)

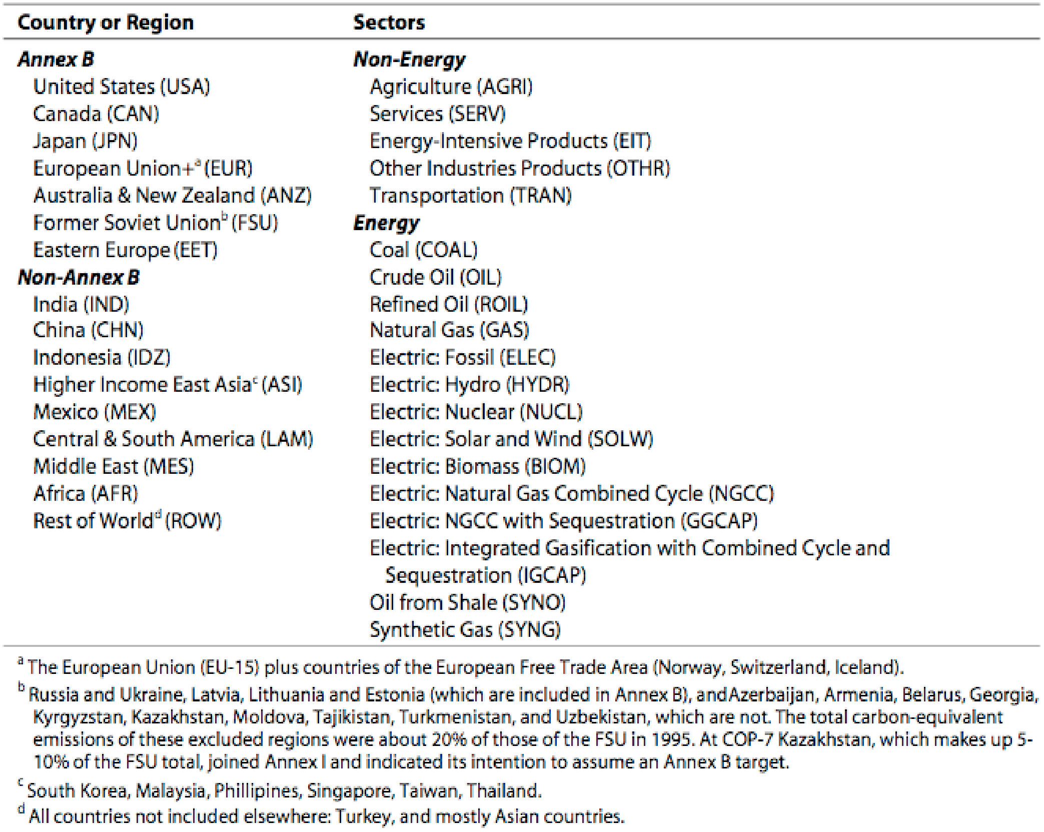
Figure 4 – Diagram of the Integrated Global Simulation Model.

The EPPA4 model is a computable general equilibrium (CGE) model that simulates the world's economy. Twelve economic sectors compete for limited economic resources, such labor, capital, and land. These economic sectors are modeled for sixteen geographic regions, including the US, Europe, the Middle East and China. (See Table 1 for list of regions and sectors.) Goods produced by the economy are traded between regions. The model is recursive-dynamic and computes equilibrium quantities and prices for all goods and factor markets in each time step, consistent with behavioral assumptions of consumption, welfare maximization and producer profit, while subject to technology characterizations, taxes, and other economic features represented in an underlying statistics database. For this research, the model was run from 2000 through 2100 in five-year time steps.

As the name EPPA implies, the model was developed primarily to assist with the prediction of future greenhouse gas emissions. The economic activity simulated during a model run generates CO_2, N_2O, PFC, HFC, SF_6, and CH_4 emissions that are stored in output files. EPPA4 has a default case called the “reference” or “business-as-usual” (BAU) scenario. The BAU scenario is a “no policy” future.

Once the BAU scenario emissions are predicted, EPPA4 can be used to compare different climate change mitigation policies. Researchers can create policies detailing what kind of regulatory mechanism is applied, when regulations will start and stop, which economic sectors are regulated, and which regions are involved. The two main types of regulatory mechanisms of EPPA4 are taxes and quotas. Often a policy might examine how a carbon tax applied in particular regions affects the economic welfare in those regions and their GHG emissions.

This research focused on varying the input parameter values of EPPA4. Normally EPPA4 is used with a “default” set of initial values that results in a single economic BAU projection. Instead of using the “default” values, values of key parameters were varied to create a range of BAU scenarios exposing the uncertainty of model results.



Country or Region	Sectors
Annex B	***Non-Energy***
United States (USA)	Agriculture (AGRI)
Canada (CAN)	Services (SERV)
Japan (JPN)	Energy-Intensive Products (EIT)
European Union+[a] (EUR)	Other Industries Products (OTHR)
Australia & New Zealand (ANZ)	Transportation (TRAN)
Former Soviet Union[b] (FSU)	***Energy***
Eastern Europe (EET)	Coal (COAL)
Non-Annex B	Crude Oil (OIL)
India (IND)	Refined Oil (ROIL)
China (CHN)	Natural Gas (GAS)
Indonesia (IDZ)	Electric: Fossil (ELEC)
Higher Income East Asia[c] (ASI)	Electric: Hydro (HYDR)
Mexico (MEX)	Electric: Nuclear (NUCL)
Central & South America (LAM)	Electric: Solar and Wind (SOLW)
Middle East (MES)	Electric: Biomass (BIOM)
Africa (AFR)	Electric: Natural Gas Combined Cycle (NGCC)
Rest of World[d] (ROW)	Electric: NGCC with Sequestration (GGCAP)
	Electric: Integrated Gasification with Combined Cycle and Sequestration (IGCAP)
	Oil from Shale (SYNO)
	Synthetic Gas (SYNG)

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

[b] Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B), andAzerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan, which are not. The total carbon-equivalent emissions of these excluded regions were about 20% of those of the FSU in 1995. At COP-7 Kazakhstan, which makes up 5-10% of the FSU total, joined Annex I and indicated its intention to assume an Annex B target.

[c] South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand.

[d] All countries not included elsewhere: Turkey, and mostly Asian countries.

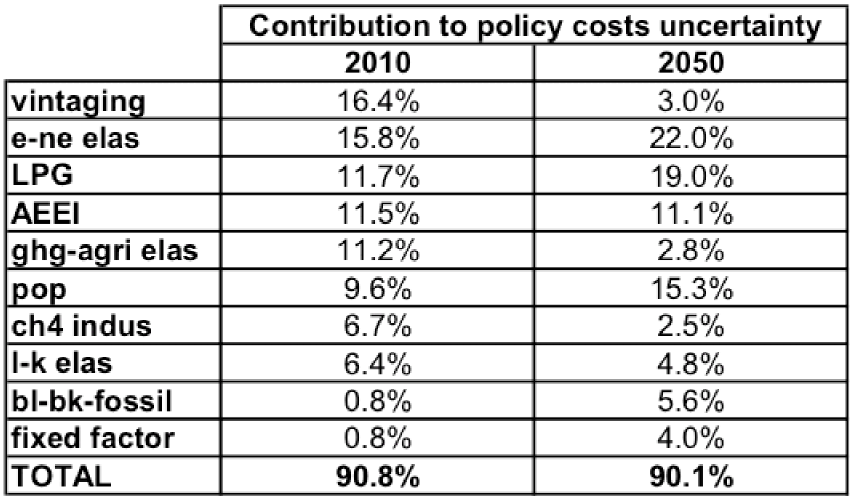
Table 1 – List of EPPA4 regions and economic sectors.

3.2 – Details of the parameter distribution functions

To explore parametric uncertainty in stabilization costs, eleven different categories of parameters were varied during a Monte Carlo simulation. These parameters were chosen follwoing a sensitive analysis performed by Cossa (2004). The eleven variables categories are:

- Labor productivity growth rate,
- Autonomous Energy Efficiency Improvement rate,
- Elasticity between energy and non-energy resources
- Elasticity between labor and capital,
- Fixed-factor elasticity
- Population growth rates
- Initial methane emission inventories by economic sector
- Vintaging coefficient
- Elasticity of methane emissions and agricultural output
- Elasticity of nitrous oxide emissions and agricultural output
- Backstop factor cost mark-ups

Cossa (2004) found that these parameter categories account for over 90% of model output variation. (See Table 2.) After the sensitivity analysis, probability density functions for the categories were constructed. Cossa constructed the PDFs using two different methods: expert elicitation and econometric literature. When past econometric studies were available they were utilized but many parameter categories were either hard to study or EPPA4 specific. The result was that many of the eleven categories were estimated through an elicitation process. It is difficult to control for bias during expert elicitation, so Cossa followed methodology outlined by Morgan and Henrion (1990).



	Contribution to policy costs uncertainty	
	2010	**2050**
vintaging	16.4%	3.0%
e-ne elas	15.8%	22.0%
LPG	11.7%	19.0%
AEEI	11.5%	11.1%
ghg-agri elas	11.2%	2.8%
pop	9.6%	15.3%
ch4 indus	6.7%	2.5%
l-k elas	6.4%	4.8%
bl-bk-fossil	0.8%	5.6%
fixed factor	0.8%	4.0%
TOTAL	**90.8%**	**90.1%**

(Source: Cossa, 2004)

Table 2 – Sensitivity analysis results showing percentage of cost variation.

This research builds significantly on previous expert elicitation and PDF estimation work (Cossa, 2004). These previously constructed PDFs were reviewed to assess their consistency with recent EPPA4 changes and new econometric research. Some PDFs were changed during this review process. Any changes are highlight in the following sections, which explain the parameter categories and provide a table describing the probability density functions.

3.2.1 – Labor productivity growth rate

Labor productivity growth (LPG) is the variable that most directly affects GDP growth. LPG describes the change in the productivity of the average worker in a region. The effective labor supply for a region in a given time period is the previous period's effective labor supply multiplied by an effect labor growth rate variable. The effect labor growth rate variable is the sum of labor force (i.e., population) growth and the LPG rate. Therefore, as the LPG increases, the effect labor supply increases (i.e., positive correlation).

For this experiment, the LPG rates from Cossa (2004) were not used. Instead, Dr. Mort Webster generated new labor productivity growth rate tables based on his recent econometric work that defined regional LPG rates. Webster created 250 tables that define the LPG rate for a region in a given time-step. He correlated short-term LPG rates across regions but did not correlated long-term rates. These 250 tables were the LPG rate initial values for the Monte Carlo simulation.

3.2.2 – Autonomous Energy Efficiency Improvement rate

Autonomous Energy Efficiency Improvement (AEEI) describes increases in energy efficiency and intra-sector structural shifts unrelated to price changes. More specifically, it is the decrease in required energy needed to produce one unit of output that cannot be explained by price changes. The AEEI is an exogenous factor that accounts for historical improvements in energy intensity declines that cannot be explained by the price factor alone (Edmonds and Reilly, 1983; Manne and Richels, 1990). The AEEI parameter is highly model dependent because of differences in energy efficiency accounting.

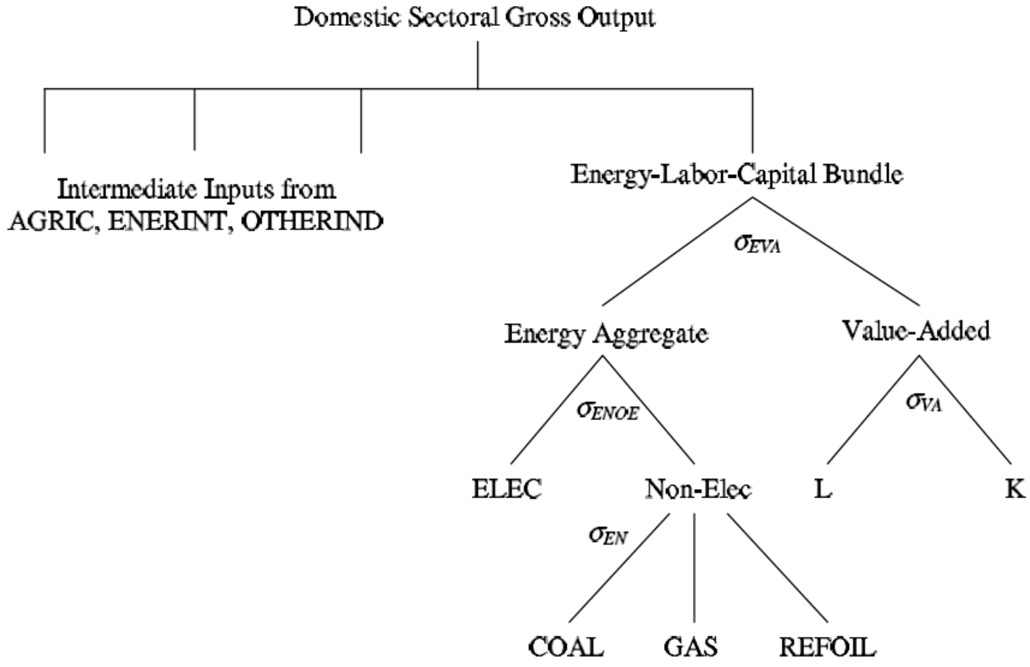
The input probability density function for AEEI was generated by an econometric study by Webster and Cho (2004). Reviewing 50 years of economic data, they concluded that a normalized distribution with a mean of 1 and a standard deviation of 0.4 would estimate AEEI, based on the limited data available. Table 3 shows the PDF values compared with the EPPA4 default parameter.

AEEI	**Certainty**	**Uncertainty**		
	EPPA Default	**Median**	**Stddev**	**Fit Type**
All regions	1.0	1.0	0.4	Normal

Table 3 – AEEI parameter values.

3.2.3 – Energy and value-added elasticity

The elasticity between energy and “value-added” describes how easy an economic sector can substitute labor and capital inputs for energy sector outputs. Figure 5 shows the nested structure of a sector in the EPPA4 model. The lower middle branch shows how energy is part of an “Energy Aggregate” bundle. The right-most branch the “value-added” goods of labor and capital. The ratio substitution between value-added and energy goods is captured by the energy/value-added elasticity parameter (i.e., σ_{EVA}). This parameter was estimated by the elicitation of six experts and then reviewed for this research. Some values were updated from previous work because of model changes. The values used are shown in Table 4.



(Source: Babiker *et al.*, 2001)

Figure 5 – The structure of the energy-intensive sector in EPPA4.

Ener/Value-added elas	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
AGRI	0.3	0.2	0.1	Gamma
CGD	0.25	0.4	0.2	Log-logistic
EINT	0.5	0.3	0.1	Gamma
ELEC	0.1	0.2	0.1	Gamma
OTHR	0.5	0.4	0.2	Beta General
SERV	0.5	0.4	0.2	Beta General
TRANS	0.4	0.4	0.2	Log-logistic

Table 4 – Energy/non-energy elasticity parameter values.

3.2.4 – Elasticity between labor and capital

Like other elasticity parameters, the labor/capital elasticity represents the ease of substituting one resource for another. In this case, it is the ratio of labor that would be required to offset one unit of capital (and vice versa). An econometrics study by Balistreri (2002) provided the dataset for PDF construction. Cossa (2004) aggregated the economic sectors of Balistreri's work to fit the EPPA4 model structure. These new PDFs were reviewed for this research. The only change was the value for the agriculture sector. Table 5 contains the values used in this study.

Labor/ Capital elas	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
AGRI	0.3	0.3	0.4	Beta General
CGD	1.0	1.5	0.3	Gamma
EINT	1.0	1.1	0.2	Beta General
ELEC	1.0	1.0	0.2	Beta General
ENOE	1.0	0.8	0.1	Gamma
OTHR	1.0	1.2	0.4	Beta General
SERV	1.0	1.5	0.3	Gamma
TRANS	1.0	0.9	0.1	Gamma

Table 5 – Labor/capital elasticity parameter values.

3.2.5 – Fixed-factor elasticity

In energy production sectors, depletable resources are represented as a fixed factor. The supply response of a sector to changing resource prices is controlled by the elasticity of substitution between the fixed factor and a bundle of all other inputs. This fixed factor elasticity is the parameterization of the effort required to extract energy resources. The values to construct the PDF were obtained by expert elicitation (Cossa, 2004). The two experts were asked how easy it would be for key resource exporters (e.g., the Middle East) to expand or restrain their production capacity. No changes were made to this parameter during the review process. (see Table 6).

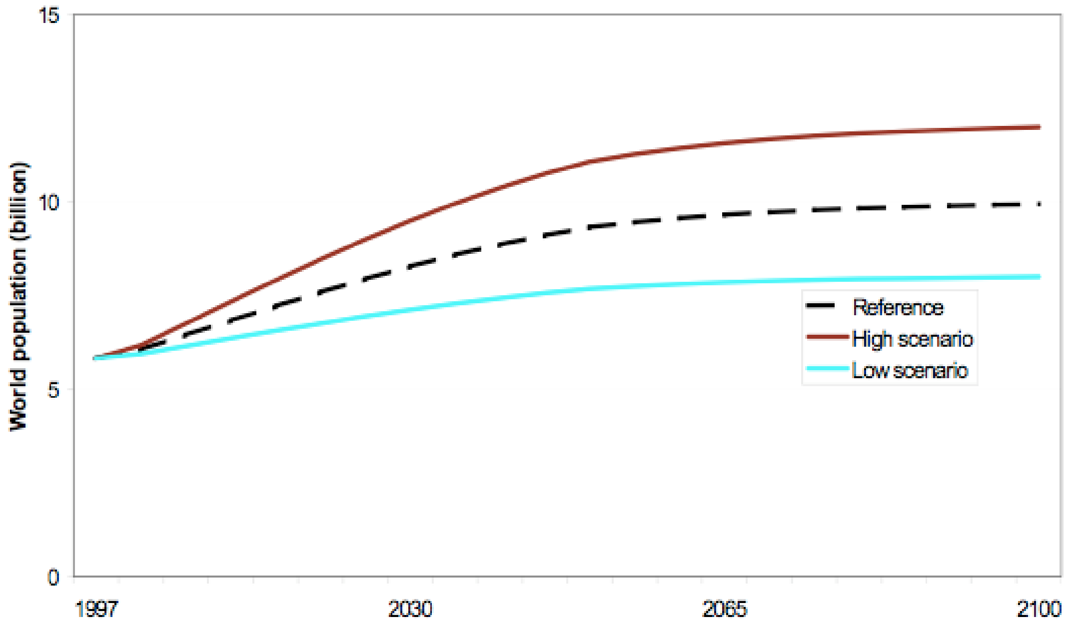
Fixed factor elas	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
Oil & gas	0.7	0.5	0.1	Beta General

Table 6 – Fixed factor elasticity parameter values.

3.2.6 – Population growth rates

Population drives labor force growth, a key determinant of GDP growth. GDP growth results in greater income and greater aggregate consumption. Because of its fundamental role in economic growth, it is no surprise that population as a key variable in the sensitivity study.

EPPA4 models population growth using the United Nations' 2000 projections. In order to calculate a PDF for these UN projections, Cossa asked experts how likely three different UN fertility scenarios were. Figure 6 illustrates the three different population scenario paths (i.e., "low", "medium" or "reference", and "high"). A PDF was constructed from the expert opinions under the assumption that the three scenarios represented the mean plus or minus one standard deviation. Table 7 shows the population numbers used for this thesis.



(Source: Cossa, 2004)

Figure 6 – UN Population fertility scenarios used for elicitation.

Population in 2100	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
World	9937 mil	9937 mil	1442 mil	Log-logistic

Table 7 – Population parameter values.

3.2.7 – Initial methane emission inventories by economic sector

Current methane emission inventories are highly uncertain. The IPCC predicts total natural and anthropogenic methane emissions to be 500-600 million metric tons (mmt) (IPCC, 2001c). A recent MIT inverse method study (Chen, 2004) narrows the estimate, putting methane emission in the lower half to the IPCC range.

This new MIT study by Chen was used as guidance for this research instead of the estimates used by Cossa (2004). Chen aggregated economic sectors differently than EPPA4's structure, so the study's emission categories were disaggregated and then recombined. This was relatively straightforward because Chen assumed that the ratio of emissions remained constant as he aggregated emission sources. The ranges were estimated for EPPA4 sectors based on the average of the relative standard deviation for a category. For example, if a category from Chen's dissertation was 100+/-10 mmt, and the aggregate category in EPPA4 had a total of 60 mmt, the standard deviation was +/-6 mmt of methane. Table 8 contains the values used for this research, normalized to a median of 1.

Methane Inventories	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
AGRI	1.0	1.0	0.280	Beta General
COAL	1.0	1.0	0.050	Beta General
DSEWAGE	1.0	1.0	0.017	Beta General
EINT	1.0	1.0	0.060	Beta General
GAS	1.0	1.0	0.060	Beta General
LANDFILL	1.0	1.0	0.017	Beta General
OIL	1.0	1.0	0.060	Beta General
OTHR	1.0	1.0	0.050	Beta General

Table 8 – Initial methane inventory parameter values.

3.2.8 – Vintaging coefficient

Capital stock flexibility is represented in the EPPA4 model by the vintaging coefficient. If the coefficient is 1.0, then all capital is completely immobile and, once used, is not part of the capital resource pool. If the value is 0, then all capital remains completely malleable and can be reallocated in the next period. The default value is 0.3, meaning 30% of the capital is immobile. The PDF for the vintaging coefficient was done by expert elicitation of five experts (Cossa, 2004) and was reviewed for this research with no changes. The median and standard deviation are show in Table 9.

Vintaging	Certainty	Uncertainty		
	EPPA Default	Median	Stddev	Fit Type
% of capital	30%	52%	16%	Gamma

Table 9 – Vintaging coefficient parameter values.

3.2.9 – Elasticity of methane/nitrous oxide emissions and agricultural output

Two additional elasticities in EPPA4 are related to the GHG emissions and agricultural output. The elasticities represent GHG emission intensity per unit of output. The two elasticities for nitrous oxide and methane emissions are done slightly different because of the agricultural sector's nested structure in EPPA4. N_2O emissions are substitutable with a "resource intensive bundle" while CH_4 emissions are substitutable with "domestic gross output" (Babiker *et al.*, 2001).

Cossa (2004) constructed the PDFs through expert elicitation about the shape of the CH_4/N_2O abatement cost curves in the agricultural sector. The PDF review process changed the PDFs by normalizing them to the EPPA4 default values (relatively standard deviation is the same). Table 10 and Table 11 contain the results.

Ag Methane Elas	**Certainty**	**Uncertainty**		
	EPPA Default	**Median**	**Stddev**	**Fit Type**
US	0.050	0.050	0.030	Pearson
JPN	0.070	0.070	0.028	Beta General
EUR	0.070	0.070	0.021	Beta General
ANZ	0.040	0.040	0.010	Beta General
FSU	0.050	0.050	0.025	Beta General
EET	0.080	0.080	0.020	Beta General
CHN	0.050	0.050	0.030	Log-logistic
IND	0.040	0.040	0.020	Beta General
MES	0.020	0.020	0.008	Beta General
LAM	0.020	0.020	0.010	Beta General
ASI	0.060	0.060	0.039	Beta General
ROW	0.030	0.030	0.012	Beta General

Table 10 – Agricultural methane elasticity parameter values.

Ag N_20 Elas	**Certainty**	**Uncertainty**		
	EPPA Default	**Median**	**Stddev**	**Fit Type**
OECD	0.040	0.040	0.006	Beta General
IDC	0.020	0.020	0.003	Beta General
FSU	0.040	0.040	0.004	Beta General
EET	0.040	0.040	0.016	Beta General

Table 11 – Agricultural nitrous oxide elasticity parameter values.

3.2.10 – Backstop factor cost mark-ups

Backstop factors represent alternative energy technologies in the EPPA4 model. While these alternative technologies are perfect substitutes with current energy production, they are priced higher than traditional fossil fuel technologies (e.g, coal and natural gas). This higher price is the "mark-up" or initial cost disadvantage of a given technology. An alternative technology, such as bio-oil energy, will enter the market when this initially higher price is lower than the cost of traditional technologies, which may occur when carbon-based emissions are regulated.

Five experts were elicited about five different backstop technologies (Cossa, 2004). (See Table 1 for a list of EPPA energy technologies.) Their answers were combined into PDFs for each technology. During the review process, the PDFs for "Synf oil" and "Gas & Coal" were shifted left and tightened. Two new backstop technologies (bio-elec and bio-oil) were added because of recent changes to the model. The table below shows the median and standard deviations used for the sampling.

Backstop	**Certainty**	**Uncertainty**		
Factors	**EPPA Default**	**Median**	**Stddev**	**Fit Type**
Synf oil	2.8	3.2	0.8	Beta General
Gas Synf	3.5	3.8	0.9	Pearson 5
IGCAP	1.18	1.2	0.1	Log-logistic
NGCAP	1.15	1.2	0.1	Beta General
NGCC	0.90	0.9	0.04	Beta General
Bio-oil	3.8	3.8	0.9	Log-logistic
Bioelec	3.8	3.8	0.9	Log-logistic

Table 12 – Backstop factor mark-up parameter values.

3.2.11 – Correlation matrix for the sampling

The correlation matrix for the Latin Hypercube sampling was the same as previous work (Cossa, 2004) and was not changed during the review process. Correlation among variables is important in order to properly represent real-world relationships. For example, AEEI is correlated with many of the elasticities because technological improvements in energy efficient are likely a sign of a larger economic trend of innovation. Innovation would not be confined to just energy efficiency but rather there would be general innovation and improvement in how all resources were used. A full explanation of the expert judgment surrounding the correlation values (shown in Table 13) is provided by Cossa (2004).

Correlations	**LPG**	**AEEI**	**E/NE Elas**	**L/K Elas**	**Fixed Fact Elas**	**Population**	**CH4 Inv**	**Vintaging**	**Ag CH4**	**Ag N20**	**Backstops**
LPG	1										
AEEI	0.8	1									
E/NE Elas	0.8	0.8	1								
L/K Elas	0.8	0.8	0.8	1							
Fixed Fact Elas	0	0	0	0	1						
Population	0	0	0	0	0	1					
CH4 Inv	0	0	0	0	0	0	1				
Vintaging	0	0.8	0.8	0.8	0	0	0	1			
Ag CH4	0.8	0.8	0.8	0.8	0	0	0	0	1		
Ag N20	0.8	0.8	0.8	0.8	0	0	0	0	0	1	
Backstops	-0.8	-0.8	-0.8	-0.8	0	0	0	0	-0.8	-0.8	1

Table 13 – Correlation matrix used for parameter sampling.

3.3 – Defining stabilization policies

For this research, two stabilization policies were created to reach different climate change targets. Using two policies allows for a comparison of costs between environmental outcomes. The two stabilization targets were defined as 550 ppmv and 650 ppmv of carbon dioxide. (These targets imply eventual stabilization, not necessarily by 2100.) The other greenhouse gases in EPPA (i.e., methane, HFC, etc.) were controlled the same for both carbon dioxide targets. For this reason, the stabilization policies will simply be referred to by their carbon dioxide concentration targets.

3.3.1 – Regulating non-carbon dioxide gases

Sarofim *et al.* (2004) discusses how previous stabilization research fails to include constraints on non-carbon dioxide gases. Gases such as methane and HFC are often relegated to footnotes or are regulated in terms of global warming potential (GWP) or “carbon equivalence”. Excluding gases or using GWP fails to achieve atmospheric temperature stabilization (Sarofim *et al.*, 2004). Additionally, studies have found that focusing solely on carbon dioxide stabilization missed win-win opportunities, including reduced economic cost (Reilly *et al.*, 2000; Sarofim *et al.*, 2004).

In light of the importance to include non-CO_2 gases, the two stabilization policies included emissions paths for the five other GHGs. The emissions paths were adopted from parallel stabilization work done for the Climate Change Science Program (CCSP, 2005). The policies used quantity constraints to reduce SF_6, CH_4, N_2O, HFC, and PFC emissions, following a linear reduction path from 2010 to 2100. (See Table 14.) The 2100 policy targets were expressed as a percentage of 1997 emissions for each gas. Figure 7 illustrates the non-carbon dioxide GHG reduction paths.

Gas	**2100 Emission Target (% 1997)**
CH4	50%
N2O	70%
SF6	5%
HFC	80%
PFC	5%

Table 14 – Non-carbon dioxide gas 2100 targets as percentage of 1997 emissions.

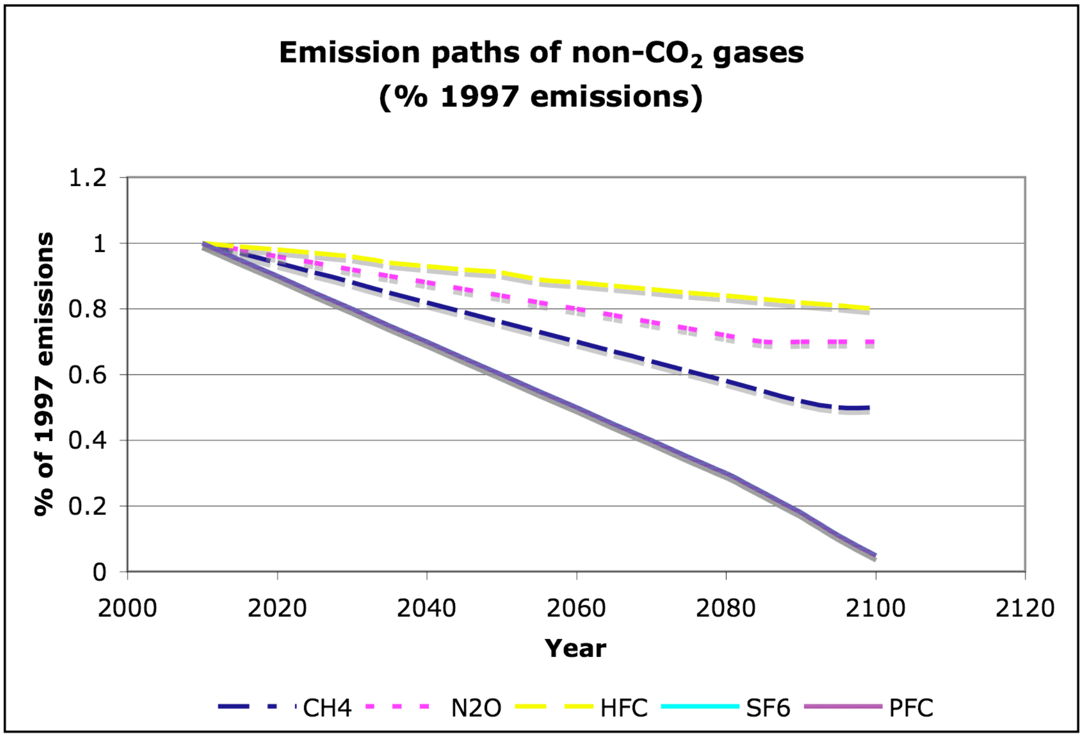


Figure 7 – Non-carbon dioxide emission reduction paths.

3.3.2 – Introducing a carbon tax

The next step was to develop a reasonable carbon dioxide emissions path through 2100. In order to allocate emission throughout the century, a carbon tax was applied to the economy starting in 2010 through the rest of the century. The tax grew at a rate of 5% year. Emissions fell over the course of the century because, as the tax increased, the cost of using fossil fuels that emit CO_2 rose, which caused industries to use less energy and less carbon-intensive energy. This method of allocating carbon emissions assures that each region bears the burden of reducing emissions at the same marginal cost of abatement.

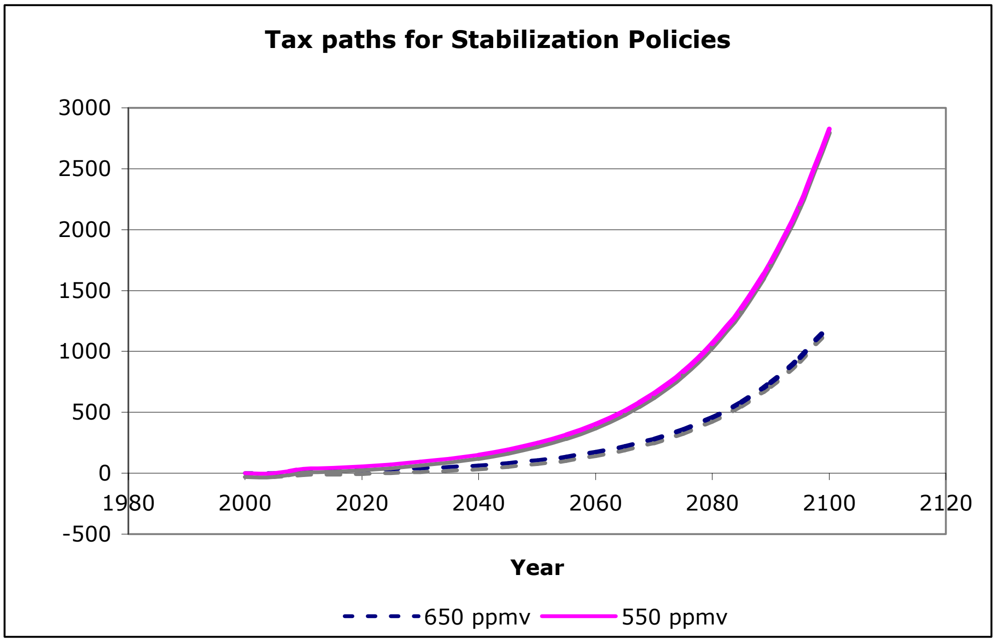


Figure 8 – The carbon tax price paths from 2000-2100.

With the 5% rate fixed, the initial tax price in 2010 was varied to create less or more stringent policies. The resulting 2010 carbon tax prices for the stabilization policies are $15/ton carbon and $35/ton carbon 650 ppmv and 550 ppmv, respectively. Figure 8 shows the relative tax paths for the two stabilization scenarios.

3.3.3 – Carbon tax was converted to a quota

The carbon tax policy was used to allocate carbon dioxide emissions over time and across regions. With the emissions allocated, the path was converted into quantity constraints by allocating carbon permits to the regions. Regions were allowed to trade their permits in order to reduce emissions by the most economical means, though no trading should occur under model runs with the default EPPA parameters. The tax and quota policy solutions were compared to ensure than the prices and emission levels were equivalent.

Switching to quotas brings an additional consideration: burden sharing. The change in regional economic welfare depends to some extent on how the tradable permits are allocated. By allotting the carbon permits to regions based their tax-policy emissions, a decision was made emissions should be reduced at equal marginal cost across all regions. Regions that could make deeper reductions at a given carbon price were given fewer permits. This means that the regions with more inelastic carbon abatement were given more permits. For quota policies under uncertainty, there is a difference of economic welfare from the permit-poor regions to the permit-rich regions. A country may become permit-poor (i.e., require additional permits) if population, economic growth rate, or another uncertain parameter causes higher than default emissions.

After this conversion, the policy scenarios used for Monte Carlo analysis included quotas for all greenhouse gases. There are two benefits of this approach: first, as mentioned before, the mathematical solver had an easier time solving the policy cases. This was important for Monte Carlo analysis because some parameter sets were particularly difficult to solve, depending the combination of initial values. Second, if quotas regulate carbon dioxide emissions, the shadow price of carbon (the price per ton) can vary for a given parameter set. This allowed for uncertainty analysis of the required carbon tax.

3.4 – Preparing EPPA4 for the Monte Carlo simulation

3.4.1 – Input and output management for large ensemble simulations of EPPA4

Monte Carlo analysis requires hundreds of runs and, thus, it is useful to automate several processes. Specifically, computer scripts were written to manage the workflow on a computer cluster. These scripts include:

- Running both the reference and policy cases
- Remotely launching EPPA4 on specific cluster nodes
- Launching the full Monte Carlo ensemble (scheduling)
- Gathering the model results for analysis

In order to perform a large number of runs quickly, the model was ported from the Windows operating system to Linux. For the final set of data, 25 computer nodes were used for approximately 6 days.

3.4.2 – Latin Hypercube sampling and 250 runs

Monte Carlo analysis can be computationally expensive to perform. A very large number of runs maybe needed to generate a high-resolution PDF of uncertainty. Fortunately there are statistical sampling techniques that reduce the number of runs required while still producing statistically significant output (Morgan and Henrion, 1990). For this thesis, Latin Hypercube sampling was used. The sampling was performed by a software package called AtRisk (a third-party Excel extension). Latin Hypercube sampling allowed for reasonable uncertainty results using a sample size of 250 runs.

4 – Analysis of the Monte Carlo simulation

This chapter details the results of the Monte Carlo simulation. Two different ensembles were run and analyzed – one for each stabilization policy detailed in Chapter 3. After the model runs were completed, the output was collected and analyzed. Fitted PDFs were constructed for carbon emissions, carbon permit price, and economic welfare changes. For each of these outputs, the median and the 90% confidence interval are reported.

Analysis of the Monte Carlo simulation revealed that a significant number of the initial 250 runs failed for each of stabilization scenarios. The analysis below was conducted with 216 and 212 successful runs for the 550 ppmv and 650 ppmv scenarios, respectively. There was insufficient time to check for systematic failures that may have skewed the results presented below. The results should therefore be used with caution.

4.1 – Uncertainty in “no-policy” carbon dioxide emissions

Before looking at carbon price uncertainty and economic welfare changes, it is important to understand the uncertainty in the underlying carbon emissions. Total carbon emissions are key to determining carbon permit demand and the cost of abatement. The uncertainty in carbon emissions, therefore, is important to explaining much of the carbon price and welfare change uncertainty. The results in this section refer to the uncertainty of emissions from the reference or no-policy scenario ensemble.

4.1.1 – Uncertainty in worldwide emissions in 2100

Worldwide carbon emissions depend on which of the 250 initial parameter sets was used. Figure 9 shows the probability density function for total carbon emissions in 2100 for the 550 ppmv policy. The distribution median was 23.7 GtC with a 90% confidence interval of 17.68-33.02 GtC. The “no policy” case using EPPA4’s default initial parameters produces 25.6 GtC in 2100.

These emission results are similar to other Joint Program studies but differ from Cossa (2004). Cossa’s emissions range was shifted right with both a higher median (32.77 GtC) and a longer right tail (runs extending to approximately 65 GtC). Reasons for the difference include: changes to the model since late-2003 (i.e., additiont of bio-oil and bio-elec technologies) and updated LPG rates from Dr. Webster (i.e., likely lower economic growth rates). The regional correlation among regions for LPG rates was also different between studies. Cossa had no correlation between regions. This research had short-term LPG correlated according to historically observed correlations. The long-term LPG rates were uncorrelated Additionally, short-term economic shocks were uncorrelated with the overall long-term uncertainty.

4.1.2 – Uncertainty in cumulative emissions from 2000-2100

Another view of carbon emissions is the cumulative emissions for the entire 21st century. Cumulative emissions are closely related to atmospheric concentrations because each year emissions accumulate in the atmosphere and are only slowly removed. EPPA4's default parameters predict emissions from 2000-2100 to total 353.5 GtC. The median of the uncertainty runs was very similar equaling 351.4 GtC with 90% confidence interval of 281.9-462.5 GtC. Figure 10 shows the distribution of the modeling ensemble. This statistic captures the significant variation in possible future carbon emissions throughout the whole century, not just a snapshot of a given year.

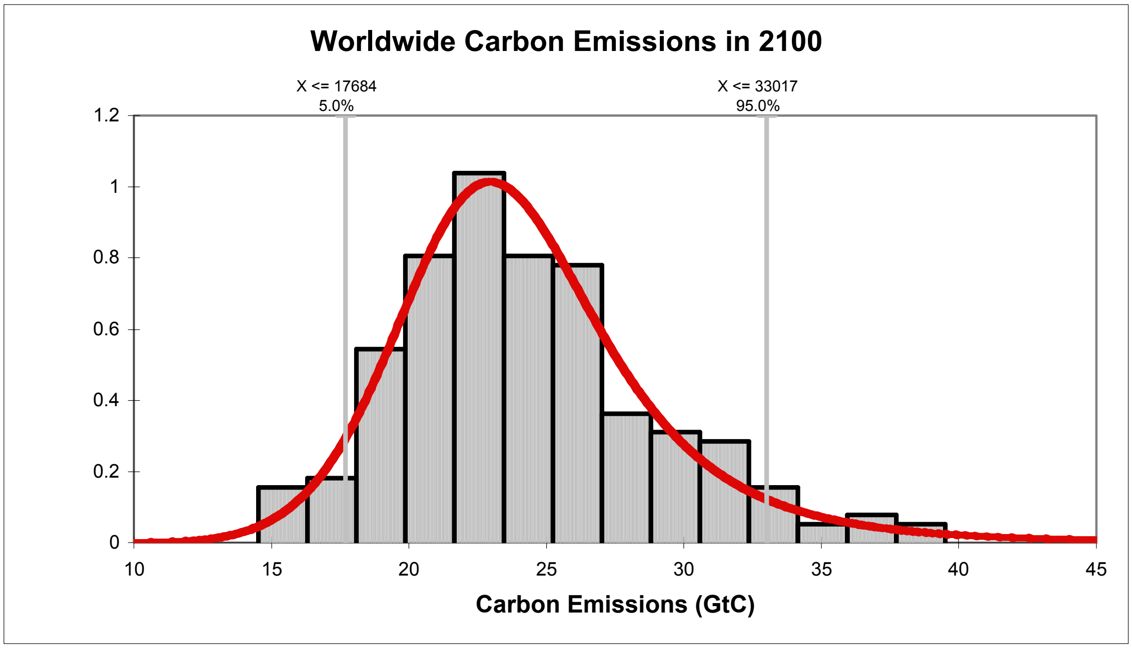


Figure 9 – Distribution of worldwide carbon dioxide emissions in 2100.

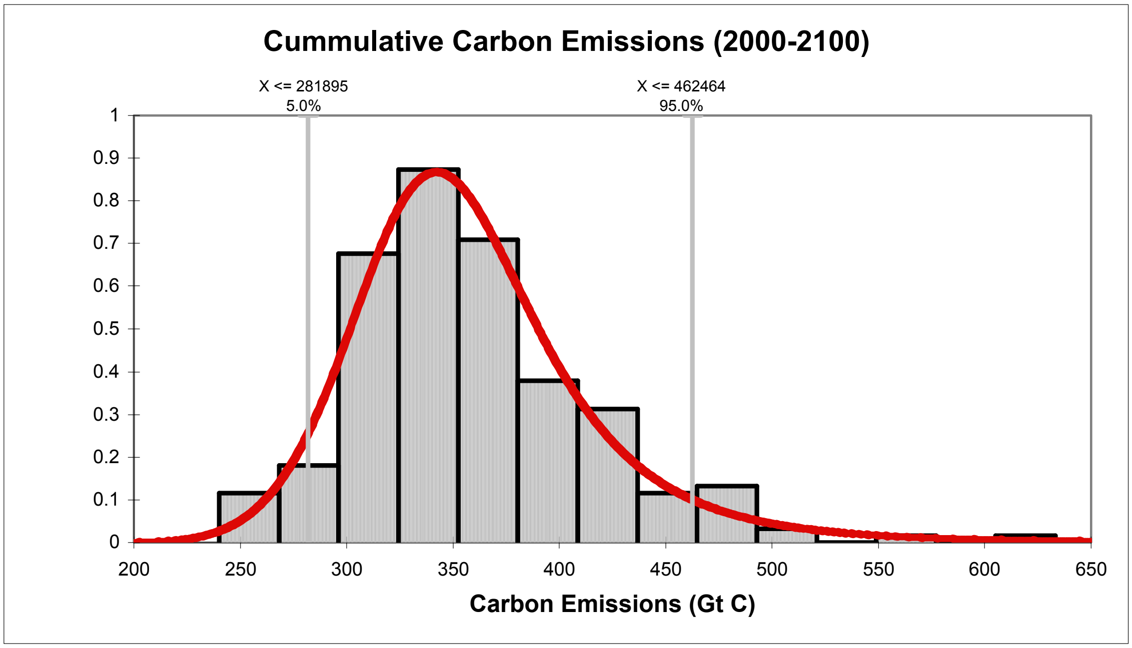


Figure 10 – Distribution of cumulative carbon dioxide emission from 2000-2100.

4.2 – Uncertainty in carbon price for stabilization scenarios

The 550 ppmv and 650 ppmv stabilization policies assigned tradable carbon permits to regions based on their response to a carbon tax (see Chapter 3). Once assigned, demand for carbon permits was a function of carbon emissions. As seen in the previous section, carbon emissions vary for different initial parameter sets. Consequently, the short-term and long-term permit price varies for different Monte Carlo simulation runs.

4.2.1 – Range of carbon prices for a 550 ppmv policy

The 2020 carbon price for the 550 ppmv stabilization policy with default EPPA4 parameters was $57/ton C. A very similar price of $56/ton C (median) was calculated for the 216 Monte Carlo runs. While these two numbers are almost equal, the simulation exposed uncertainty in carbon price estimates (the 90% confidence interval is $18.7-$123.1/ton C). The coefficient of variation is 0.57. Figure 11 shows the PDF of carbon prices in 2020.

The uncertainty in the carbon price grows as the century progresses. By 2100, the median carbon price is $3,690/ton C (compared to $2,830 for the default policy run) with a 90% confidence interval of $1,260-$11,200/ton C. (See Figure 12.) The coefficient of variation is 0.95, which is much larger than in 2020.

The carbon price uncertainty poses a problem when designing mitigation policies. In the short- or long-term, policies that define strict emission caps might have higher or lower than expected costs. Additionally, the large coefficient of variation requires any carbon price prediction to be qualified appropriately.

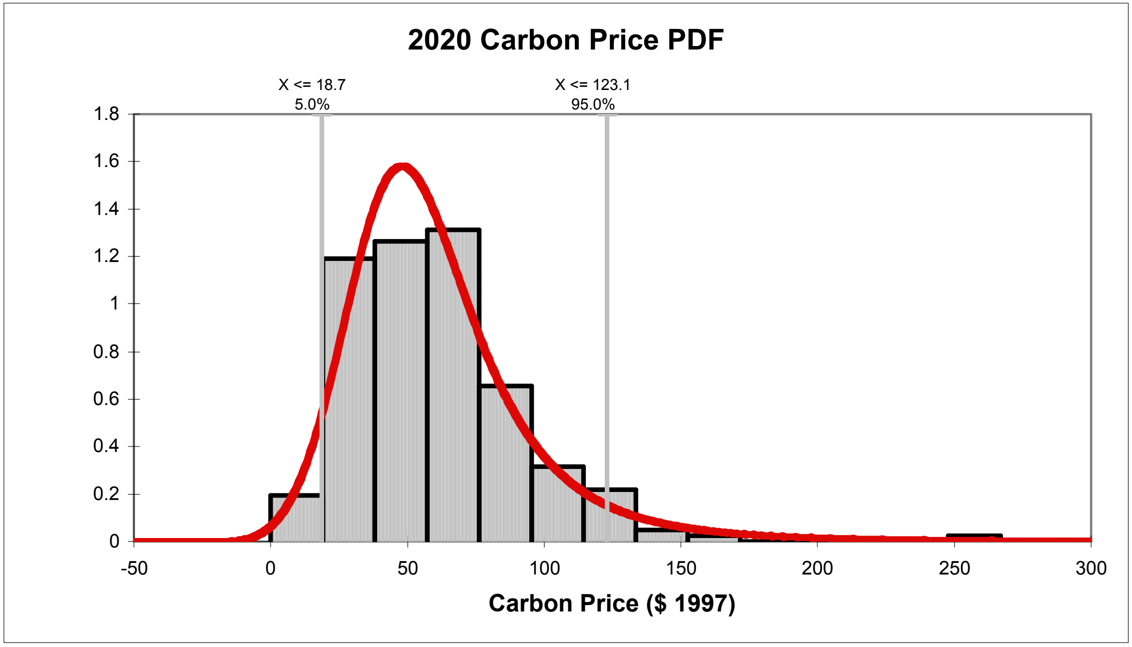


Figure 11 – Distribution of carbon prices in 2020.

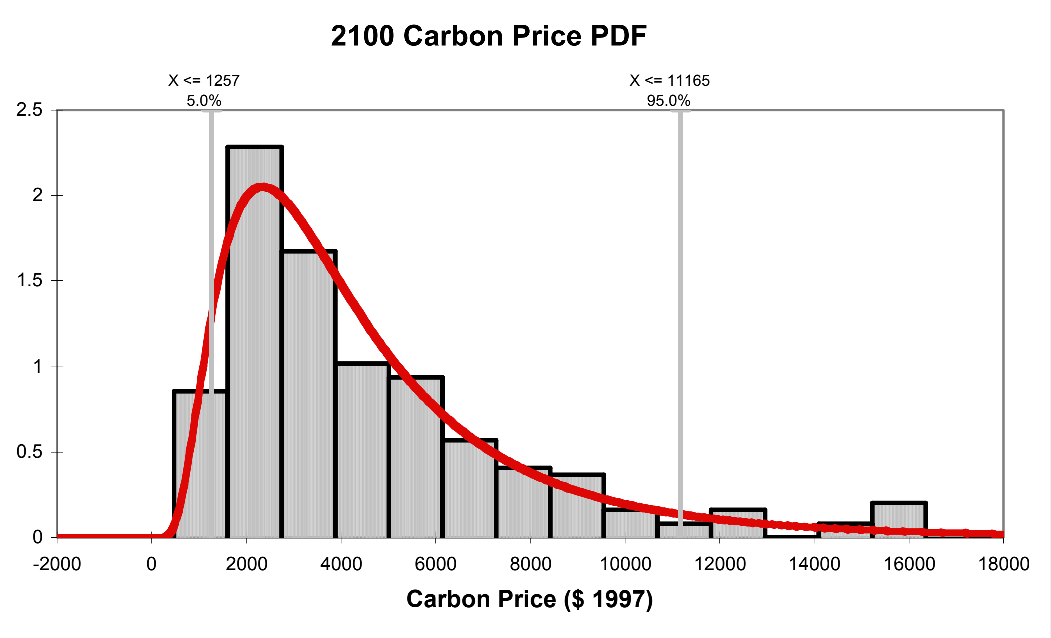


Figure 12 – Distribution of carbon prices in 2100.

4.3 – Changes in economic welfare

Climate stabilization policies have a variety of economic ramifications. The policy may promote particular sectors of the economy, favor non-carbon technologies, and cause economic welfare impacts, I focus here on changes to economic welfare in four regions: China (CHN), the European Union (EUR), the Middle East (MES), and the United States (US). These four regions were chosen because they represent both key players in the creation of climate policy and countries with very different circumstances. The US and EU are wealthy and energy efficient. The Middle East is an example of energy exporter countries, whose economies rely heavily on oil production. China is a developing economy that is energy-intensive. All four of these regions are likely to be vital to future climate change mitigation efforts.

The allocation of carbon permits has direct effects on regional economic welfare impacts. As noted in Chapter 3, this research allocates permits based on a tax-derived emissions path. This allocation method causes some regions (e.g., oil-exporting regions) to have negative welfare changes. Other permit allocation schemes could worsen or improve the economic well being of a region (Babiker and Jacoby, 1999; Babiker *et al.*, 2000).

Welfare changes (i.e., changes in economic consumption) were calculated for every successful Monte Carlo simulation. For each of the four regions, the change in welfare was calculated as a percentage of the reference case (i.e., "NoPolicy") welfare:

$$\frac{(StabPolicy_i - NoPolicy_i)}{NoPolicy_i} \quad \text{, where i = run index 1,...,216}$$

The results in this section are for the near-term welfare changes of the 550 ppmv stabilization policy. The results for the 650 ppmv policy are summarized in the following section.

4.4 – Uncertainty in welfare changes for a 550 ppmv policy

As a cautionary note, the economic welfare values in the EPPA4 model use market exchange rates (MER). This method does not account for differences in regional economic purchasing power, which prevents easy cross-regional comparisons. This section presents results in terms of regional welfare deltas to give idea of relative impact magnitude. Welfare change impacts need to be converted using a purchasing power parity conversion for further cross-region comparisons.

4.4.1 – Welfare change in 2020

China In the near-term, China's economic welfare is not significantly impacted by the stabilization policy. The distribution (shown in Figure 13) is narrow with a median of -0.7% and a

90% confidence interval of -2.7% to 1.6%. The impact to the Chinese economy appears to be minor, with a slight tendency toward decreased welfare. This may be because China's terms of trade are slightly better under a policy (Babiker and Jacoby, 1999; Babiker *et al.*, 2000). The prices of China's exports will increase more than the price of their energy imports. Any reduction in economic growth caused by the policy may be offset by the change in the terms of trade.

European Union For the European Union, a 550 ppmv stabilization policy could be welfare-neutral. The PDF (Figure 14) is centered on 0% welfare change (median = 0%). Compared with China the EU has more variance in the distribution. The 90% confidence interval is -0.37% to 0.39%, smaller than that of China meaning the EU takes less risk implementing a policy. The economic analysis is similar to that of China: the EU's term of trade improvements offsets reductions to negative economic growth impacts.

Middle East The Middle East is likely to have a decrease in economic welfare for the range of values used in this Monte Carlo simulation. Figure 15 illustrates the PDF with all samples having a negative change in welfare. The median is -4% with a 90% confidence interval of -8.4% to 0%.

The Middle East is the only region among the sample shown here with definite negative short-term welfare prospects. This can be explained as an effect of their heavily oil-exporting economy. When carbon dioxide is regulated, the price of using oil rises causing the demand for oil to fall. When overall oil demand drops, the world price of oil also falls. For the Middle East (and other oil exporters) this has devastating terms of trade effects. The value of Middle East oil exports declines considerably, while the cost of manufactured goods from other regions rises (because of the carbon tax). The end result is the Middle East can buy fewer foreign goods with its exports, resulting in a decline of economic welfare (Babiker and Jacoby, 1999).

United States The United States is the only region with a positive median in the short-term (median = 0.1%). While the median is only slightly positive, the 90% confidence interval is skewed right (-0.12% to 0.58%, as shown in Figure 16). While the United States has a chance to have a slight drop in economic welfare, it is the only region actually benefit from enacting the climate stabilization policy. Under global carbon restrictions, the mechanisms that hurt the Middle East help the United States. The US benefits a lower world oil price because it imports much of it oil. While the carbon regulations increase the price of domestic goods, the US' terms of trade improve slightly more than the policy's negative impact on economic growth.

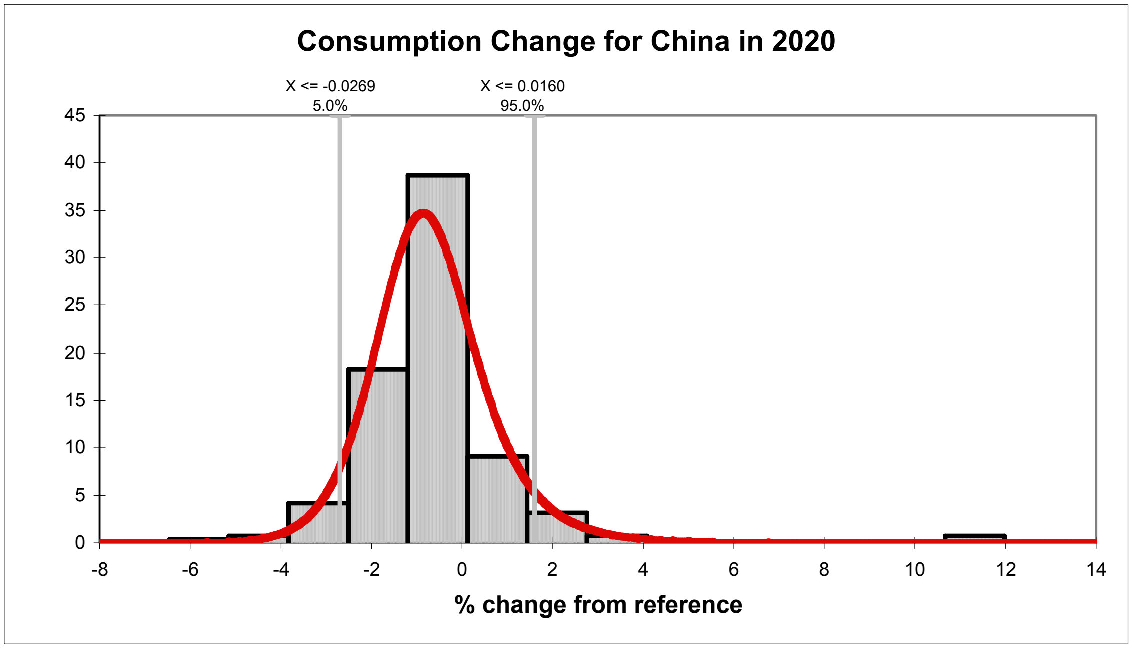


Figure 13 – Distribution of welfare changes for China in 2020.

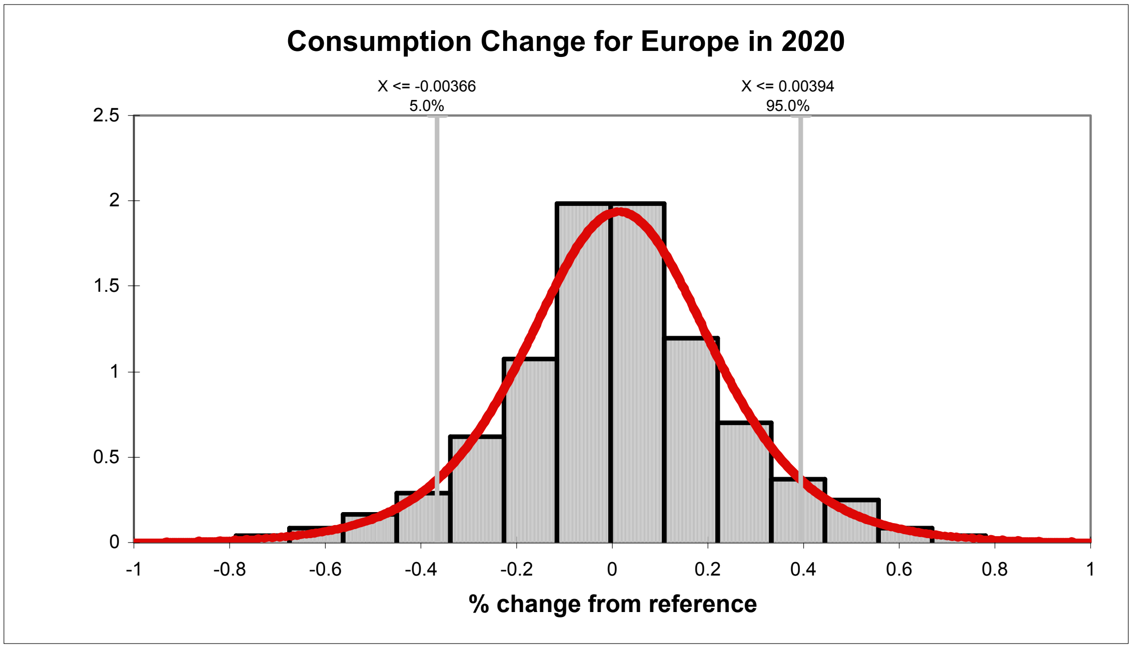


Figure 14 – Distribution of welfare changes for the European Union in 2020.

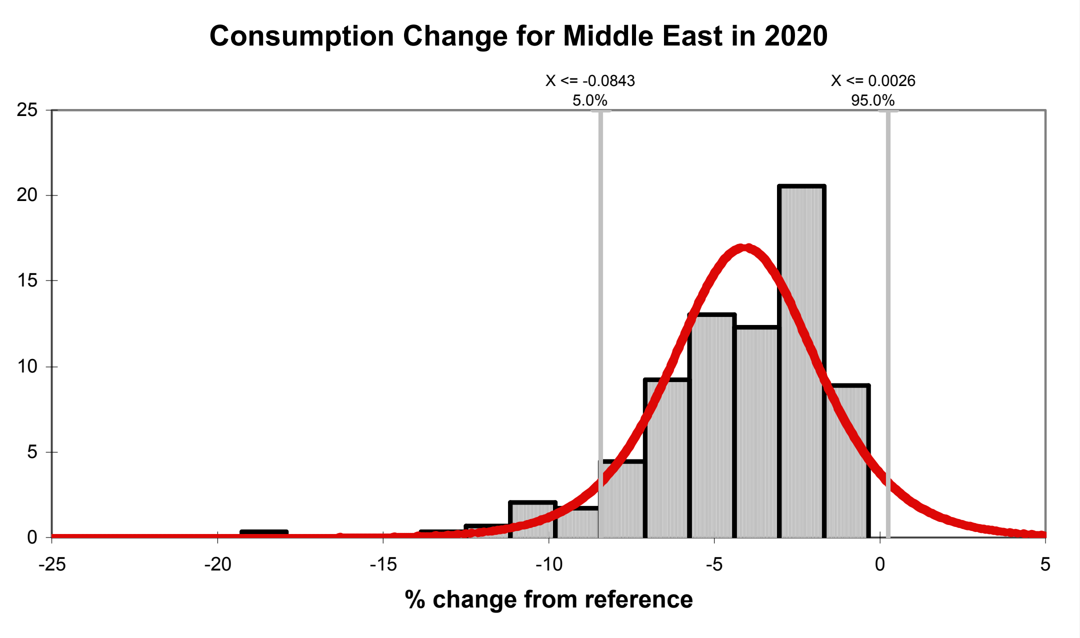


Figure 15 – Distribution of welfare changes for the Middle East in 2020.

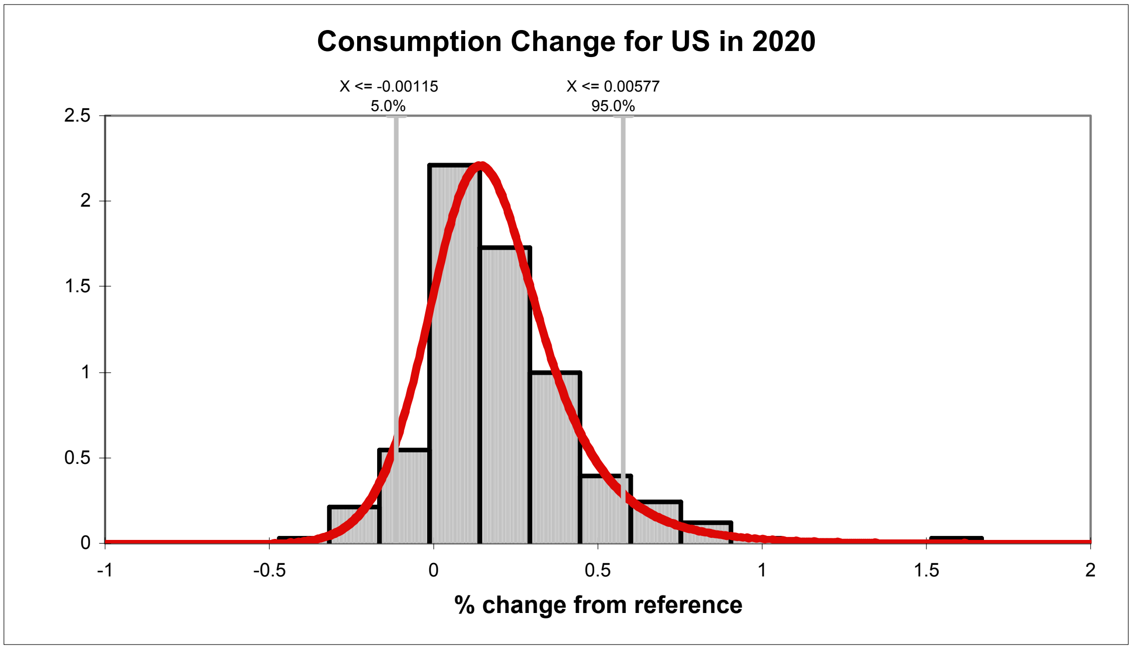


Figure 16 – Distribution of welfare changes for the United States in 2020.

4.4.2 – Welfare change for China in 2100

China In 2020, China had rather neutral prospects with regard to economic welfare changes. By 2100, the stabilization policy causes a large decrease, as shown in Figure 17. The median welfare change is -44% with a 90% confidence interval of -76.7% to -8%.

The stabilization policy causes significant impact to China's economic welfare for several reasons: 1) their energy-intensive economy, 2) the initial allocation carbon permits, and 3) rapid economic growth. Under a stabilization policy, economies that are energy intensive will be impacted more significant because the cost of fossil fuel inputs rises significantly. The high energy costs slow China's rapidly growing economy causing the loss in economic welfare. Additionally, because China's economy is more energy intensive, it will become an importer of carbon permits causing a flow of economic wealth out of China and into other regions. China's economic growth rate can be quite high, especially when compared to the three other regions. Simulation runs that used high LPG rate values produced reference results with large economic consumption. For these runs, the carbon quotas slowed growth considerably, causing the largest welfare losses.

European Union Figure 18 shows that the European Union's economic welfare change is skewed to the left. The runs in the lower tail (i.e., largest welfare decreases) are probably the runs with high growth rates. The stabilization policy will likely cause a loss of economy welfare for the region (median = -5%). The impact is significantly less than in China though. Also, unlike China, there is a chance that the EU will actually increase their welfare under the 550 ppmv policy scenario (90% confidence interval is -18.7% to 3.5%).

Middle East The Middle East's economic welfare declines considerably by 2100. The median decrease is -42% with a 90% confidence interval of -68.8% to -15.7%. Overall, the distribution is not significantly skewed in either direction (see Figure 19).

The results are similar to China, but the cause is different. In 2100, the Middle East's oil-exporting economy is impacted as in 2020 but more severely. The range of losses might be explained by the significance worldwide oil demand and the uncertainty in 2100 carbon emissions. If worldwide carbon emissions are in the lower fractiles (see Figure 9), the low carbon price would increase oil demand and the world price of oil will be higher. This situation would likely lessen the impact on the Middle East. The opposite would be true if carbon emissions were in the higher fractiles, causing a more significant welfare loss. The Middle East always has negative welfare changes because of terms of trade changes under stabilization policy.

United States In 2100 the United has a negative median (-4%) and a 90% confidence interval of -17.7% to 4.3% (see Figure 20). There is some change that the United States may have a positive economic welfare change under a 550 ppmv stabilization scenario. The reasons are similar to the 2020 analysis, but the uncertainty in carbon emissions increase the economic uncertainty in 2100.

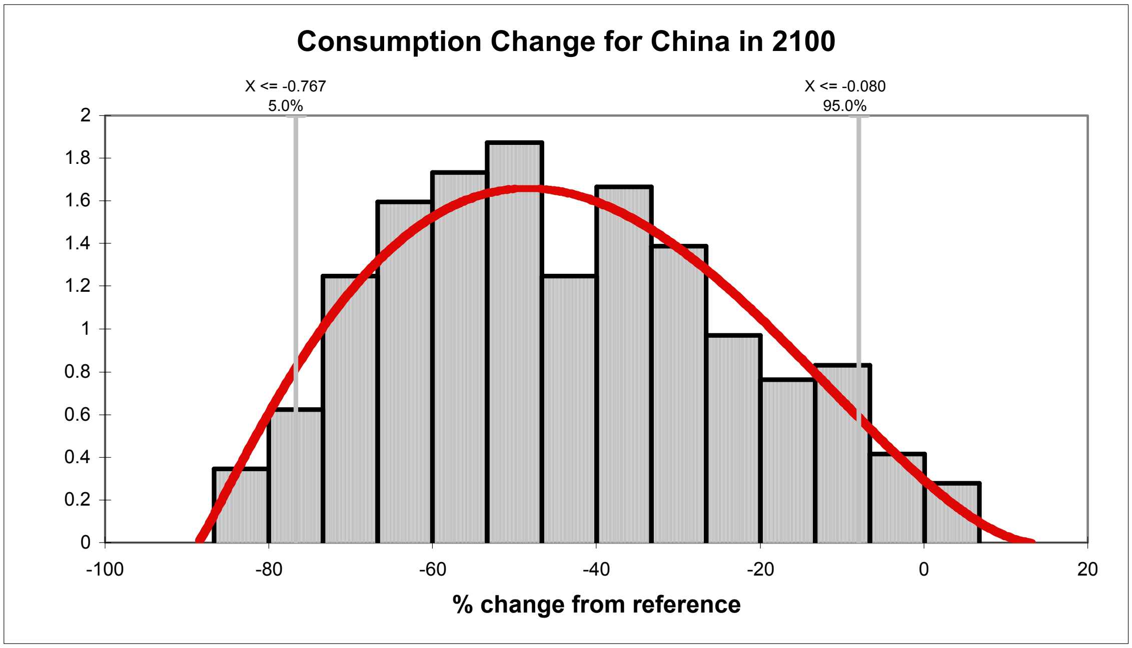


Figure 17 – Distribution of welfare changes for China in 2100.

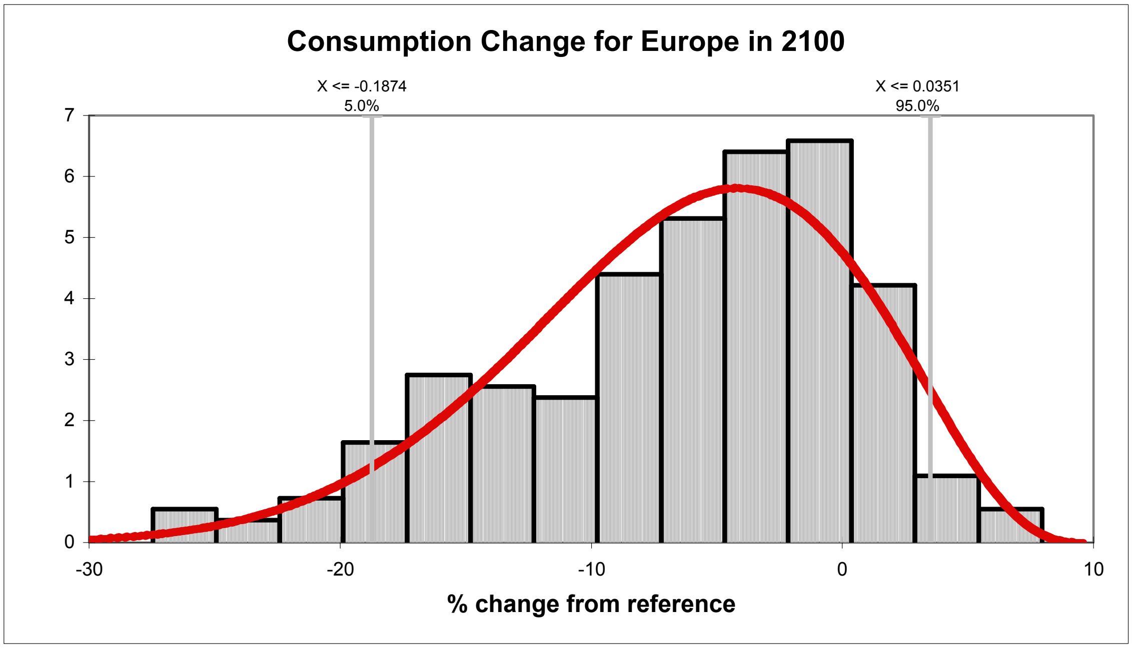


Figure 18 – Distribution of welfare changes for the European Union in 2100.

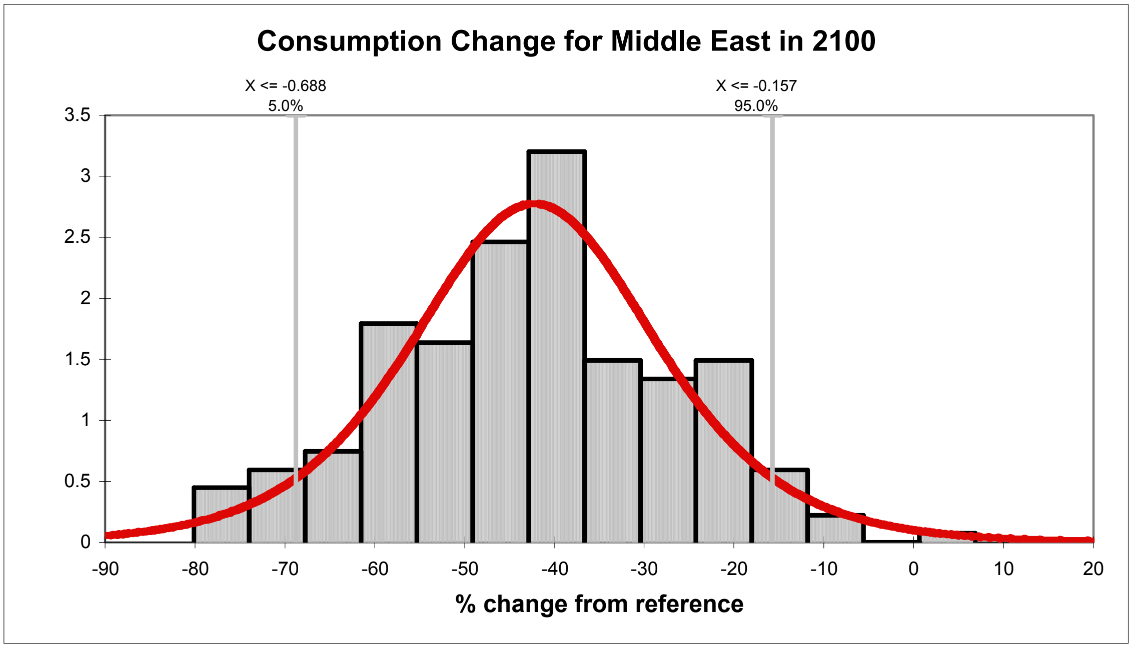


Figure 19 – Distribution of welfare changes for the Middle East in 2100.

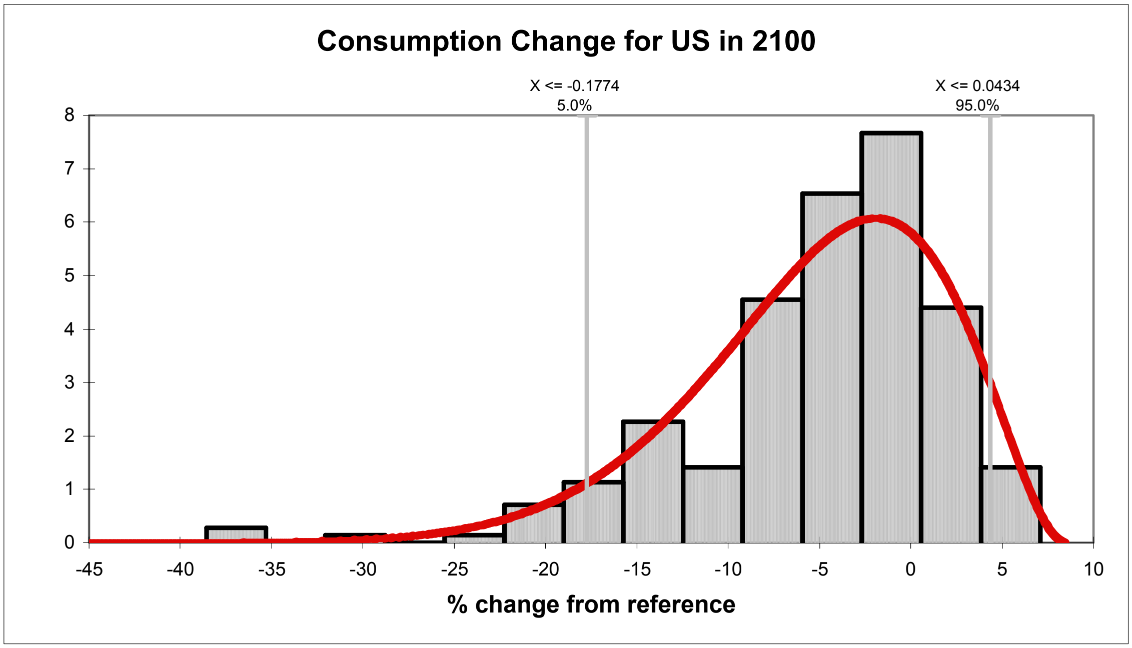


Figure 20 – Distribution of welfare changes for the United States in 2100.

4.5 – Comparison of 550 ppmv and 650 ppmv policies

The 650 ppmv stabilization policy results are qualitatively similar to the 550 ppmv policy. For instance, uncertainty in carbon prices is larger in 2100 than 2020. When examining the welfare change results, China and the Middle East are still impacted harder than the EU or US. The welfare distribution for the 650-policy are shifted right, meaning that welfare changes are less damaging than the 550-policy. This conclusion intuitively makes sense because the carbon constraints are looser. Table 15 compares the details of the two policy scenario distributions.

	550 ppmv Policy (n=216)		**650 ppmv Policy (n=212)**	
Output	**Median**	**90% Confidence Interval**	**Median**	**90% Confidence Interval**
Emissions				
2100	23.7 GtC	17.7 to 33.0 GtC	23.6 GtC	17.6 to 33.0 GtC
2000-2100	351 GtC	281.9 to 462.5 GtC	349 GtC	281.3 to 459.0 GtC
Carbon Price				
2020	$56	$18 to $123	$26	$1 to $70
2100	$3,685	$1,260 to $11,170	$1,263	$368 to $3,624
Welfare Change				
2020 CHN	-0.7%	-2.7% to 1.6%	-0.3%	-2.1% to 2.0%
2020 EUR	0.0%	-0.37% to 0.39%	0.1%	-0.18% to 0.49%
2020 MES	-4.0%	-8.4% to 0.26%	-2.3%	-8.1% to -0.18%
2020 US	0.1%	-0.12% to 0.58%	0.2%	-0.05% to 0.54%
2100 CHN	-44.0%	-76.7% to -8%	-43.2%	-75.1% to 1.6%
2100 EUR	-5.0%	-18.7% to 3.5%	-0.8%	-8.5% to 6.8%
2100 MES	-42.0%	-68.8% to -15.7%	-33.3%	-61.5% to -6.1%
2100 US	-4.0%	-17.7% to 4.3%	-2.8%	-11.5% to 5.9%

Table 15 – Comparison of output PDFs between stabilization scenarios.

5 – Policy implications of economic uncertainty

Uncertainty in climate change predictions is a persistent hurdle for policymakers. In the US, scientific and economic uncertainty has turned policy debates into calls for more research. While some consider this a policy-stalling tactic, more research is needed to more fully understand the uncertainty in climate change projections regardless of present political positions.

Additional research can take a significant amount of time, though, and many regions of the world are pushing forth with mitigation plans. How can policymakers write solid mitigation policy today given the uncertainties in cost/benefit estimates? This chapter explores this question in several steps. First, basic principles for solid climate change policy are outlined. Next, the stabilization policies used in this research are reviewed through a political economy lens. Permit allocation and burden sharing are discussed in search of feasible policy alternatives. Finally, these new policy options are analyzed in an uncertain world.

5.1 – Designing climate change policies for uncertainty

Climate change science and economic research will continue to reveal new information. Climate change policies will need to evolve in light of this new information. Additionally, policies will have to respond to societal changes, such as birth rate fluxes and social priority shifts. A climate change policy will need to have a flexible structure and a built-in review process. to be effective and long lasting.

This research shows that short-term welfare risks are relatively low. Most regions have negligible welfare change and a tight 90% confidence interval in 2020. Public perception of welfare change maybe different, though, if carbon prices are higher than expected. Policymakers should consider that the carbon price uncertainty in 2020 is significant. Mitigation policies should be designed to respond to possible high carbon prices and unforeseen ramifications (e.g., public outcry) that may undermine policy support.

In the longer-term, policy flexibility will be more important because economic risks increase. A policy process should assess and respond to new economic and scientific information, thus managing the volatility of long-term uncertainty. One climate change policy that implements this approach is the UN Framework Convention on Climate Change. The Convention sets forth core principles but allows the policy mechanisms to change over time. The Kyoto Protocol is the first implementation agreement, but other protocols will likely be passed. These new protocols will be informed with the latest climate change research.

Judging how the market will respond is difficult when designing flexible environmental policies. Markets generally prefer policy and regulatory stability that allows for long-term financial planning. A flexible climate policy could send mixed signals to the market. This market problem is complex and beyond the scope of this research.

5.2 – Using permit allocation and side payments to build consensus

Climate change is not caused by GHG emissions of a single country but by total worldwide emissions. There are many different ways to allocate emissions among countries to reach a stabilization target. The allocation scheme of a particular policy defines how the policy's burden is shared.

The stabilization policies used in this research allocated permits based on a progressively higher carbon tax. The initial carbon tax price grew at a 5% discount rate. The emissions path generated by the tax policy was then convert into carbon quotas. Regions were assigned tradable carbon permits equal to their quota. As shown in the welfare sections of Chapter 4, some regions had larger welfare decreases than others using this allocation method.

Other permit allocation schemes could have reached the same stabilization targets. For instance, permits could be allocated using a formula that considers likely economic growth rates, disproportionately giving permits to countries growing faster. Another method might assign permits based on the exports of a country. Regions such as the Middle East would be allocated more permits to offset likely terms of trade welfare losses. Such an allocation could build mitigation policy support by equalizing economic risks and offsetting potential economic burdens (Babiker and Jacoby, 1999; Babiker *et al.*, 2000).

Another policy method to share economic risks among regions is direct monetary payments (Babiker *et al.*, 2000). Economic side payments from the US to China, for instance, might enable China to agree to a stabilization policy that would otherwise be politically infeasible. If a payment scheme were created using the numbers generated by this research, the US in 2100 would pay China a median value of $1,230 billion dollars (1997 $; 90% confidence interval of -$346 to $101 billion dollars). This amount would make China welfare-neutral under the stabilization policy and only decrease US economic welfare by 1.8% (US Welfare distribution has a median of $67,4500 and a 90% confidence interval of $5,030 to $8,660 billion dollars). This side payment calculation does not account for general equilibrium effects, specifically impacts on US welfare.

5.3 – Permit allocation and direct payment under uncertainty

Uncertainty in economic predications makes side payments and permit allocation schemes more difficult. Policies could set fixed payments or permit allocations, but this might create unexpected welfare changes. Regions that grow slower than expected will receive payments/permits larger than their economic harm. The stabilization policy would actually increase their welfare above a no-policy world. Conversely, countries making payments (or surrendering permits) would be harmed more than necessary by the fixed policy.

Uncertainty complicates compensation scheme negotiations. Agreeing upon an economic baseline for the payments will prove challenging because of the economic risks of being locked-in. Economic baselines could be indexed (i.e., to growth rates) and the payments recalculated, but renegotiating might also be politically infeasible.

6 – Conclusions and Follow-on Research

Stabilization policy costs are important because policymakers use a cost/benefit framework to analyze policy options. Economic modelers make assumptions of key parameters that can dramatically affect cost estimates. This research exposes some of the uncertainties of the EPPA4 model and their policy implications.

The Monte Carlo simulation results show that the structure of stabilization policy regulations has regional economic welfare effects. Carbon permits allocated by a tax-based emissions path favored energy importers with developed economies (e.g., the US and the EU). Countries with energy-intensive economies (e.g., China) will likely have negative welfare changes because of strict carbon policy constraints. Oil exporters (e.g., the Middle East) will also be negatively impacted because of terms of trade fluxes.

These insights have implications for stabilization policy design. The uncertainty surrounding economic projections expose some countries to larger economic risks. Policies could be designed to share risks by implementing different permit allocation methods. Direct payments are another means to compensate countries disproportionately disadvantaged by a stabilization policy.

This research was limited by time by time and not questions. Cost uncertainty can be explored in many additional ways, either by modifying this thesis' methodology or by focusing on other forms of uncertainty. The following sections details additional research suggestions.

Proportional reduction of non-carbon dioxide gases

The non-carbon dioxide gases (i.e., methane, etc.) were regulated by setting a 2100 target and allocated quotas based on a linear reduction path. Further research could explore different emission allocation schemes. One method might be to reduce these gases based proportional reductions of carbon dioxide. For instance, a carbon tax policy could be used to reduce future carbon emissions from the reference case. The same proportional carbon reduction path could then be assigned to non-carbon dioxide gases. This might make the non-CO_2 allocation scheme less arbitrary and also increase the solvability of the EPPA4 model.

Review and update the parameter distributions

With the scope of this thesis, it was necessary to adopt many of the parameter PDFs developed by Cossa (2004) without substantial changes. In follow-on research, the PDFs should be review to make sure the fit type is logical (i.e., no possibility of negative values for non-negative variables).

Additional expert elicitation could be conducted and the latest economic literature should be reviewed for new studies.

Cost uncertainty due to carbon uptake uncertainty

This research exposed economic uncertainties in a hypothetical world of climate certainty. The stabilization policies were assumed to reach their respective targets as long as carbon emissions were constrained appropriately. Another economic uncertainty study could vary a carbon uptake uncertainty parameter. The emission quotas would be adjusted appropriately to account for changes in carbon uptake using a reduced form atmospheric concentration equation. By introducing uptake uncertainty, the economic costs due to climate science uncertainty could be explored.

Alternative permit allocation schemes

Permit allocation schemes directly affect regional economic welfare impacts of a policy. Additional research might compare various allocation methods (with global emissions following the 5% tax path). Some possible methods of allocation include giving energy-intensive regions more permits to allow for growth and transferring permits from OECD countries to the developing countries to make them welfare neutral.

Update population trends

The population trends used in the EPPA default case and for this research are based on the UN 2000 population projections. These trends have been updated by the UN to reflect lower fertility rates in many countries. Other groups, such as IIASA, have also published lower population projections that those currently being used. Further research should use an updated projection, which will likely lower worldwide carbon emissions.

Doubling of vintaging elasticities

There are two parameters ("siggv" in the model) that describe the elasticity in vintaging capital stocks. A sensitivity study could be conducted to see how model output is affected. One suggestion is to compare a double of the parameter values.

Urban Air Pollutants

When designing stabilization scenarios for this research, care was taken to prescribe emission reductions for all GHGs. EPPA4 also predicts emissions of non-GHGs, including CO, PM_{10}, SO_2, and other urban air pollutants. Other non-climate change policies (e.g., the Clean Air Act in the US) regulate these gases because of their negative environmental and health effects.

Urban air pollutant regulations were developed independently of climate change policies and will likely be uncoupled in the near-term. Because of their independence from any particular climate policy scenario, the emissions paths of these gases should be reflected not in a policy case, but in the reference case of the EPPA4 model. Urban air pollutants will likely follow their ever-tightening historical trends for OECD countries and become increasing regulated in non-OECD countries. China, for instance, is lowering urban air pollution even in the absence of a climate change policy.

The urban air pollution restrictions in the reference case used for this research may need to be updated. The Joint Program recently did an econometric study (Asadoorian, unpublished) of past urban air pollution trends. The reference case uses these new statistical trends, but there has been no uncertainty study to explore these new numbers. A simple comparison between the historical trends and twice (2X) the historical emission reduction rate might shed some light on how non-GHG regulation affects climate change mitigation costs (i.e., one Monte Carlo batch with 1X reductions compared with another 250-run batch with 2X reductions.

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