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Analyzing Impacts of Climate Change on Energy Market using Bottom-up and Top-down Models

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ANALYZING IMPACTS OF CLIMATE CHANGE ON ENERGY MARKET USING BOTTOM-UP AND TOP-DOWN MODELS

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by

Duan Zhang

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Abstract

Analyzing Impacts of Climate Change on Energy Market using Bottom-up and Top-down models

by

Duan Zhang

With the growing concern about the effects of climate change, various policies have been proposed or implemented in the United States to limit its greenhouse gas emissions. For example, in 2015, the Obama government has proposed Clean Power Plan (CPP), aiming to reduce carbon pollution by shifting electric power sector toward cleaner energy sources. This is coupled with an increased attention by research communities, government, and the power sector on exploring resilience options and adaptation measures to climate change impacts. In order to implement cost-effective resilience options, it is important for the regional planner and policymakers to understand not only the local economic impacts of climate-change-induced hazards, but also the spillover effect to other sectors and regions.

The thesis focuses on two main themes. The first theme involves examining two types of emission trading programs considered under the CPP: a mass-based cap-and-trade (C&T) program and a performance-based trading program. While a mass-based program sets a total emission cap for a region, a performance-based program under the CPP relies on trading the emission rate credits (ERCs), which represent an equivalent MWh of energy generated from or saved by zero associated CO_2 emissions, to reduce emission costs. The proposed research examines the theoretical properties of the performance-based policy and compares its market

performance to a traditional mass-based C&T program using bottom-up simulation models that account for transmission and technology heterogeneity. The second theme entails developing a top-down computable general equilibrium (CGE) model with bilateral commodity trade flow to investigate the regional economic impacts of climate-change-induced extreme weather events, such as sea-level rise, with a focus on natural gas sector in the northern California region.

Dedicated to my beloved family,

for their unconditional support throughout my studies.

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Chapter 1

Introduction

1.1 Introduction and Background

Climate change has already led to observable impact on the environment. The impacts extend beyond a pure increase in temperature, affecting ecosystems and communities in the United States and around the world. The impacts include rising temperature, greater climate variability, changes in precipitation, more droughts and heat waves, stronger and more intensive hurricanes, etc (US GCRP, 2017). Particularly, sea level is projected to rise another 1 to 4 feet by 2100, resulted from melting land ice and thermal expansion of seawater. The intergovernmental Panel of Climate Change (IPCC) predicts an increase in global mean temperature of less than 2.5 to 10 degrees Fahrenheit above 1990 levels over the next century (Stocker et al., 2013). In that case, the impact of climate change on the society and environment is likely to be even more severe.

United States has been working at the front line to combat climate change by adopting mitigation and abatement policies. However, the U.S. climate policy has been driven mainly by state or regional effort, such as the Regional Greenhouse Gas Initiative (RGGI) in the northeast United States and California AB 32. RGGI is the first mandatory multi-state carbon emission Cap-and-trade (C&T) program to reduce emissions from power-sector sources, which was implemented in year 2009 (RGGI). The plan consists of individual CO_2 budget trading programs in each RGGI state, which together create a tradable regional market for CO_2 allowances. California's program represents the first multi-sector C&T program in the United States and was implemented in 2012, including large electric power plants and large industrial plants at first, with inclusion of other sectors in the following phases. Other than C&T programs, complementary policies, which are non-price instruments that regulate emission reductions, are also widely adopted, such as the Renewable Portfolio Standard, energy efficiency programs, and demand-side management.

In order to evaluate climate change mitigation strategies and set appropriate emission reduction targets, policymakers need to carefully evaluate the abatement cost and economic impact. Quantitative modeling can support the understanding of cost and economic impact of different strategies for GHG emissions and it plays a prominent role in climate policy debate (Peace and Weyant, 2008). Among different industries that contribute significantly to GHG emissions, the electricity sector has drawn considerable attention from policymakers and research communities. In 2017, electricity production generates the second largest share of greenhouse gas emissions (27.5%) and 62.9% of electricity generation comes from burning fossil fuels, mostly coal and natural gas (US EPA, 2018). Compared to other large GHG emission contributing sectors, such as transportation and industry(29% and 22%, respectively), the centralized nature of large-sized fossil fuel burning generation makes it more practical to implement and achieve carbon emission reduction goals. Bottom-up process-engineering models help support strategic decision-making and can help to achieve an efficient transition to a low-carbon energy system.

While bottom-up process-engineering models in the electricity sector are widely used in climate-related policy study, with a special focus on the electricity sector, another stream of climate change-related research focuses on applying top-down macroeconomic models to capture the economy-wide feedbacks on prices, commodity and factor substitution, income, and economic welfare. Unlike bottom-up models with explicit technological representation for electricity sector, top-down models neglect the details of technology but represent the interaction of different markets by exploring the substitution among resources. The difference in the structure and scope of bottom-up and top-down models indicates that each type of model has its own advantage in addressing different subsets of research questions related to climate and energy policy studies. Top-down models are well developed to assess the macroeconomic cost of carbon emission abatement since the cross-sectoral and cross-region spill-over effect are fully accounted for. Bottom-up models, on the other hand, are commonly used to explore the impacts of carbon emission constraints on the energy technology portfolio of electricity system, in order to identify lowest-cost abatement opportunities or design energy policies such as technology-based subsidies or emission regulations (Wing et al., 2008).

Computable General Equilibrium (CGE) and Leontief Input/Output (IO) models are two most commonly used top-down models (Wene, 1996). CGE models are constructed as a system of simultaneous equations derived from the first-order-conditions of agents' optimization problems. Economic agents, such as households, firms, and government, make their decisions about their economic activities based on prices prevailing in the market, which are endogenously determined. Similar to CGE models, input-output models capture all the monetary market transactions between industries and final consumers. They allow modelers to examine the detailed representation of a region's industrial structure and keep track of how changes in some sectors of an economy affect other sectors in the region. The biggest difference between an CGE model and an Leontief Input-Output model is that CGE models account for substitution effects among industrial production inputs, among consumer's final choices, as well as imports and exports with local goods for Armington composite. Leontief models, on the other hand, capture the linear relationship of sales between industries for intermediate use. A squared matrix of inter-industry transactions, called the transactions matrix, is the heart of an input-output model. In this matrix all the monetary transactions between businesses in different sectors are recorded. The development of an CGE model relies on the inputs from a Social Accounting Matrix, which entails a more comprehensive list data. In addition to the transactions matrix, SAM also requires monetary flow between industry and institutions, such as import/exports, investment, government.

The CGE models are one of the most common tools based on a top-down modeling framework to analyze the long-term economic implications of climate change policy (Wang and Chen, 2006). They are widely used to study the impacts of climate-change-induced hazards. An extensive list of applications using CGE models to evaluate the impacts of sea-level rise could be found in the literature (Darwin and Tol, 2001; Joshi et al., 2016;Bosello et al., 2012; Pycroft et al., 2016). Among various climate-induced hazard, sea-level rise is likely to pose significant risks on the natural gas system. The key gas facilities that might be impacted by sea-level rise and storm surge include compression stations and regulation stations. Operation failure of the key facilities will limit end users' access to a reliable supply of natural gas. Being able to foresee the impacts of sea-level rise on key natural gas facilities will not only help us identify the facilities at risk, but also serve as the basis for developing climate change resilience options. By developing an CGE model that captures the interaction among sectors and regions, the researcher is able to quantify the spill-over impact of sea-level rise on the gas system.

1.2 Research Objective and Contribution

The principal objective of my research is to study the impacts of climate change and energy policies on the power sector and regional economy by leveraging the strength of bottom-up and top-down models. The dissertation focuses on two themes.

In the first theme, the research analyzes the economic outcomes and efficiency implications of the proposed Federal Clean Power Plan (CPP) by considering the interactions between power and the emission permit trading markets. Bottom-up market equilibrium models that allow for interactions of multiple markets are analyzed. The richness of technological details embedded in bottom-up models allows models to be carefully tailored to specific time horizons, geographic scope, technologies, and market conditions. The detailed model specifications also make it widely applicable to answer various energy policy questions by conducting economic and welfare analysis.

While the models in the thesis are applied to study the interation between CO_2 emission trading markets and electricity markets, they could easily be extended to analyze multiple non-market-based energy regulations, such as carbon tax or renewable portfolio standards (RPS). Moreover, whereas social welfare implications are studied under carbon markets, the model could also be used to quantify other economic impacts, such as electricity prices and market efficiency, under different policy scenarios and market structures. The model formulation accounts for carbon policies both in mass-based C&T format, and under performance-based emission rate structure. The model formulation equivalence developed between two policies is especially important for analyzing performance-based policy and the modeling approach could be easily extended to other performance-based energy regulations, such as Low Carbon Fuel Standard (LCFS) in California.

The second theme focuses on developing a regional CGE model with detailed spatial resolution of the northern California region in order to understand how climate-change induced hazards, e.g., sea-level rising, will impact the regional economy through service disruptions of gas suppliers. Climate change characterized by increased ambient temperatures is likely to cause thermal expansion and melting of land ice, which leads to sea-level rise. Presumably, sea-level rise will pose some natural gas facilities at risk and impact the access of natural gas for coastal population. Being able to identify and quantify the negative impacts on the gas system and the rest of economy caused by sea-level rise will help inform better decisions on developing mitigation plans and resilience options. A CGE model is well suited for this purpose by accounting for market interactions among energy and other markets.

Unlike bottom-up models that fail to capture the interaction among energy system and the rest of the economy, top-down CGE models explicitly represent the micro-economic behavior of the market participants, but neglect the technical details in the energy sector. Top-down models are commonly used for assessing the macroeconomic costs of carbon emission abatement and its economy-wide impacts on prices, commodity and factor substitution, income and economic welfare.

To summarize, the thesis focuses on (1) understanding the market outcomes and efficiency of CPP, and (2) quantifying medium-run economic impacts of climate-change-induced hazards on the northern California natural gas system.

1.3 Outline of Dissertation

This thesis is organized as follows. In Chapter 2, I briefly review the modeling approaches. Special attention is given to describe the difference between the top-down and bottom-up modeling approaches. I present, in Chapter 3, the study on inefficiencies of CPP using bottom-up models by answering the questions identified in Theme 1. Chapter 4 discusses the analysis of Theme 2: climate-change-induced economic impacts of the California natural gas system using top-down CGE model. The detailed model formulations and results are presented. Finally, I discuss the integration of bottom-up and top-down models in Chapter 5. The proofs and detailed data description of Theme 1 and extensive results for Theme 2 are documented in the Appendix.

Chapter 2

Approaches/Methods

2.1 Bottom-up Model

Energy models based on a bottom-up formulation, also known as process-based engineering-economic models, usually embody technical and engineering details and also allows for modeling of firms' behavior. These models simulate or optimize the operation, investment in power generation by companies and consumption by consumers while accounting for physical systems, e.g., transmission grid, market rules, institutional settings, policies and etc. They are useful and appropriate to be applied to assess changes in technology choices, operations and investment decisions in response to climate-change policies. However, the analysis can only be focused on one sector.

The first part of my research studied the effectiveness and the distributional effects of the proposed CPP policy as well as its impact on the utility sector by (a) establishing a tractable theoretical model (solved with closed-form solution techniques) to generate contestable hypotheses and (b) developing a bottom-up large-scale process-based energy market model calibrated with the PJM electricity market to validate the hypotheses in (a) and quantifying the "magnitude" of impacts in terms of distribution of economics rent among firms, consumers as well the shift of pollution emissions. The results presented in Chapter 3 are based on the following publicly available datasets: i) electricity supply side, the EIA-860 form (Energy Information Administration) contains unit- or boiler- level technology information; EIA-923 form documents fuel cost and other operation information and ii) demand side: consumption or load data can be extracted from PJM website. The model in the baseline is calibrated with EPA CEMS (Continuous Emission Monitoring System), which records hourly operational data, as well as eGrid (Emission & Generation Resource Integrated Database), which contains yearly plant-level operation data.

2.2 Top-down Model

As the name computable general equilibrium (CGE) model suggests: "C" represents that the result is computed numerically; "G" represents that it's a economy-wide general model; and "E" represents that macroeconomic balance is achieved where each optimizing agent has found its best response subject to their budget constraints and all factor and commodity markets are cleared. Top-down CGE (Computable General Equilibrium) models, which are based on calibrated production functions coupled with implied sectoral demand, are commonly used to examine impacts of the whole economy when facing exogenous shocks. The models not only quantify initial market changes induced by exogenous shocks but also simulate their spillover effect to rest of the economy. Income effects are estimated by modeling different market agents, such as households and government. Market agents make their decision on activity level, based on the price information prevailing the the market. With a policy change or market shock, deviation of prices will drive the model to reach new equilibrium, where the supply equals demand for all commodity and factor markets. The models are capable of examining inter-sectoral and regional effects of price changes and demand shifts through supply-demand relationship among all commodities in an economy. The models are not appropriate for analyses of monetary or fiscal policies, owing to the fact that they only focus on relative price changes and flows of goods and services (Hosoe et al., 2010). Compared to bottom-up models, the top-down models lack technological details, which are essential for identifying technology pathways if used for analyses of climate-change mitigation assessment.

This part of the research aims to develop a regional CGE model to address the vulnerability of the Northern California natural gas system when subjecting to climate-change-induced weather events. More specifically, the study models the impacts of sea-level rising that lead to damage either on a specific pipeline or a facility, e.g., compressor stations. The analysis aid in understanding and quantifying the spillover effects of gas supply service disruptions to other sectors and regions. This thesis reports the results of a multi-region multi-sector CGE model calibrated with 2013 IMPLAN data in Chapter 4.

Chapter 3

A Study on Inefficiencies of US Federal Clean Power Plan Using Bottom-up Models

3.1 Background

Historically, the US climate policy has been driven mainly by state or regional effort, such as the Regional Greenhouse Gas Initiative (RGGI) in the northeast United States and California AB 32. One major change recently is the introduction of the Clean Power Plan (CPP) by the Environmental Protection Agency. The plan will reduce carbon pollution by shifting electric power sector toward cleaner energy sources at a steady but achievable pace (US EPA, 2015a). CPP calls for a cut of carbon dioxides (CO_2) emissions from fossil-fueled power plants by around 32% below the 2005 level by 2030. EPA projects that there will be a reduction of

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870 million tons of carbon pollution in year 2030 alone, compared to 2005 baseline level[1] (US EPA, 2015b).

While the proposal establishes state specific targets with various "building blocks" that lay out possible reduction strategies, it leaves states and the electric power sector with considerable flexibility as for how to achieve their goals. More specifically, a state can decide to adopt either a default "performance-based" standard where pounds or tons of CO_2 emission per megawatt hour electricity generated is measured, or an equivalent "mass-based" standard, such as in a cap-and-trade (C&T) regime based on their projection of GDP growth. The mass-based standard and performance-based standard are implemented in very different ways.

Under a mass-based cap-and-trade policy, a cap is imposed on each state to limit its overall emissions from the power sector in the permit program. Generators will need to purchase allowances that could offset their total carbon emissions. Power generators will face the same abatement cost under the same C&T program, no matter what technology they deploy. C&T programs for the power sector have already been designed and operated in several parts of the United States, such as RGGI (RGGI, 2013) and California AB 32 (CA EPA, 2006). RGGI is the first mandatory multi-state carbon emission C&T program to reduce emissions from power-sector sources, which was implemented in year 2009 (RGGI). The plan consists of individual CO_2 budget trading programs in each RGGI state, which together create a tradable regional market for CO_2 allowances. The proceeds, generated mainly from allowances auctions, are reinvested in strategic energy and

[1] Currently, the enforcement of the plan is halted by Supreme Court until a lower court rules in the lawsuit against plan (Wolf, 2016). Under Trump's new administration, the future of the policy is even more obscure. On March 28, 2017, President Trump signed an executive order mandating the EPA to review the plan (Davenport and Rubin, 2017). On June 1, he announced U.S. withdrawal from the Paris Agreement (Cama and Henry, 2017). Although CPP faces legal challenges, its theoretical property remains to be interesting to academic communities.

consumer benefit programs. The program allows market forces to determine the most efficient and economic means of reducing emissions and create incentives for investments in clean energy. As a result, through 2013, the RGGI states have experienced a reduction of over 40 percent in power sector CO_2 pollution since 2005 (RGGI, 2015). On the other hand, California's program represents the first multi-sector C&T program in the United States and is implemented in 2012, including large electric power plants and large industrial plants at first, with inclusion of other sectors in the following phases. It aims to reduce greenhouse gas (GHG) emissions from regulated entities by more than 16 percent between 2013 and 2020 and reduce total GHG emissions to 1990 levels by 2020 (CARB).

Unlike a mass-based program that fixes the total emission, a performance-based policy may be met by either reducing total emission, or increasing energy output, especially from low-emitting or non-emitting sources. Performance-based emission reduction program is not as common in the United States. In the final rule of CPP that EPA issued on August 3, 2015, EPA proposed a model performance-based trading rule, i.e., emission rate credits (ERC) trading scheme. Under performance-based standards, ERCs are created to allow the plants to adjust (offset) their actual emission rate downward to meet the state-level emission rate goal by purchasing ERCs from market. In other words, ERC is a tradable instrument that represents the MWh of actual energy generated or saved with zero associated CO_2 emissions. The final model rule could be adopted by a state, and will also serve as a backstop. That is, if a state fails to submit a satisfactory plan, EPA will choose to impose it as a performance-based federal plan for those states.

One concern that has received increasing attention is the efficiency of a performance-based policy in comparison to a mass-based policy when subjecting them to the same emission level. Economic theory suggests that the mass- and performance-based programs would provide economic incentives that might alter a firm's production decisions in a very different way (Bushnell et al., 2015). Under a mass-based policy, the efficiency is achieved if all the units subjecting to the same emission cap face the same emission abatement cost, regardless of their generation technology. Yet, under a performance-based program, different technologies when facing an equal ERC price are expected to have different abatement costs. Therefore, efficiency under a performance-based program is achieved only if the firms have the same technology (i.e., with same emission rate) and subject to the same abatement cost across the region.

Furthermore, whereas the regulatory body at state level as well as the industry might value the "flexibility" to a great extent, the fact that the territory of a regional power/electric market, such as PJM (Pennsylvania-Jersey-Maryland) or NEISO (New England Independent System Operator), typically goes beyond the state boundary and encompasses a number of states makes it challenging to evaluate the effectiveness of the policy. CPP allows both regional and state-by-state implementation under performance-based regulation. With a regional plan, states are subject to a uniform performance-based standard, and therefore form a regional market to explicitly trade ERCs. While with a state-by-state implementation, each state is subject to its own performance-based standard. They may still trade permits implicitly within the regional power market[2]. Even in the simplest case that allows explicitly trading of emission permits, the fact that plants

[2]Mathematically, it is assumed that a generator h with an emission rate of E_h generates x_{hi} MWh electricity to state i. Regional performance-based policy requires all states subjecting to a regional rate E^{rate}, i.e., $\frac{\sum_{hi} E_h x_{hi}}{\sum_{hi} x_{hi}} \leq E^{\text{rate}}$. While state-by-state performance-based policy sets state-by-state emission rate targets E_i^{rate}, and the emission constraint is $\frac{\sum_h E_h x_{hi}}{\sum_h x_{hi}} \leq E_i^{\text{rate}}, \forall i$.

with different emission rates will incur a different abatement cost suggests that a performance-based policy is unlikely to be efficient. For a situation that allows trading implicitly, the market outcome is likely to deviate further away from an efficient outcome when the equilibrium permit price differs by states. Given that producers are allowed to sell power to consumers in other states in a regional market, evaluating policy performance and the resulting welfare distribution is a challenging problem as it is complicated by state's choice of policy.

This section explores the theoretical properties of the performance-based policy. The analysis proceed in three ways. First, an analytical model is developed with a two-state setting to explore the conditions under which the permit price between these two states will converge. Second, a three-state simulation-based model that accounts for transmission and heterogeneity of technologies is developed to evaluate the market outcome when a) multiple states are subject to a regional performance-based policy, b) multiple states are subject to state-by-state performance-based policy, and c) states are subject to a traditional mass-based policy. The comparison is made possible by limiting analysis to the case that each scenario is subject to the same total emission. This allows us to bypass calculating "cost of pollution" in welfare analysis. Third, a PJM electricity market calibrated with 2012 data is simulated to quantify the impact on social surplus.

In this section, the analysis have following findings. First, our theoretical analysis finds that permit prices of different states will converge if suppliers opt to sell power to all states. The analysis also shows that the difference in power prices between states can be expressed as a function of permit price as well as default performance rate. Second, our simulation results suggest that performance-based regulation effectively inflates market demand (owing to the cross-subsidy property of performance-based program that subsidizes high cost, low emission units) and increases the permit prices compared to the mass-based regulation. Third, it is concluded that the welfare comparisons between the regional and state-by-state performance-based policy is ambiguous. Finally, PJM-based simulation indicates that a mass-based policy remains most efficient, even only marginally when compared to performance-based policies. In particular, most consumers surplus gains under performance-based policies owing to cross-subsidy effects are negated by decline in producers surplus and allowance rents transferred to the government.

The remainder of the section is organized as follows. In Section 3.2, the chapter provides a brief literature review on the studies related to CPP or to performance-based policy in general. Section 3.3 presents an analytical model to study the effects of a state-by-state performance-based emission program. Formulation of models that account for transmission and heterogeneity of technologies as well as institutional setting of policies are presented in Section 3.4. The model is then applied in Section 3.4 to a simple three-state numerical study and to a PJM-based analysis in sections 3.5 and 3.6, respectively. Section 3.7 concludes our findings and addresses our future work.

3.2 Literature Review

There is a growing interest in studying performance-based policy. Unlike a mass-based C&T that fixes the total emission, a performance-based target may be met by either reducing the total emission, or increasing the energy output, especially from low-emitting or non-emitting sources. By inflating electricity output level, the aggregate emission may increase or decrease. Holland et al. (2009) theoretically study the performance-based carbon standard at transportation sector, i.e., the low carbon fuel standard (LCFS). They show the possibility that increases in carbon pollution from ramping up production of the low carbon fuel can outweigh decreases in high carbon fuel production, resulting in a possible increase in net carbon emissions. Since energy efficiency programs are allowed to generate ERCs to show the avoided electricity generation under performance-based CPP, overestimation of gains from energy efficiency programs might reduce the stringency of a performance-based standard (Fowlie et al., 2014). That is, a state emission rate goal might be fulfilled without lowering the total carbon emission. This suggests that the welfare effects for such a program are undetermined. Several studies focus on illustrating inefficiency in performance-based carbon policies. For example, Holland et al. (2015) show that LCFS cannot be efficient, and the efficiency loss when comparing to a mass-based C&T policy is quite large. The reason is that the performance-based policy acts as an implicit tax on technology with a carbon intensity above the standard, but as a subsidy for technology with a carbon intensity below the standard. The *efficient* principle, which requires any fuel emitting carbon to be taxed but not subsidized, could not be attained. Bushnell et al. (2015) analyze the potential effects of the CPP policy options, i.e., performance- or mass-based policy, in terms of electricity market outcomes and state adoption incentives. They conclude that adopting performance-based regulation by states may not result in an efficient market supply of energy and lead to varied abatement costs and less cost-effective market outcome, because performance-based regulation may only be efficient if carbon price is equal to the social cost of carbon and the rate standard is equal across all the states. Through a corporative game theoretical approach, they show that adopting a performance-based regulation is a dominant strategy for states from both consumer's and producer's point of view. In a long-run analysis, de Vries et al. (2014) show that performance-based policy generates lower welfare than mass-based policy because the output subsidy under performance-based policy drastically increases the size of clean energy. Holland (2012) also concludes that performance-based cannot attain the first-best outcome whereas an emission cap can. However when there is emission leakage, he shows that performance-based policy could in fact dominate second-best mass-based policy, since the implicit output subsidy can prevent leakage which might have occurred under an emission cap.

As a relatively new policy, studies on CPP, are also limited until recently. Palmer and Paul (2015) evaluate the performance-based trading standard and mass-based policies using several criteria, including cost-effectiveness, distributional consequences, administrative burden and other environmental outcomes. They conclude that allocation of allowances and scope of technologies covered by the policy greatly affect the economic efficiency and distributional consequences. They argue that the most economically efficient policy is one that (1) imposes an explicit price on CO_2 emissions, (2) does not incorporate an incentive for either electricity generation or consumption as a performance-based standard does, and (3) makes a productive use of allowance revenue. They draw a similar conclusion with Bushnell et al. (2015) that mass-based options are likely the most economically efficient policies. Davis et al. (2016) discuss the CPP's "building blocks" or decarbonization strategies in details and study their effects of emission reduction for different states. With an analysis of US electricity generation data for the past fourteen years, they examine to what extent the CPP targets may impact the most pollution-intensive part of states' generation portfolios. Gerarden et al. (2016) study the interaction between an upstream (e.g., producers) policy of incorporating a carbon adder into federal coal royalties, and downstream (e.g., consumers) emission regulation of CPP. They apply an integrated planning model to show that if CPP is binding, the royalty adder would reduce the allowance price because it bears some of the compliance cost of the CPP program. Furthermore, the adder produces additional emission reductions by reducing leakage, and reduces the wholesale power prices under a mass-based CPP with a reverse effect under a performance-based policy.[3] On the other hand, top-down modeling approaches are also deployed to analyze the policy impact of CPP. For example, Cai and Arora (2015) simulate CPP with a computable general equilibrium model and show that not considering the heterogeneity of generation technologies would underestimate the size of the carbon price but overestimate the economic cost of mitigation.

This chapter contributes to the current literature on CPP or to performance-based policies in general in several facets. First, to our best knowledge, the work is the first one that explicitly derives conditions under which an efficient or inefficient market outcome is achieved under a performance-based program. Second, this study establishes the equivalence between a mass-based trading and an ERC-based trading market. These equivalence allows to compare market outcomes between these two policies in the simulation section. Third, the simulation model compares the market efficiency under mass-based, regional and state-by-state performance-based policy in terms of surplus, market demand, permit prices and power prices, etc. Particularly, the market outcomes are explored under a state-by-state policy and the chapter highlights the fact that the permit prices among different states might diverge or converge.

[3]Similar findings from Tsao et al. (2011) regarding policy interaction between C&T and Renewable Portfolio Standard are illustrated that making one policy more stringent would weaken the market incentive, which the other policy relies upon to attain its intended policy target.

3.3 Analytical Model

3.3.1 Equivalence between ERC and Mass-based Permit Program

EPA established the equivalence between performance- and mass-based goals by multiplying the state's emission rate target with the anticipated electricity production accounting for economic growth factors that affect electricity consumption. Under a performance-based program, the trading instrument in the associated market is ERC with a unit of \$ per MWh ERC. On the other hand, a more intuitive allowance under a mass-based policy will be in \$/ton. The analysis now establishes the equivalence between a ERC and a mass-based permit trading program assuming that two programs are subject to the same constraint on aggregated emissions. First, consider the EPA's CPP rule, ERC of a generator h with an emission rate of E_h and sells 1 MWh of its generated energy to state i whose policy rate is E_i^{rate} is defined as the MWh of actual energy generated or saved with a zero-associated CO_2 emission or $\frac{E_i^{\text{rate}}-E_h}{E_i^{\text{rate}}}$. Thus, the ERC produced by this generator for selling x_{hi} MWh of energy becomes

$$\text{ERC}_{hi} = (\frac{E_i^{\text{rate}} - E_h}{E_i^{\text{rate}}})x_{hi}. \tag{3.1}$$

Intuitively, in order to meet the performance-based emission reduction goal, state i is required to show compliance with the regulation. So the actual emission rate for each state, measured by dividing the total emission mass by the total energy output, should be less than the default emission rate determined by the regulation.

$$\frac{\sum_h E_h x_{hi}}{\sum_h x_{hi}} \leq E_i^{\text{rate}} \qquad \forall i \tag{3.2}$$

Rearranging (3.2), an equivalent formulation is obtained as follows:

$$\sum_{h}(E_h - E_i^{\text{rate}})x_{hi} \leq 0 \qquad \forall i \qquad (p_i^{CO2} : \$/ton), \tag{3.3}$$

When $E_i^{\text{rate}} \times x_{hi}$ is substituted by a fixed emission cap, the dual variable for this constraint is the price of CO_2 emission permit under a mass-based program. If further dividing the two sides of the inequality (3.3) with the default emission rate standard for state i, and reverse the sign of the numerator, it yields the following expression:

$$\sum_{h}(\frac{E_i^{\text{rate}} - E_h}{E_i^{\text{rate}}})x_{hi} \geq 0 \qquad \forall i \tag{3.4}$$

Or equivalently, with (3.1), it could be rewrote (3.4) as follows.

$$\sum_{h} \text{ERC}_{hi} \geq 0 \qquad \forall i \qquad (p_i^{erc} : \$/MWh) \tag{3.5}$$

Equation (3.5) states that in order to comply with the performance-based CPP policy, a state will need to collect a non-negative amount of ERCs. The model therefore establishes the equivalence of the ERC permit price (\$/MWh) and mass-based permit price (\$/ton) for state i when both policies are subject to same level of aggregate emissions:

$$p_i^{erc}(\$/MWh) = p_i^{CO2}(\$/ton)E_i^{\text{rate}}(ton/MWh) \tag{3.6}$$

3.3.2 A Simple Two-state Example

With the equivalence of two types of permit trading programs in mind, this analysis considers a two-state model to explore the conditions under which the performance-based policy can be efficient. It is assumed that there is one firm generating electricity in each state, while each state is subject to a state-specific performance-based regulation. As illustrated in Figure 3.1, firm a has one plant at state 1, and firm b has one plant at state 2. The electricity generated is denoted as x_{fij} indicating the amount of power generated by firm $f \in a, b$ is transmitted from state i to state j. States 1 and 2 are subject to its respective performance-based standard E_1 and E_2. The model further uses a function $B_j(q_j)$ to denote gross benefit, where the derivative of benefit function is equal to the electricity price (i.e., $B_j' = P_j$), instead of specifying the inverse demand function at each state. Moreover, $C_f(q_f)$ denotes each firm's cost function to generate electricity. It is assumed that $B_j' > 0$, $B_j'' \leq 0$ and $C_f' > 0$, $C_f' \geq 0$. Consider a social planner's welfare maximization problem as follows:

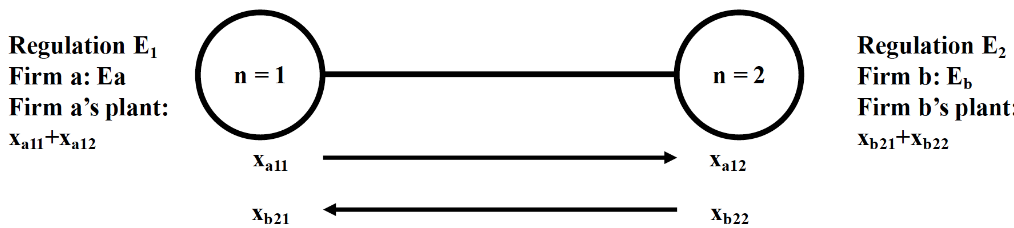


Figure 3.1: Two-state analytical power market illustration

$$\max_{\mathbf{x} \geq \mathbf{0}} \quad B_1(x_{a11} + x_{b21}) + B_2(x_{a12} + x_{b22}) - C_a(x_{a11} + x_{a12}) - C_b(x_{b21} + x_{b22}) \quad (3.7)$$

$$
\begin{aligned}
\text{s.t.} \quad & x_{a11} + x_{a12} \leq X_a && (\rho_a)\\
& x_{b21} + x_{b22} \leq X_b && (\rho_b)\\
& x_{a12} - x_{b21} \leq T && (\lambda^+)\\
& -(x_{a12} - x_{b21}) \leq T && (\lambda^-)\\
& (E_a - E_1)x_{a11} + (E_b - E_1)x_{b21} \leq 0 && (p_1^c)\\
& (E_a - E_2)x_{a12} + (E_b - E_2)x_{b22} \leq 0 && (p_2^c)
\end{aligned}
$$

The objective function in (3.7) is to maximize social welfare by subtracting the total generation cost (last two terms) from the gross benefit (first two terms). There are six constraints associated with the problem with dual variables placed in the parenthesis to right of each constraint. The first two constraints restrict the generation from each firm to its capacity, followed by the transmission capacity constraints. The last two equations ensure that the emission performance-based targets are met for states 1 and 2 with their dual variables p_1^c and p_2^c indicating the permit prices in each state, respectively.

Since the problem formulated is a convex programming problem, a global optimal solution could be found using Karush-Kuhn-Tucker (KKT) conditions. The first-order conditions (FOCs) associated with (3.7) are displayed in (3.8)–(3.15), where the symbol "$\perp$" denotes complementarity. [4]

[4] For two factors $\mathbf{x}$ and $\mathbf{y}$, the expression $\mathbf{0} \leq \mathbf{x} \perp \mathbf{y} \geq \mathbf{0}$ implies that $\mathbf{x} \geq \mathbf{0}$, $\mathbf{y} \geq \mathbf{0}$ and $\mathbf{x}^T\mathbf{y} = 0$.

$$0 \le x_{a11} \perp P_1 - C_a' - \rho_a + p_1^c(E_1 - E_a) \le 0 \tag{3.8}$$

$$0 \le x_{a12} \perp P_2 - C_a' - \rho_a - \lambda^+ + \lambda^- + p_2^c(E_2 - E_a) \le 0 \tag{3.9}$$

$$0 \le x_{b21} \perp P_1 - C_b' - \rho_b + \lambda^+ - \lambda^- + p_1^c(E_1 - E_b) \le 0 \tag{3.10}$$

$$0 \le x_{b22} \perp P_2 - C_b' - \rho_b + p_2^c(E_2 - E_b) \le 0 \tag{3.11}$$

$$0 \le \rho_a \perp x_{a11} + x_{a12} - X_a \le 0 \tag{3.12}$$

$$0 \le \rho_b \perp x_{b21} + x_{b22} - X_b \le 0 \tag{3.13}$$

$$0 \le \lambda^+ \perp x_{a12} - x_{b21} - T \le 0 \tag{3.14}$$

$$0 \le \lambda^- \perp - (x_{a12} - x_{b21}) - T \le 0 \tag{3.15}$$

The equilibrium then can be solved by assuming the last two conditions in (3.7) are binding so that the permit prices, p_1^c and p_2^c, are positive[5]. Combining the FOCs and market clearing conditions (last two constraints of (3.7)), the model could be solved analytically. In total, there are 10 equations and 10 variables including 4 primal variables of generation x_{fij} and 6 dual variables of permit prices p_1^c and p_2^c as well as transmission and capacity constraints. The system is squared since the number of conditions equals the number of unknown variables. The conditions are derived under which the permit prices are equal across these two states.[6]

[5]If they are not binding, the emission constraints will have no impact on the dispatch pattern of the electricity and is, therefore, not of our interest in this analysis.

[6]Although focusing on two firms in the market, the model is readily extended to any number of firms (greater than two). It is viable to add any number of firms by having conditions like (3.8)–(3.9) (firms at state 1) and/or like (3.10)–(3.11) (firms at state 2). The analysis limit the attention to a two-firm situation mainly for the ease of exposition. However, extending to the case of more than two states is likely to be more challenging as it involves loop flows. This analysis therefore relies on the simulation-based approach in Section 4 to study cases with this complication.

Proposition 1. *In the case of (i) or (ii), the price of permit will be equal between these two states or* $p_1^c = p_2^c = p^c$ *holds.*

(i) All the firms have $x_{fij} > 0$ *for all* j .

(ii) At least two firms have $x_{fij} > 0$ *for all* j. *Other firms are either with* $x_{fij} > 0$ *for all* j *or with* $x_{fij} = 0$ *for all* j.

This proposition suggests that if all the generators supply their power to all states in the interconnected system, or at least two are doing so while some other generators are shut down completely, the market is efficient with the same permit prices across the whole regional power market. Consider the permit is one of the input factors that a generator needs to acquire in order to produce output. Intuitively, if a generator finds that the gross margin in a state is higher due to its lower permit cost, it will increase its sales to this state, thereby increasing the permit price of that state.[7]

With (3.6), one can then covert p^c to the performance-based permit price ERC by multiplying it with E_j or $p^c \times E_1$ and $p^c \times E_2$, respectively. This suggests that unless $E_1 = E_2$, the performance-based permit price of ERCs is likely to be different among states. The implication of the proposition is that the performance-based regulation may lead to an efficient market where the emission abatement costs faced by firms at different states are the same only if each state is subject to the same policy target. Otherwise, the efficiency is only realized within the same group of technologies even when the price of the performance-based permit is the same across the whole market.

Proposition 2. *In the case of (iii),* $p_1^c \neq p_2^c$.

[7] Within the framework of locational marginal pricing, the gross margin that can be earned by a generator with a positive sale to all states, including permit cost, will be equal even with transmission congestions.

(iii) Only one firm has $x_{fij} > 0$ for all j, and there exists at least one firm with $x_{fij} > 0$ for some but not all j.

In case (iii), only one generator supplies power to all the states, whereas at least one other generator provides a positive quantity to some states but not to all the remaining states. Follow the same argument as in proposition 1, if one generator finds it economic desirable *not* to supply power to all the states, the permit price then will be different among states. Mathematically, the generators, which supply power to some states but none for others, will create a slack quantity (either positive or negative) from the zero output FOCs in conditions (3.8)–(3.11). (See appendix for the proofs). The positive or negative slackness will prevent equating the permit prices across states in the equilibrium. In this case, the abatement cost (in terms of $/ton) is different for generators with same technologies (emission rate) as long as they are located in different states.[8]

Proposition 3. *In the case of (iv), the impact on permit price is ambiguous. That is, either $p_1^c = p_2^c$ or $p_1^c \neq p_2^c$ is possible.*

(iv) No firm is with $x_{fij} > 0$ for all j. In other words, some firms sell a positive quantity to a subset of states while some firms shut down completely.

In this case, no firm sells a positive output to all states whereas some firms sell a positive quality to some states but not to all the states; some other firms do not produce at all. Analogy to previous discussion, the firms with a positive output will create a slackness in (ϕ in the appendix) their corresponding zero

[8]By a similar deduction, it is also concluded that the following scenario will not constitute a equilibrium: two firms with $x_{fij} > 0$ for all j, and there exists at least one firm with a positive sale to some states. For instance, $x_{a11}, x_{a12} > 0, x_{b21}, x_{b22} > 0, x_{c11} = 0, x_{c12} > 0$ or $x_{c11} > 0, x_{c12} = 0$. Then $p_1^c = p_2^c$ is derived from conditions for firms a and b. But there is also $p_1^c \neq p_2^c$ from conditions for firm c and others. These two permit price conditions are therefore contradicting each other. Thus, it is not an equilibrium to have two or more firms supply power to all the states while some firms supply to only a subset of states.

output FOCs (3.8)–(3.11). The differences in the slackness created by each firm plays a key role for the uncertain outcome with regard to the permit prices. If the slackness is the same for all the firms, the permit price is also the same across the states; otherwise, if there are differences between slackness of firms, the prices will diverge. The market outcome in this case is uncertain.

Proposition 4. *In the case of (i) or (ii) where $p^c_1 = p^c_2 = p^c$, the difference in power price is expressed as $P_1 - P_2 = -\lambda^+ + \lambda^- + p^c(E_2 - E_1)$. If there is no transmission congestion, $P_1 - P_2 = p^c(E_2 - E_1)$.*

It is concluded that when the permit prices across the states are the same for the whole market, the difference in the power price is affected by transmission charges $(-\lambda^+ + \lambda^-)$, uniform permit prices (p^c), as well as difference in performance-based emission regulation between two states $(E_2 - E_1)$. In fact, in absence of p^c or $p^c = 0$, the relationship reduces to the well known principle that difference between a pair of power prices is equal to transmission charge between the two states. Considering a situation with an unlimited transmission capacity so that $\lambda^+ = \lambda^- = 0$, the difference in power prices is only determined by $p^c(E_2 - E_1)$. In other words, even if there is no transmission congestion, power price across states could be different, reflecting varying stringency of performance-based standard among states within an interconnected market, i.e., $P_1 - P_2 = p^c(E_2 - E_1)$. The chapter illustrates this in the two-state simulation in Section 3.5.

3.4 Simulation Model

In the previous section, the study derived the conditions for an efficient emission allowance market analytically. In this section, it focuses on a simulation-based model accounting for transmission network and heterogeneity in generation technology. The model is applied to a simplified three-state case study as well as to a PJM market calibrated with 2012 data. Three-state case study allows us to illustrate the theoretical properties of the policies and explore origin of inefficiency under state-by-state performance-based policy by explicitly analyzing power plants' output decisions, whereas the PJM market simulation illustrates the welfare distribution and ranking of different policy scenarios.

3.4.1 Model Formulation

Mixed Complementarity Formulation

The analysis follows the model of Hobbs (2001) and Chen et al. (2011) , with an additional consideration of ERC trading markets. The model assumes perfect competition in both electricity and permit markets. In particular, the model advances the work by Chen et al. (2011) to account for ERC sales of producer f when selling power from state i to state j.[9] The analysis first presents optimization problem faced by entities in the market: producers, load serving entities (LSEs), and consumers, followed by market clearing conditions that define commodity prices.

Producer f solves its profit-maximization optimization problem by choosing variables x_{fihj}, representing power generated by firm f at plant h in state i trans-

[9]The analysis presents the model herein as each sate is represented by a single node. In reality, a single state can be accounted for by multiple nodes or a single node can encompass more than one state. In the latter case, the modeling technique in Section 6 requires splitting nodes by creating artificial nodes and arcs. More details are discussed in Section 3.6.

mitted to state j. Its optimization problem is formulated as follows:

$$
\begin{aligned}
\underset{x_{fihj}}{\text{Maximize}} \quad & \sum_{i,h\in H_{fi},j} p_{fihj}x_{fihj} - \sum_{i,h\in H_{fi}} C_{fih}(\sum_{j} x_{fihj}) - \sum_{i,h\in H_{fi},j} (w_j - w_i)x_{fihj} \\
\text{s.t.} \quad & \sum_{j} x_{fihj} \le X_{fih} \quad (\rho_{fih}) \qquad \forall i,h \in H_{fi} \qquad (3.16) \\
& x_{fihj} \ge 0 \qquad \forall f,i,h \in H_{fi}, j
\end{aligned}
$$

The three terms in the objective function are total revenue, product cost and transmission charges/revenue, respectively. In addition to non-negativity constraint, the output sales x_{fihj} need to be less than or equal to its capacity (the dual variable associated with the constraint is placed in the parenthesis).

LSE is modeled as deciding procurement quantities z_{fihj} to maximize the "net" benefit on behalf of the consumers.

$$
\begin{aligned}
\underset{z_{fihj}}{\text{Maximize}} \quad & P_j^0(\sum_{f,i,h\in H_{fi}} z_{fihj}) - \frac{P_j^0}{2Q_j^0}(\sum_{f,i,h\in H_{fi}} z_{fihj})^2 - \sum_{f,i,h\in H_{fi}} (p_{fihj}z_{fihj}) \\
& + \sum_{f,i,h\in H_{fi}} p_j^{erc} ERC_{fihj} \qquad (3.17) \\
\text{s.t.} \quad & z_{fihj} \ge 0 \qquad \forall f,i,h \in H_{fi}, j
\end{aligned}
$$

The first two terms in the objective function are total benefit (area under demand function). The net benefit is calculated by subtracting total benefit (first two terms) with procurement cost (third term) and ERC cost/revenue. The last term in the objective function is the emission cost for LSE if it holds negative units of ERCs or the emission revenue if it holds positive units of ERCs. The only constraint associated with LSE's problem is the non-negativity of z_{fihj}.

ISO's problem is to maximize benefit of using scarce transmission resources by deciding variable y_i, net injection (+) or withdrawn (−) with its optimization problem is displayed as follows.

$$\underset{y_i}{\text{Maximize}} \quad \sum_i w_i y_i \tag{3.18}$$

$$\text{s.t.} \quad \sum_i PTDF_{ki} \cdot y_i \leq T_k \quad (\lambda_k) \qquad \forall k$$

The w_i is wheeling charge, which is exogenous to ISO's problem but endogenous to the model. The flow in the network is modeled by linearized direct-current (DC) flow without loss using power transfer distribution factor (PTDF)(Schweppe et al., 2013).

Three market clearing conditions are associated with this problem, one for each commodity: wheeling fee (w_i), procurement cost (p_{fih}) and ERC prices (p_j^{erc}), respectively.

$$w_i \text{ free} : y_i = \sum_{fjh} z_{fjhi} - \sum_{fhj} x_{fihj} \qquad \forall i \tag{3.19}$$

$$0 \leq p_{fihj} \perp x_{fihj} - z_{fihj} \geq 0 \qquad \forall f, i, h \in H_{fi}, j \tag{3.20}$$

$$0 \leq p_j^{erc} \perp \sum_{f,i,h \in H_{fi}} ERC_{fihj} \geq 0 \qquad \forall j \tag{3.21}$$

The equilibrium model is solved by combining the three market clearing conditions with the following first-order condition from producer, ISO and LSE's problems. The problem is squared in a sense with equal number of equations (3.19) - (3.26) and unknown variables ($w_i, p_{fihj}, p_j^{erc}, x_{fihj}, p_{fihj}, z_{fihj}, y_i, \lambda_k$).

$$0 \leq x_{fihj} \perp -(p_{fihj} - C'_{fih}(\sum_j x_{fihj}) - (w_j - w_i) - \rho_{fih}) \geq 0, \forall f, i, h \in H_{fi}, j \tag{3.22}$$

$$0 \leq \rho_{fih} \perp -(\sum_j x_{fihj} - X_{fih}) \geq 0, \forall f, i, h \in H_{fi} \tag{3.23}$$

$$0 \leq z_{fihj} \perp -(P_j^0 - \frac{P_j^0}{Q_j^0} \sum_{f,i,h \in H_{fi}} z_{fihj} - p_{fihj} + \sum_{f,i,h \in H_{fi}} p_j^{erc} ERC_{fihj}) \geq 0, \quad \forall f, i, h \in H_{fi}, j \tag{3.24}$$

$$y_i \text{ free} : w_i - \sum_k \lambda_k PTDF_{ki} = 0, \forall i \tag{3.25}$$

$$0 \leq \lambda_k \perp -(\sum_i PTDF_{ki} y_i - T_k) \geq 0, \forall k \tag{3.26}$$

Quadratic Problem Formulation

In this section, the power market is modeled as a single social welfare maximization problem using quadratic programming (QP) approach. The QP formulation will yield the same modeling result with MCP formulation but it's much more computationaly efficient. Both power market and emission permit market are modeled as competitive markets in which the producers are price takers. The producers are described by their marginal production cost, carbon emission rate, and the physical characteristics such as location, fuel type and production technology. The demand is represented by inverse linear demand function, in which the parameters are derived from the least-cost model formulation with the actual observed demand.

The objective function is to maximize the social welfare, which is the total benefit minus the total cost. The constraints include generation capacity constraint, transmission capacity constraint, nodal balance, system transimission balance constraint and emission constraint, etc. Depending on ERC trading or CO_2 mass trading model deployed, the emission constraint can be formulated in two ways.

$$
\begin{aligned}
\max_{x_{fihj}, y_i} \quad & \int_0^j (P_j^0 - \frac{P_j^0}{Q_j^0} \sum_{fih} x_{fihj}) - \sum_{fih} C_{fih} (\sum_j x_{fihj}) \\
\text{s.t.} \quad & \textstyle\sum_j x_{fihj} \leq X_{fih} \qquad \forall f, i, h_{fi} \\
& -T_k \leq \sum_i PTDF_{ki} \cdot y_i \leq T_k \qquad \forall k \\
& y_i = \sum_{fjh} x_{fjhi} - \sum_{fhj} x_{fihj} \qquad \forall i \\
& \sum_i y_i = 0
\end{aligned}
$$

$$\sum_{fih} (\frac{E_{fih} - E_j^{\text{rate}}}{E_j^{\text{rate}}} x_{fihj}) \leq 0 \quad (p_j^{erc}) \qquad \forall j \tag{3.27}$$

$$\sum_{fih} (E_{fih} x_{fihj}) - E_j^{\text{rate}} \sum_{fih} x_{fihj} \leq 0 \quad (p_j^{CO_2}) \qquad \forall j \tag{3.28}$$

As shown in equation (3.27), ERC could be used as a trading instrument so that the total ERC amount for each state is balanced to zero. The emission constraint can equivalently apply an emission mass cap for each state as shown in equation (3.28). The mass cap will be determined by the rate-based standard and total power that is transmitted to node j.

3.4.2 Scenarios

Four scenarios are considered, which represent a variety of combinations of policy choices. Scenarios (a) is the baseline, representing no regulation, i.e., “business as usual” case. Scenarios (b) is mass-based policy case in which the system operates under a single mass-based emission cap. Scenarios (c) represents the case that states are subject to a regional performance-based policy. Scenarios (d) considers a state-by-state performance-based policy case under which each state is subject to its own performance-based standard while selling power in a regional market. The emission cap at scenarios (b) is subject to the aggregating total emission level under the state-by-stat performance-based policy, i.e., scenarios (d). Finally, for finding solution in scenarios (c), the model iterates over regional emission standard until the total emission is equal to the mass-based and state-by-state performance-based policies. Those four scenarios (a)–(d) are commonly applied to both three-state as well as PJM studies in Sections 5–6.

3.5 Three-state Case Study

3.5.1 Assumptions

While the model in (4.1) can easily be solved in a large-scale real system, this analysis first concentrates on a simple three-state setting to explore the theoretical properties of the performance-based policy. There are three states, $i = 1, 2, 3$, with generators and customers in each location, competing in a regional power market. Each state is interconnected with the other two states by a single transmission line with a transmission capacity limit. Demand in each state is represented by an inverse demand function, $p_i(q_i) = P_{i0} - (P_{i0}/Q_{i0})q_i$, with P_{i0} and Q_{i0} being the price and quantity intercepts, respectively. There are three producers, $f = 1, 2, 3$, each may have multiple generators at different locations. Each generator h is subject to its capacity limit, CO_2 emission rate, and a linear marginal cost: $\mathrm{MC} = B_{1fih}x_h + B_{0fih}$ with B_{1fih} and B_{0fih} being slope and intercept of cost function. All the data are documented in the appendix.

Two sets of data are applied to the three-state example separately - "low-emission rate" and "high-emission rate" data.[10] This setup allows us to examine the impact of emission rate on market outcomes under different policies in order to illustrate propositions in Section 3. The total emission for scenarios (b)–(d) with "low-emission rate" is subject to 902.4 *tons*, while with "high-emission rate" is subject to 589.4 *tons*.

3.5.2 Market Level Results

First focus on Table 3.1, the low-emission rate scenarios, when plant 8 has an emission rate of 0.249 ton/MWh. Several observations emerge from Table 3.1. First, all the scenarios with a carbon regulation, either a mass- or performance-based policy, result in a lower social surplus compared to baseline scenario (a).[11] This is an intuitive result as imposing any form of policy would effectively increase producer's production cost, thereby increasing power prices, and suppressing demand. For example, in comparison to baseline (a), power prices increase by 2.0 - 52.7% among three states. As alluded to earlier, the lower power prices under performance-based policy, scenarios (c) & (d), effectively inflate demand, leading to more production by 0.65 and 0.59% for scenarios (c) & (d) in contrast to (b),

[10]The difference between two datasets lies simply in the emission rate of plant 8, in which the low emission rate data has an emission rate of 0.249 ton/MWh, while high emission rate data has an emission rate of 1.249 ton/MWh.

[11]Of course, I am aware of the fact that the comparisons do not account for benefit of avoided damage by emission reduction in scenarios (b)–(e).

even all three scenarios are subject to an equivalent emission of 902.4 *tons*. The resulting equilibrium power prices are partially driven by the permit price under different policies.[12] In this case, it is observed that the permit price is lowest in mass-based case (b), followed by regional (c) and state-by-state (d) trading performance-based cases. Partially owing to the flexibility provided under the regional performance-based policy, which allows some states violating their state-specific constraints with such violation to be offset by an additional emission reduction elsewhere in order to maintain total emissions equal to 902.4 *tons*. As a result, the regional policy leads to a lower permit price of 19.5 $\$/ton$ in comparison to 22.4 $\$/ton$ in scenario (d). Finally, mass-based policy (b) yields a lower permit price. This is mainly because in addition to an emission cap of 902.4 *tons* in scenarios (c) and (d), these two scenarios also require plants with same emission to face same abatement cost. In fact, plants with a different emission rates will be subject to a different abatement cost, except when the permit price is equal to zero. In other words, the "system" under scenarios (c) and (d) is subject to additional requirement, leading to a higher permit price. The lower permit price in (b), however, does not imply a lower power price. This is owing to the fact that cross-subsidy under the performance-based policy effectively subsidizes high cost, low emission units, which also is more likely at margin, thereby lowering the power prices. The lower power prices would inflate quantity demanded by consumers as well as elevate demand of tradable permits, leading to a higher permit price. For example, sales-weighted power prices (column C in Table 3.1) indicates that power prices under the performance-based policies, i.e., scenarios (c) and (d), are lower

[12] With this set of data, scenario (d), when each state is subject to a state-by-state performance-based policy, yields a uniform permit price of 22.4 $\$/ton$, implying that plants with a same emission will be subject to the same abatement cost even they are located at different states. The analysis will examine the case when the resulting permit prices are diverged in Table 3.2.

Table 3.1: Market outcomes under the low-emission rate scenarios

Scenario	Region	(A) Power Prices [$/MWh]	(B) Nodal Emission [ton]	(C) Sales-weighted Power Prices [$/MWh]	(D) Permit Prices [$/ton]	(E) Total Generation [MWh]	(F) Total Emission [ton]	(G) Producer Surplus [$/hr]	(H) Consumer Surplus [$/hr]	(I) ISO Surplus [$/hr]	(J) Government Revenue [$/hr]	(K) Social Welfare [$/hr]
	1	55.5	524.0									
(a) Baseline[i]	2	37.8	175.0	40.9	NA	2,069.1	1,091.0	26,945.5	131,791.5	1,590.2	NA	160,327.0
	3	20.1	392.0									
	1	58.8	500.5									
(b) Regional Mass-based Policy[ii]	2	44.1	175.0	47.3	9.3	1,941.6	902.4	29,636.6	120,249.6	1,324.6	8,426.9	159,637.6
	3	29.4	226.9									
	1	56.6	510.2									
(c) Regional Performance-based Policy[iii]	2	43.4	175.0	46.3	19.5	1,954.3	902.4	36,040.3	122,375.3	1,188.9	NA	159,604.4
	3	30.2	217.3									
	1	58.2	508.0									
(d) State-by-state Performance-based Policy[iv,*]	2	41.1	175.0	47.0	22.4	1,953.0	902.4	37,485.3	120,968.8	1,137.1	NA	159,591.1
	3	30.7	219.4									

[i] No emission constraint is applied.
[ii] The mass-based emission cap is 902.4 *tons* for scenario (b).
[iii] All the states are subject to a regional emission performance-based target of 0.4618 ton/MWh.
[iv] States 1–3 are subject to a state-by-state performance-based target of 0.4, 0.6, and 0.5 ton/MWh, respectively.
[*] Calculation of *effective* permit price under performance-based policy is based on equation (3.6).

than that under mass-based policy (b) by 1.0 $\$/MWh$ (2.1%) and 0.3 $\$/MWh$ (0.6%), respectively. This also reflects on the lower consumer's surplus under the mass-based policy (b). Although with lower power prices and a higher emission cost (more than two times greater) for cases (c) and (d) when comparing to (b), the sizable carbon payment, transfer to the government, under scenario (b) for acquiring the allowances leads to a lower producer surplus. Under an auction-based allocation program, the mass-based C&T program will result in a carbon revenue for government (column J)[13]. On the other hand, similar to a RPS policy, the net subsidy under a performance-based policy will be null as gain (when the emission rate lower than the target rate) and loss (when the emission higher than the target rate) will be negating each other. For ISO's surplus, the lower endogenously determined wheeling charges under scenario (d) lead to a lower surplus, followed by scenario (c) and (b). Overall, mass-based policy remains the most efficient as measured by the social surplus (column I in Table 3.1). Finally, it is observed that the social welfare of regional policy case (c) is higher than state-by-state policy (d). However, this relationship is ambiguous, and it is elaborated in Section 3.6.

The results for high-emission rate scenarios in Table 3.2, with an emission

[13] Had allowances been allocated to producers or retained by consumers, the economic rent of allowances will be added to producers or consumers' surplus, respectively.

Table 3.2: Market outcomes under the high-emission rate scenarios

Scenario	Region	(A) Power Prices [$/MWh]	(B) Nodal Emission [ton]	(C) Sales-weighted Power Prices [$/MWh]	(D) Permit Prices [$/ton]	(E) Total Generation [MWh]	(F) Total Emission [ton]	(G) Producer Surplus [$/hr]	(H) Consumer Surplus [$/hr]	(I) ISO Surplus [$/hr]	(J) Government Revenue [$/hr]	(K) Social Welfare [$/hr]
	1	55.5	524.0									
(a) Baseline [i]	2	37.8	175.0	40.9	NA	2,069.1	1,438.0	26,945.3	131,791.5	1,590.2	NA	160,327.0
	3	20.1	739.0									
	1	90.7	381.7									
(b) Regional Mass-based Policy [ii]	2	56.7	140.6	84.7	75.7	1,216.7	589.4	16,564.5	63,449.5	9,128.6	44,621.5	133,764.0
	3	90.0	67.0									
	1	81.9	414.4									
(c) Regional Performance-based Policy [iii]	2	44.8	175.0	74.9	254.8	1,267.3	589.4	48,146.8	72,860.3	11,599.3	NA	132,606.5
	3	99.6	0.0									
	1	102.6	410.1		291.8							
(d) State-by-state Performance-based Policy[iv,*]	2	34.5	175.0	82.9	142.5	1,264.8	589.4	64,500.0	59,856.4	5,320.0	NA	129,676.4
	3	91.1	4.3		291.8							

[i] No emission constraint is applied.
[ii] The mass-based emission cap is 589.4 *tons* for scenario (b).
[iii] All the states are subject to a regional emission performance-based target of 0.4661 ton/MWh.
[iv, *] Same as Table 3.1

rate of 1.249 ton/MWh for plant 8, are similar to the results observed regarding power prices and welfare as discussed earlier for the low-emission rate scenarios in Table 3.1. Scenarios with an emission regulation imposed, i.e, scenarios (b) - (d), result in a lower social welfare compared to baseline scenario (a). With an increased production cost for scenarios (b)–(d) due to compliance of the emission regulation, the demand is decreased, and power prices are higher except for state 2 in scenario (d), in which the power price is reduced from 37.8 $\$/MWh$ in baseline (a) to 34.5 $\$/MWh$ in scenario (d). This is partially owing to the discrepancies in permit prices among different states. Similar to Table 3.1, the permit prices is lowest in mass-based scenario (b), followed by the regional performance-based scenario (c). Different from Table 3.1, the permit prices (column D) in state-by-state performance-based scenario (d) are diverged among three states with the permit price equal to 291.8, 142.5 and 291.8 $/ton for states 1–3, respectively. In this case, even though the trading is allowed among the states, permit prices do not converge among all the states. Therefore, same technology at different locations, e.g., states 1 and 2, will face a different carbon abatement cost. Since the total emission cap for high-emission rate scenarios (589.4 ton) is much more stringent compared to low-emission rate scenarios (902.4 ton), a much higher government carbon revenue is observed under scenario (b). The producer surplus has therefore been greatly suppressed with such a large carbon allowance payment. Finally, one abnormality when comparing consumers surplus in Table 3.2 is that even scenario (d) has a lower sale-weighted power price, its consumers surplus is actually lower than that of scenario (b). This is chiefly because the relatively high price in state 1, 102.6 \$/MWh or by a margin of 10 \$/MWh, thereby a much lower consumers surplus associated with state 1. Overall, mass-based policy (b) remains most efficient, followed by regional performance-based (c) and state-by-state trading performance-based policy (d).

Finally, the analyses in Tables 3.1–3.2 indicate that the regional policy outperforms the state-by-state policy based on social surplus. However, this observation, in terms of order of the social surplus, is ambiguous. Consider formulating a social surplus maximization problem with performance standard (either a regional or a state-by-state rate) as a decision variable in addition to power sales and other variables. A explicit performance-based model will explicitly impose an additional condition to the model to equqating the performance standard among all the states. This additional condition will truncate the set of feasible solution and might lower the objective value, i.e., social surplus. In this case, the social surplus under a regional performance standard could be worse than that of the state-by-state rate scenario. Therefore, it is concluded that the efficiency ranking of the regional and state-by-state policy observed in Tables 3.1–3.2 is an artifact owing to the data used in the analysis. Yet, the mass-based policy remains to be the most efficient ones.

3.5.3 Firm Level Results

The analysis addresses firm level outcomes in this subsection with a focus on state-by-state performance-based scenario (d). As observed in the previous sub-

Table 3.3: Plant-level generation output of state-by-state performance-based scenario (d)

Plant	low-emission rate			high-emission rate		
	State 1	State 2	State 3	State 1	State 2	State 3
1	116.1	35.9	98.0	41.5	75.2	133.3
2	106.0	16.7	77.4	200.0	0.0	0.0
3	170.1	95.1	158.1	0.0	260.2	0.0
4	95.1	2.1	52.8	150.0	0.0	0.0
5	114.5	13.4	72.2	200.0	0.0	0.0
6	181.9	0.1	18.0	178.7	0.0	21.3
7	0.0	0.0	0.0	0.0	0.0	0.0
8	228.4	61.7	110.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0
10	30.5	76.8	22.4	0.0	4.6	0.0

section, under a performance-based trading program with state-by-state standard, the sales patterns are related to the permit prices. Table 3.3 reports the sales of each generator (by row) to states 1–3 for scenarios (d) with low-emission rate and high-emission rate data for columns 1–3 and 4–6, respectively. Table 3.3 suggests a different sales patterns between two datasets. While plants 7 & 9 produce zero under these two scenarios due to their high emission rate, sale decisions by the other plants are changed between the two scenarios. In particular, plants 2–6 and 10, while sell a positive quantity in low-emission rate scenario, they supply only to a subset of states in high-emission rate scenario. For example, plant 2 supplies its generation to all the states in low-emission rate scenario, but only to state 1 in high-emission rate scenario. Overall, consistent with Proposition 1, generators either sell to all the states (i.e., $x_{fij} > 0$ for all j) or shut down their production completely (i.e., $x_{fij} = 0$ for all j) in low-emission rate scenario, leading to a uniform permit price among all the states. On the other hand, fewer than two generators sell to all the states while the others sell to a subset of states in high-emission rate scenario, leading to a divergence of the permit price among states. Thus, the results in high-emission rate scenario are consistent with Proposition 2.

Finally, even the transmission charge, w_i, was not reported in Tables 3.1–3.2, the relationship of power prices, transmission charges and the permit prices is also consistent with Proposition 4. For example, with a charge of 25.3 $\$/MWh$ from hub (state 3) to state 1 in Table 3.1 under low-emission rate scenario, the power price difference is equal to 27.5 $\$/MWh$ (= 58.2 - 30.7). It can be calculated by first multiplying permit price 22.4 $\$/ton$ and performance-based target difference between states 1 and 3, which is 0.1 ton/MWh (= 0.5 - 0.4), and then adding wheeling charge of 25.3 $\$/MWh$ to it (22.4 $\times$ 0.1 + 25.3 = 27.5).

3.6 Policy Experiments of PJM Market

In the previous section, the analysis develops a simple three-state model to illustrate the efficiency implication under performance-based policy and compare the market outcomes of different policy options. However, the model is highly simplified with only three states, ten power plants and single period, thereby not representing any particular market in U.S. In this section, model is applied to PJM regional electricity market. In what follows, the section starts by describing the construction of the dataset, followed by a baseline calibration and discussion of the results for efficiency implication.

3.6.1 Data and Assumptions

An electric power market for Pennsylvania-Jersey-Maryland (PJM) interconnection is constructed in the same fashion as the three-state example. PJM acts as Independent System Operator (ISO) since 1998. It operates a centrally dispatched, competitive wholesale electric power market that, as of December 31, 2016, had installed generating capacity of 182,449 MW and serving more than 65 million people. It runs a day-ahead energy market, a real-time energy market, a reliability pricing model (RPM) capacity market, a regulation market, a synchronized reserve market, a day-ahead scheduling reserve (DASR) market and a financial transmission rights (FTRs) market. The analysis simulates a subregion of PJM interconnection encompassing Maryland, New Jersey, Delaware, Pennsylvania, Virginia, and West Virginia for the baseline year 2012, which accounts for more than half of the load of the entire PJM regional market. Figure 3.2 displays the study region, which contains old PJM footprint, consisting of 21 aggregated nodes and 28 transmission lines. Each node represents one or a portion of territory operated by a load serving entity. In order to simulate the state-by-state case, in which different states are subject to their respective performance-based emission standards, the nodes are aggregated such that no node spans over more than one state. In other words, each node is located within one state, and a state might encompass a few nodes. Since 2012 is the baseline year for CPP policy, the model simulates the baseline at the same year assuming that each state is subject to an emission standard.

The scenarios are the same as the three-state case study in the previous section. Similarly, all scenarios are subject to the same level of emission. The analysis mainly rely on publicly available data supplemented with proprietary data for the analysis. The detailed information concerning data is provided in the Appendix.

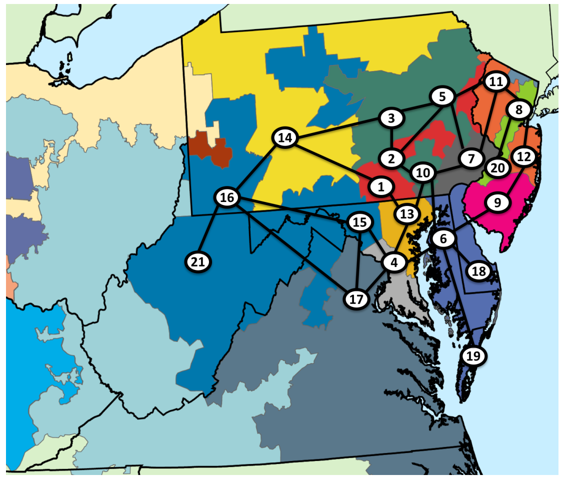


Figure 3.2: PJM nodes and transmission lines

3.6.2 Calibration

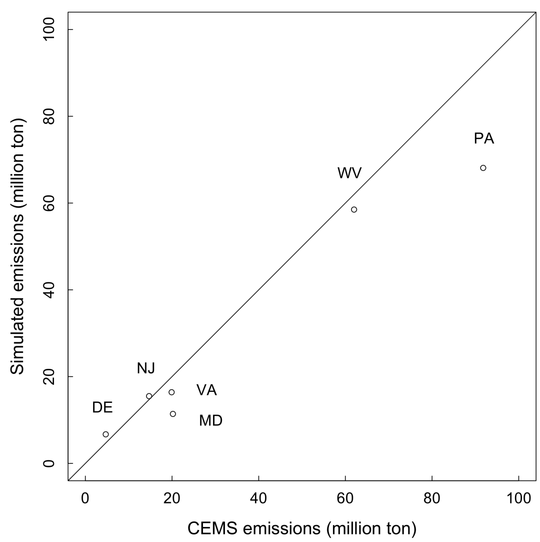


Figure 3.3: Plot of simulated emissions of baseline against CEMS reported emissions in 2012

The simulated emissions are aggregated to state level for comparison to 2012 continuous emission monitoring system (CEMS) data. CEMS dataset is maintained by US EPA that reports the hourly emissions from the most pollution-intensive power plants. The analysis aggregates the hourly CEMS CO_2 emissions to state level for 2012. Figure 3.3 plots the simulated emissions against reported emissions for the matched CEMS generating units. Each point represents a pair of simulated emission (y-axis) to CEMS emissions (x-axis) by a state. If the emission is perfectly predicted, the point will lie on the 45-degree line. Otherwise, if a point falls under (above) the 45-degree line, it underestimates (overestimates) the emissions. In general, the figure suggests that the model performs moderately well in predicting emissions since the points are not too far from the 45-degree line. However, the analysis underestimates emissions from some states, particularly Maryland and Pennsylvania, indicating that less pollution-intensive generating units are dispatched from those states in the model.

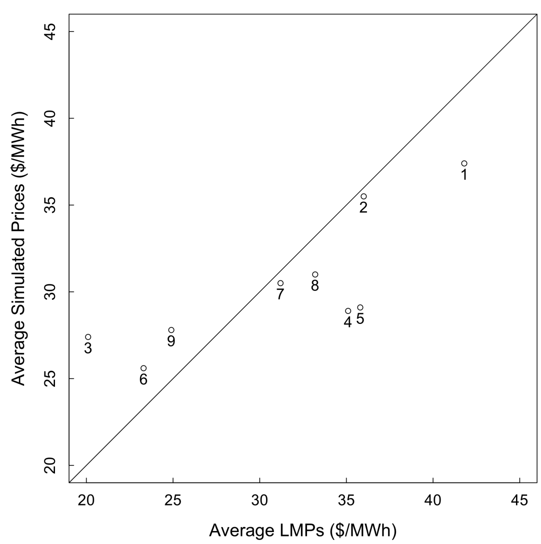


Figure 3.4: Plot of simulated electricity prices of baseline against LMPs in 2012

The simulated price is then compared to 2012 locational marginal prices (LMPs) reported by PJM. The analysis averages the hourly LMPs for PJM by nine time blocks and compare them with sales-weighted average price derived from the baseline simulation. The comparison result is displayed in figure 3.4. Similar to figure 3.3, 45-degree line indicates perfect prediction of prices. Although gathered around the 45-degree line, the figure suggests that the price pairs are less dispersively distributed. In other words, the high-demand (periods 1, 4 and 5 particularly) are underestimated while the low-demand hours at night time (periods 3, 6 and 9) are overestimated. Moderate-demand periods are well predicted (i.e., periods 2 and 7).

3.6.3 Results

The simulated PJM market outcomes are presented in Table 3.4. Similar to the previous three-state example, a lower average power price (column A) for performance-based scenarios (c) and (d) is observed compared to mass-based scenario (b), due to the cross-subsidy effect, which subsidizes high-cost, low-emission generating units. The low power price effectively leads to a demand inflation under performance-based policy, mainly due to an expansion of output from fossil fuel plants. As discussed earlier, performance-based policy could be partially met by increasing output from lower-emitting plants. The cross-subsidy effect further makes higher cost technology, such as natural gas, economically viable, leading to an increased dispatch from fossil fuel in general.

Table 3.4: PJM market outcomes under different emission regulation scenarios

Scenarios	(A) Average Power Price [$/MWh]		(B) Permit Price [$/ton]	(C) Total Generation [million MWh]	(D) Fossil Generation [million MWh]	(E) Total Emission [million ton]
(a) Baseline	32.0		NA	475.0	246.9	178.4
(b) Regional Mass-based Policy	39.8		9.3	472.7	236.8	161.0
(c) Regional Performance-based Policy	35.4		15.1	474.0	242.7	161.0
(d) State-by-state Performance-based Policy	35.4	MD	14.7	474.0	242.6	161.0
		NJ	15.1			
		PA	15.1			
		DE	15.1			
		VA	15.1			
		WV	14.9			

Table 3.5: Welfare outcomes under different emission regulation scenarios

Scenarios	(F) Producer Surplus [million $]	(G) Consumer Surplus [million $]	(H) ISO Surplus [million $]	(I) Government Revenue [million $]	(J) Social Welfare [million $]
(a) Baseline	5,622.1	379,397.4	275.4	NA	385,295.0
(b) Regional Mass-based Policy	7,747.7	375,693.9	304.1	1,494.4	385,240.0
(c) Regional Performance-based Policy	7,116.7 [-8.144%]	377,761.8 [+0.550%]	333.9 [+9.822%]	NA	385,212.3 [-0.007%]
(d) State-by-state Performance-based Policy	7,125.2 [-8.035%]	377,753.2 [+0.548%]	334.1 [+9.870%]	NA	385,212.4 [-0.007%]

[i] The number within square bracket represents the relative change compared to mass-based scenario (b).

Partially owing to this increased supply from fossil fuel, the demand for emission permits arises, and it results in a significantly higher permit price for performance-based scenarios (c) and (d) than mass-based scenario (b).

Table 3.5 presents the results of welfare distribution. The number in percentage within the square bracket represents the relative surplus change in percentage terms of performance-based policy compared to mass-based policy. Under mass-based scenario (b), government collects $1,494.4 million from producers assuming the permits are allocated via auctions. Even with this amount of payment, producer surplus under the mass-based policy is still higher than performance-based scenarios (c) and (d) because the lower power prices for performance-based scenarios suppress the producer surplus as shown in column (F). On the contrary, consumers benefit from the lower prices as shown in column (G) where the consumer surplus of scenarios (c) and (d) are higher than mass-based scenarios by approximately 0.55% for both scenarios. Consistent with Section (5), mass-based scenario remains to be the most efficient with the highest level of social welfare compared to performance-based scenarios, even only marginally.

From scenarios (c) and (d), the rank of social welfare relationship between regional and state-by-state policies is ambiguous. Recall in the three-state example, higher social welfare under performance-based is observed when the states are subject to a regional standard. However, with the similar setting in which all scenarios are subject to the same total emission level, the ranking is reversed in PJM simulation. That is, it is observed that the social welfare is higher under the state-by-state policy scenario (d) than that of regional trading scenario (c). To unveil this welfare relationship, consider an alternative way of solving the equilibrium problem by reformulating it as a quadratic problem (Hobbs, 2001). For the scenarios (c) & (d), their respective policy can be represented by equations (3.29) and (3.30), respectively.

$$\sum_{f,i,h\in H_{fi},j} E_{fih}x_{fihj} \leq E^{\text{rate}}(\sum_{f,i,h\in H_{fi},j} x_{fihj}) \quad (p^{CO_2}) \tag{3.29}$$

$$\sum_{f,i,h\in H_{fi}} E_{fih}x_{fihj} \leq E_j^{\text{rate}} \sum_{f,i,h\in H_{fi}} x_{fihj} \quad (p_j^{CO_2*}) \qquad \forall j \tag{3.30}$$

Both scenarios optimize social welfare with respect to the same technical constraints except with different emission constraints (3.29) and (3.30). In mathematical term, to prove the ambiguous relationship of two cases, first prove that the feasible set of one scenario is neither the subset nor the superset of the feasible set of the other scenario. In other words, the feasible sets of the two cases should be intersected each other, rather than one contains the other. Therefore, the analysis only needs to identify one feasible solution of one scenario that is not feasible for the other scenario. First, the feasible solution of the regional policy scenario (c) is evaluated. To maintain the same total emission, the regional emission rate in scenario (c), 1327 ton/MWh for PJM simulation, lies within the range defined by state-by-state policy rate in scenario (d): $[1260, 1337]$ ton/MWh. Thus, if substituting the optimal solution of the regional performance standard (c) into the state-by-state scenario (d), there is no guarantee that the solution will satisfy constraints (3.30). In other words, under the regional policy scenario (c), plants have the flexibility to adjust the output such that the regional emission rate target is satisfied but for some states, the state-by-state emission rate target might be violated. As a result, the optimal solution to the regional performance scenario (c) might violate the emission constraints under state-by-state scenario (d), leading to infeasible solution. Second, it is shown that the feasible solution to state-by-state policy scenario (d) could be infeasible for the regional policy scenario (c). Take the PJM case as an example, the optimal solution of the state-by-state policy scenario (c), thus the feasible solution as well by definition, violates the emission constraint (3.29) of the regional policy (c), indicating that feasible set of the state-by-state policy scenario (d) is not a subset of the feasible set defined by regional policy scenario (c). To summarize, the analysis shows that solution set of regional policy scenario (c) is neither a subset nor a superset of state-by-state scenario. It is concluded that the relationship between social welfare for regional and state-by-state performance-based policy is therefore ambiguous.

3.7 Conclusions

US Federal Clean Power Plan (CPP) has given states considerable flexibility in choosing either a performance-based target, or the corresponding mass-based target to show their compliance. Under the CPP, polluting sources rely on trading ERC (energy reduction credits) to equating their abatement costs. While the cost impacts and incentives for mass-based cap-and-trade (C&T) policy are well studied, the market outcomes and impacts of implementing a performance-based program remains unclear. One possibility is that states or regions may be able to inflate their electricity generation from low-emitting or non-emitting sources, and increase deployment of energy efficiency programs, to lower the average emission rate, without decreasing the total carbon emission. Moreover, different performance targets mandated by these states within an inter-connected regional electric market might not result in a cost-minimizing solution even when the ERC permit prices are equal across all the states, thereby undermining the efficiency of a C&T program.

This section studies the properties of a CPP-typed performance-based policy. The chapter first develops an analytical model to derive the conditions under which an efficient performance-based C&T could occur. In particular, the analysis shows that if each state adopt its own performance standard, it requires subjecting each state to the same level of performance target for the performance-based C&T policy to be efficient. On the other hand, if each state adopts a different performance standard, equating marginal abatement cost (\$/ton) of technologies with same emission rate in different states through an ERC C&T program will not likely to occur. The analysis also shows that in absence of transmission congestion, the power price across states could be different, reflecting varying stringency of performance-based standard among states within an interconnected market.

Two simulation-based models accounted for transmission and heterogeneity of technologies are also developed to evaluate market outcome when multiple states are subject to a performance-based policy. The analysis consider two types of performance-based policies: a regional performance-based policy that states join a regional permit market, and a state-by-state case where states are subject to state-by-state rate standard. The analysis have the following findings. First, the comparison of social surplus between the regional and state-by-state performance-based policies is ambiguous, neither will outperform the other. Second, even if the permit price under the mass-based policy is lower than that of the regional and state-by-state performance-based policies by a significant margin, the power price could actually be much higher, leading to a lower level of consumers surplus. This is owing to the fact that the cross-subsidy under the performance-based policy effectively lowers the marginal cost of low-emitting generators, which typically with a higher marginal cost and are more likely to be at margin. Third, even with the ERC trading, the permit prices among different states could diverge, leading to an economic inefficiency in abating pollution. Even if the ERC permit prices (in $/ton/MWh) among different states converge, efficiency is not guaranteed since different states are subject to different performance-based standards. Finally, both the numerical simulations also suggest that a mass-based policy remains to be the most efficient among all the policies considered when all policies are subject to the same aggregate emissions.

Introduction of the CPP dramatically changes the policy landscape and alters the playing field of US climate policy. While state government and the polluting industry might welcome the flexibility provided by the CPP, the policy imposes another layer of uncertainty to this already complicated issue. This section addresses the efficiency of performance-based policy within CPP by comparing it to the mass-based policy when they are all subject to the same aggregate emissions, and highlights the origins of inefficiency. However, there are a number of research questions that were left unanswered. One important question that has been partially addressed by the existing research is the market outcomes when a state strategically decides to either adopt a performance- or a mass-based policy. A state also decides whether to join and form a regional cap-and-trade program or isolated operates its program. Those decisions by states obviously have a significant welfare implication as it involves substantial wealth transfer between producers, consumers and state government across state boundaries. Methodologically, solving or analyzing collaboration among states is challenging as it requires simultaneously solving each state's problem when subjecting best responses from other states. The resulting problem could be an equilibrium problem with equilibrium constraints with no favorable theory pertinent to its solution properties. Those considerations are left to future work.

Chapter 4

A Study on Climate-change-induced Economic Impacts of the Northern California Natural Gas System Using Top-down Models

4.1 Background

Understanding the economic impacts of climate change is becoming an important component of managing critical infrastructures, e.g., the gas system, that are essential to maintain society's lifeline. It helps the industry identify key components of the infrastructure that are subject to climate-change related risks and is critical to the overall system's recovery so as to allow the industry prioritize its resources to choose suitable resilience options to adapt to climate change. Among all the climate change issues in California, the energy sector's vulnerability is an important issue to address, especially the natural gas system. Without information on the vulnerability of the natural gas system, or the economic implications resulting from its disruption, neither government nor industry will be able to implement cost-effective resilience options to harden the system in order to avoid the damage caused by catastrophic events. Climate-change-induced hazards in California include sea-level rising, coastal flooding, wildfire, droughts, storm events, and other extreme events (OEHHA, 2018). They are likely to increase risks for natural gas systems when the locations of the natural gas pipelines or compressor stations are in impacted hazard areas. The consequences of gas system disruption due to climate-change-induced hazards could be significant since many industries and households in California rely heavily on natural gas as their primary energy input. For example, 28% of California energy consumption involved natural gas in 2016. More than two-fifths of California's utility-scale net electricity generation relies on natural gas, and two-thirds of California households uses natural gas for home heating (US EIA, 2018). Thus, the reduction in gas supply is likely to adversely affect other sectors' production activities.

This chapter details the development of a regional economic Computable General Equilibrium (CGE) model to address the vulnerability of the Northern California natural gas system to climate-change-induced weather events. The model is a static U.S. state-level CGE model, accounting for bilateral trade flows among regions in order to quantify the spillover effects of service disruption onto other sectors and regions. CGE models are constructed as a system of simultaneous equations derived from the first-order-conditions of agents' optimization problems, as well as the market clearance conditions for each commodity and factor market. Economic agents, such as households and firms, make their decisions about their economic activities based on prices, which are endogenously determined within the model. One of the most important features in CGE modeling is the Armington assumption (Armington, 1969), which explicitly models the imperfect substitution of goods produced domestically and imported from other regions or countries. The extent of this imperfect substitution is modeled by the elasticity of substitution in constant elasticity of substitution (CES) functions for inputs and by the elasticity of transformation in constant elasticity of transformation (CET) functions for outputs, in order to represent their difference (McFadden, 1963). The analysis mainly focuses on the short- to medium-run scenarios[1].

The structure of a typical CGE model is illustrated in Figure 4.1. Each representative household is endowed with primary factors, such as labor and capital. The households then provide these factors to various sectors in exchange for their revenue. In order to increase their utility, households spend their revenue for private consumption of goods or savings/investment. Each industry/sector produces goods or services with the primary inputs, including value-added labor and capital, natural resource, and intermediate goods. A production function is used to link all the input factors of a sector to its gross output. The production functions usually take the form of a CES function, a Cobb-Douglas function, a Leontief type function or a nested combination of these functions. The gross output from the production process is then assigned to local goods, domestic exports, and international exports through a CET function. As alluded to earlier, this is because, by Armington assumption, local goods, domestic, and international export goods are similar but slightly different goods. The local goods are then combined with domestic imports and international imports through a bi-level nested CES func-

[1] In short-run and medium-run analysis, limited substitution in production and demand processes is allowed and they represent the relatively worse case. The "extreme short-run" case needs to use Input-Output (IO) approach, where no substitution is allowed.

tion to form Armington composite goods, which are used for final consumption, including household consumption, investment, government consumption, and intermediate good consumption. With the model represented in a complementarity format [2], it can be solved for the equilibrium activity levels and prices in order to gauge the regional and sectoral impacts given an exogenous shock to the economy.

In the following sections, this chapter will introduce the literature in regional CGE models. The model specification is illustrated in the model assumptions, data, and model formulation subsections, followed by results from illustrative scenarios and discussion. The detailed implementation of the GAMS or General Algebraic Modeling System (`https://www.gams.com/`) codes is also displayed in appendix.

[2]The complementarity condition could be denoted with "$\perp$" symbol as $0 \leq f(x) \perp x \geq 0$. It solves for a vector of variables x to meet the conditions of the form $f(x) \geq 0$, $x \geq 0$, and $f(x)^T x = 0$, where f(x) is a vector-valued function.

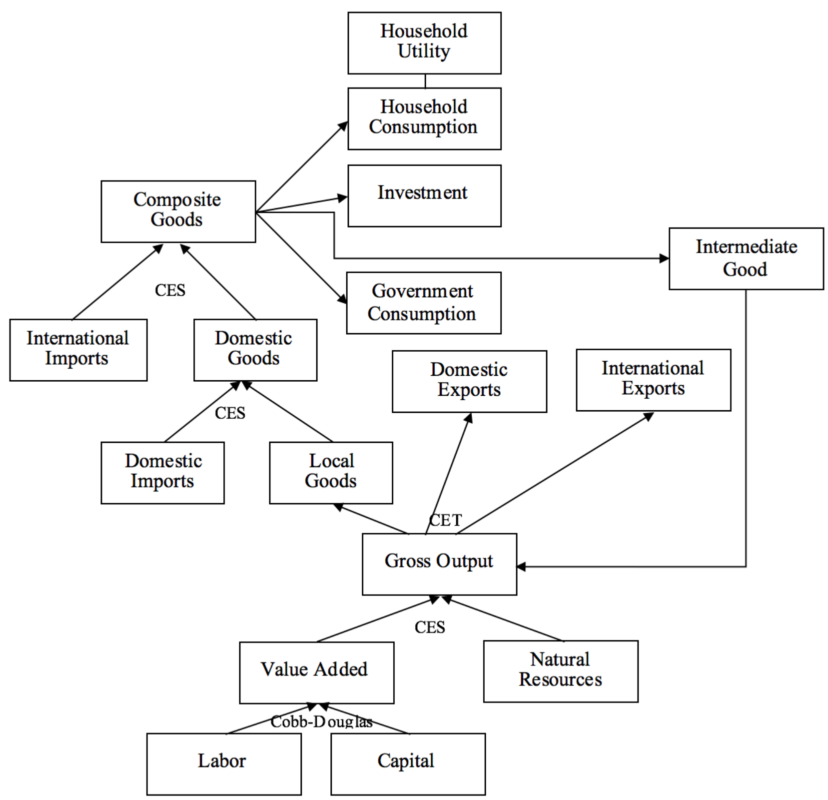


Figure 4.1: Structure for monetary and commodity flow in CGE modeling

4.2 Literature Review

CGE has been a widely used economic tool to investigate regional economic impacts. Specifically, several CGE models have been constructed to study regional impacts of climate change on the energy-related sector either at the U.S level or at a global level. For example, the Applied Dynamic Analysis of the Global Economy (ADAGE) model, developed by Ross (2007), examines a number of economic, climate-change, and trade policies at international, national, U.S. regional and U.S. state levels. The Multi-Region National - North American Electricity and Environment (MRN-NEEM) model described in Tuladhar et al. (2009) aggregates the U.S. states into nine regions and represents each region with a single representative household. Sue Wing et al. (2011) develop a dynamic recursive international CGE model with twenty-four regions, each with twenty-six industrial sectors and two representative agents (i.e., government and household). Rausch and Rutherford (2009) provide a detailed model formulation and computational tools for building US state-level CGE models with IMpact analysis for PLANning (IMPLAN) data for 2006. These data include input-output tables of 508 commodities and sectors, nine classes of households and six types of government agents. The authors present a highly stylized model, which serves only as a basis for a realistic model for policy analysis. In terms of model formulation, they construct general equilibrium in a complementarity format, since it is convenient, robust, and efficient. This equilibrium is defined by a vector of activity levels, a non-negative vector of prices, and a non-negative vector of income constraints. However, the model does not incorporate specifications related to production structure and trade. For example, the model applied the same CES production functions to all sectors without differentiating sectoral production structures. The model also does not include bilateral trade flows of each commodity between U.S. states, which is crucial when assessing cross-border impacts.

Caron et al. (2015) further advance the U.S. model developed by Rausch and Rutherford (2009) and construct a global CGE model with U.S. state-level details for analyzing trade and environmental policies. They integrate U.S. state-specific economic data with a GTAP-based international trade model. The paper uses multiple data sources, including (1) IMPLAN data for state-level input-output data and intra-national trade flows, (2) the Global Trade Analysis Project (GTAP) dataset of international production structure and international trade flows, (3) Origin of Movement (OM) and (State of Destination) SD from the U.S. Census Bureau for bilateral trade flows between international regions and U.S. states, (4) State Energy Data System (SEDS) from the U.S. Department of Energy for energy data. The model is a general-equilibrium multi-sector, multi-factor, multi-household Armington trade model, which is also formulated as a mixed-complementarity problem, similar to Rausch and Rutherford (2009).

A major contribution of Caron et al. (2015) is that their model tracks bilateral trade flows between states and countries, making it possible to explicitly evaluate the effects of a trade-facilitating or trade-restricting policy on a specific U.S. state or international region. The authors follow the Armington assumption to differentiate goods produced by local (within-state or within-region), domestic (within-U.S.), and international origin in a three-level nesting structure and represent the import structures using CES functions. Another contribution lies in its representation of the physical energy flows, the aggregation of energy sectors, and the production structures of the energy industries. In particular, it replaces the U.S. states input-output and trade flow data from IMPLAN with physical energy data from State Energy Data System (SEDS). By doing so, the paper advances the representation of carbon emissions when examining carbon leakage from California's Cap & Trade (C&T) policy. Moreover, the paper represents production with natural resource inputs, including coal, natural gas, crude oil and land. The production functions are then grouped into six types based on different production technologies for different sectors, including primary fuels, refined oil, electricity, agriculture, and non-energy industries. Thus, carbon emissions can be derived from the consumption of fossil fuels by industry and final demand sectors. For the structure of production functions, instead of using the common functional forms of production possibilities and preferences, including Leontief-, Cobb-Douglas, and CES functions, in the conventional coefficient form, they used calibrated form, which simplifies the calculation of free parameters in production and demand functions and serves as a basis for the model (Böhringer et al., 2003). Regarding the substitution elasticities in different types of CES production functions, the authors use the parameter values in Paltsev et al. (2005).

Paltsev et al. (2005) develop the Emissions Prediction and Policy Analysis (EPPA) model, which is a recursive-dynamic multi-regional general equilibrium model of the world economy, built on GTAP dataset and emissions data. Their major contribution includes the derivation of sector-specific differentiated production functions and substitution elasticities. EPPA considers a nested structure of five aggregated sectors: (1) services, industrial, transportation, energy intensive and other industries, (2) agriculture, (3) electricity, (4) primary energy sectors including coal, crude oil, and gas, (5) and refined oil sector. The refined oil sector is distinct because it uses crude oil as an intermediate input in its production, rather than being in the energy nest. The model also has a particularly detailed representation of the electricity sector to model the technology choices among various fuel types. Moreover, EPPA provides reference values of substitution elasticities for both production and consumption process, as based on an extensive literature review.

Similar to EPPA, Rausch et al. (2011) develop the U.S. Regional Energy Policy (USREP) model to study the distributional effect of carbon pricing. USREP is similar to EPPA in terms of sectoral detail, production structure, and elasticity-related parameters, but with a greater geographic scope. Since the model allows for heterogeneity in regions and household income levels, it is useful to evaluate distributional economic effects over regions and income groups. The model disaggregates the U.S. into twelve regions with five non-energy sectors, i.e., agriculture, services, energy-intensive, other industries, and transportation, and five energy sectors, i.e., coal, crude oil, refined oil, natural gas, and electricity. Moreover, the model distinguishes three different representations of intra-national regional trades, depending on the type of commodity. First, the bilateral trade flows of all non-energy goods are modeled as imperfectly substitute Armington goods. Second, energy goods other than electricity are modeled as homogeneous goods, with a national pool for domestic exports and imports (Rausch and Rutherford, 2009). Third, the model delineates six regional electricity pools in order to be consistent with the national grids under the Independent System Operator (ISO)/ Regional Transmission Organization (RTO) and the Federal Energy Regulatory Commission (NERC) structure. In each regional pool, electricity is homogeneous, while there are limited power trade flows allowed between regional pools, except for the Electric Reliability Council of Texas (ERCOT), which is treated as an isolated system. Unlike the small open economy assumption assumed by Rausch and Rutherford (2009), this paper models the U.S. economy as an open economy by specifying elasticities for world export demand and world import supply functions.

This analysis constructs a U.S. CGE model accounting for multi-sector, multi-region and multi-households. The model follows the formulation by Rausch and Rutherford (2009), with advancement in specification of production structures and construction of bilateral trade flows. The model flexibly aggregates the sectors and regions into desirable resolution. The elasticities used in CES functions are derived mainly from Paltsev et al. (2005) and Rausch et al. (2011). This model could be applied to analyze various climate-change-related events and policies and is especially useful in analyzing the climate-change impacts on natural gas system.

4.3 Model Assumptions

A multi-sector, multi-region static CGE model is constructed in the analysis. This section presents the main features and key assumptions of this model. The implementation of the model is similar to the modeling framework developed by Rausch and Rutherford (2009), with a benchmark dataset calibrated to the IMPLAN state-level and county-level data in 2013. Table 4.1 presents the definition of indices and sets used in the model.

Table 4.1: Indices and sets

Indice	Set definition
s	Sector or industry
g	Commodity (good or service)
r, rr	Region
fa	Factor
h	Household

The variables indicating the activity level of different agents are presented in Table 4.2, while price variables are presented in Table 4.3.

Table 4.2: Variables or activity levels in the CGE model

Variable	Description
$Y_{s,r}$	Sectoral production by sector s in region r
$A_{s,r}$	Armington aggregation
$C_{h,r}$	Household consumption by household type h in region r
$GOV_{pub,r}$	Public output
INV_r	Investment
$RH_{h,r}$	Income of representative household
$GOV_{pub,r}$	Income of government agents
$TAXREV$	Income of tax revenue agent

Table 4.3: Price variables of CGE model

Variable	Description
$py_{s,r}$	Sectoral output prices
$p_{s,r}$	Domestic output prices
$pa_{s,r}$	Armington aggregate prices
$pc_{h,r}$	Household consumption prices
$pn_{r,s}$	Intra-national trade prices
$pgov_{pub,r}$	Public output prices
$pinv_r$	Investment prices
$pf_{fa,r}$	Factor prices of factor fa in region r
pfx	Foreign exchange
$ptax_r$	Business tax prices

4.3.1 Producers

Each production sector or industry is assumed to minimize its cost with a production function that is assumed to use a constant-returns-to-scale[3] technology. The production function of each sector may deploy a combination of Leontief-type, Cobb-Douglas-type, and CES-type technology. Following the implementation in Böhringer et al. (2003), this study uses the calibrated share form, which is based on the benchmark price-quantity pair of the model, to represent production func-

[3] A constant-returns-to-scale technology is when an increase in inputs (capital and labor) cause the same proportional increase in output.

tions and demand preferences. The calibrated share form simplifies the calculation of free parameters (i.e., share coefficients for production or demand functions), as compared to the conventional coefficient form, in which the computationally-intensive inversion of production (or demand) functions is required.

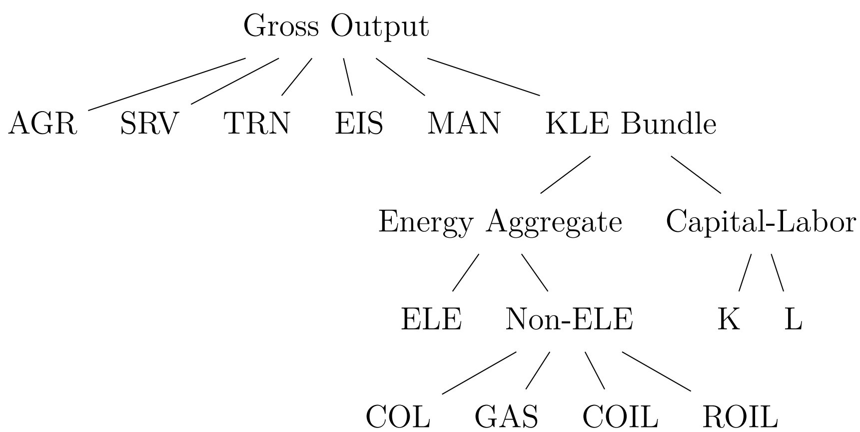
For each sector s in region r, the production function is expressed as:

$$Y_{s,r} = F_{s,r}(K_{s,r}, L_{s,r}, X_{1,s,r}, \cdots, X_{G,s,r})$$

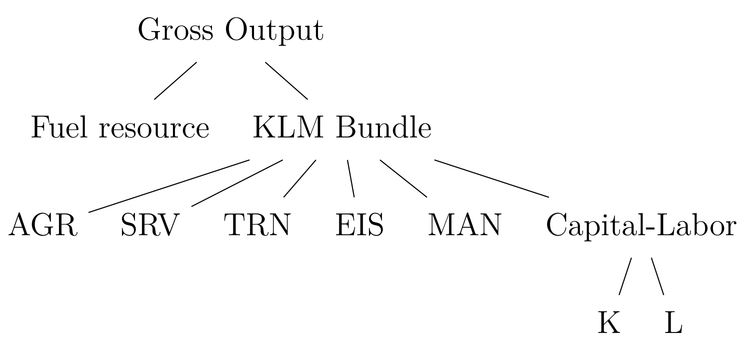
where $K_{s,r}$, $L_{s,r}$, $X_{g,s,r}$ are capital, labor and produced intermediate inputs, respectively. Natural resources, including coal, natural gas, crude oil, etc., are also incorporated as produced intermediate inputs to production functions.

The nested structure of production functions is depicted in Figure 4.2. By differentiating the production structure of different sectors and by applying a nested CES structure, the model is able to flexibly account for different elasticities of substitution of different input resources. For example, the elasticities of substitution between capital and labor, and between coal and natural gas can be assigned different values.[4] This specification of elasticities allows for more realistic representation of production functions.

[4]Sector definition: AGR - Agriculture, SRV - Service, TRN - Transportation, EIS - Energy-intensive, MAN - Manufacturing, ELE - Electricity, COL - Coal, COIL - Crude Oil, ROIL - Refined Oil.



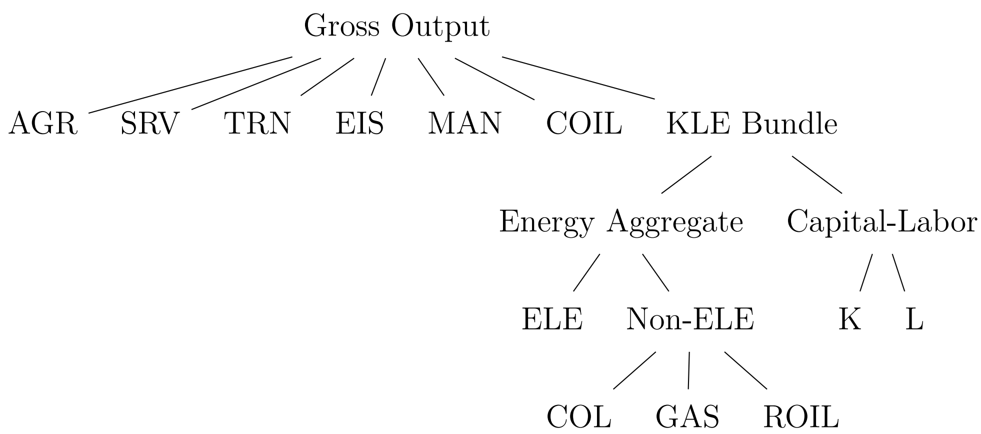
(a) Agriculture, Services, Transportation, Energy-intensive industries, Other manufacturing industries



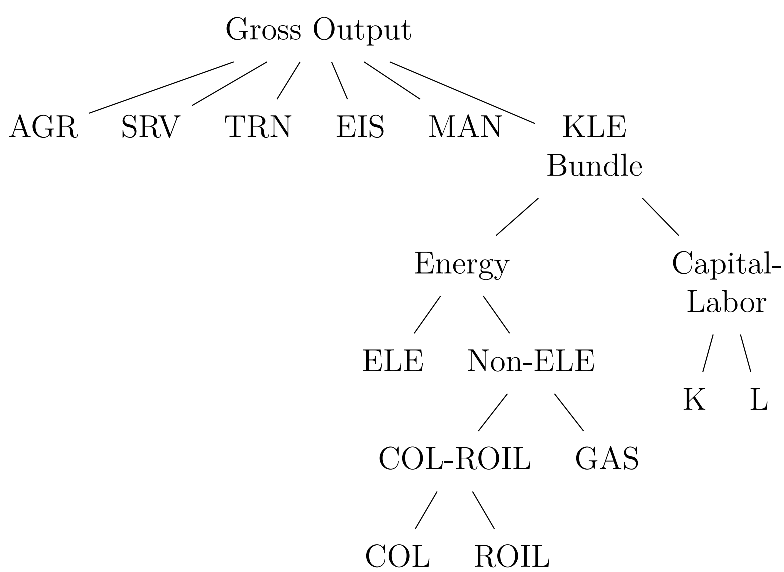
(b) Coal, Gas, Crude oil

Figure 4.2: Structure of production sectors: (a) Agriculture, Services, Transportation, Energy-intensive industries, Other industries, (b) Coal, Gas, Crude oil.

For illustration purpose, the electricity sector is used as an example to explain the nested production structure, although the same kind of analysis can be applied to all the other nested structures. As shown in Figure 4.2d, the electricity sector is represented by a five-level nest of CES production functions. In the bottom nest, coal, and refined oil constitute a “COL-ROIL” bundle with an elasticity of substitution σ_{co}. Then, combining COL-ROIL with natural gas with an elasticity of substitution σ_{cog}, the “Non-ELE” aggregate is formed. At the next level, an CES aggregate of energy composite is formed, where the elasticity of substitution between electricity and the Non-ELE aggregate is represented by σ_{enoe}. There is also a Cobb-Douglas aggregate of value-added (i.e., capital and labor). In the second nest from the top tier, the “KLE” bundle is separated into energy aggregate and value-added aggregate, with an elasticity of substitution σ_{eva}. Last, in the top tier nest, all non-energy sectors enter the production function together with the “KLE” bundle, with a Leontief type of technology where no substitution is assumed among the different inputs. The output of the production function ($Y_{s,r}$) is distributed to the local region, domestic export, and international export. The allocation of the output among these three markets is determined by a CET function. The benefit of a nested production structure is that the substitution effect between each pair of inputs could be adjusted and simulated, and therefore it allows for representing production processes in a more realistic way.



(c) Refined Oil



(d) Electricity

Figure 4.2: (continued). Structure of production sectors: (c) Refined oil, (d) Electricity.

4.3.2 Consumers

In each region r, the model distinguishes nine different representative households h defined by their levels of household income. The consumer is modeled as an agent who maximizes his/her utility, which is derived from consuming goods. Labor and capital, including proprietary and non-proprietary capital, are endowed to consumers, so that consumers receive income from producers for providing their labor and capital. They then use the income received to consume commodities to increase their utility. Household income is allocated between investment savings and private consumption. The model assumes a constant level of total investment volume based on benchmark data. The investment demand is represented by a Leontief aggregation of Armington goods. As a result, the household income net of investment is available for consumers to spend. Consumer preference is a three-tier nested CES function of goods consumption, as depicted in Figure 4.3.

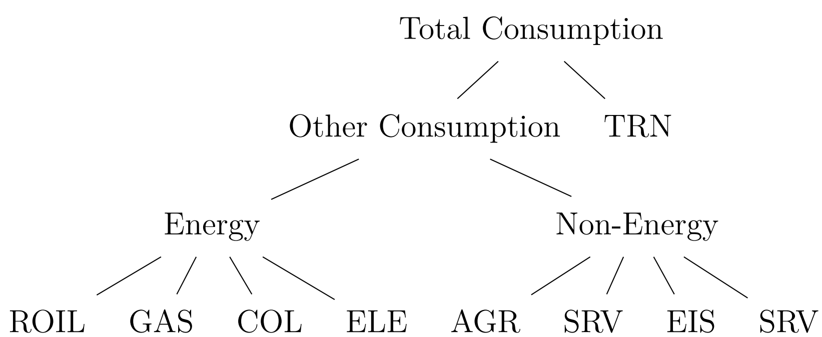


Figure 4.3: Nested Structure for Private Consumption/ Households

4.3.3 Government and Taxes

In each region, government activity is represented at three levels: federal, state, and local. Government is the entity that purchases commodities as public consumption and collects business taxes from production outputs paid by the purchasers of the produced commodities. As for the investment process, it is assumed that public consumption is a Leontief composite of Armington goods, where the commodity share is derived from benchmark data.

4.3.4 Bilateral Commodity Trade Flow

The supply of final goods and intermediate and final consumption are all differentiated following the Armington assumption, where goods imported/exported are considered to be imperfect substitutes for those produced/consumed locally. The degree of the difference between them can be measured by a parameter, i.e., the elasticity of substitution. The model distinguishes goods by local (within region), domestic (within the U.S.), and international origin and destination, using a two-tier nest for the Armington composite CES function, and a one-tier nest for the gross output CET function, as shown in Figure 4.4.

The Armington composite, i.e., the final consumption of good s in region r, is a CES composite of international imported good and national composite. In the second tier, the national composite is a CES composite of local output from region r, and domestic imports from U.S. regions other than r. By this specification, the analysis models the U.S. border effect by assuming that domestically imported goods are closer substitutes for the locally produced goods than international imported goods. The nested CES functions are represented by Equation (4.1):

$$\begin{cases} A_{s,r} = [\theta_{s,r} II_{s,r}^{\rho_i^{IM}} + \eta_{s,r} NC_{s,r}^{\rho_i^{IM}}]^{1/\rho_i^{IM}} \\ NC_{s,r} = [\pi_{s,r} LO_{s,r}^{\rho_i^{DM}} + \sum_{rr \neq r} \phi_{s,rr,r} R_{s,rr,r}^{\rho_i^{DM}}]^{1/\rho_i^{DM}}, \end{cases} \tag{4.1}$$

where $A_{s,r}$, $II_{s,r}$, $NC_{s,r}$, and $LO_{s,r}$ represent the Armington composite, international imports, national composite, and local output in region r and good s, respectively. $R_{s,rr,r}$ represents the domestic imports from region rr to region r for good s. $\theta_{s,r}$,$\eta_{s,r}$,$\pi_{s,r}$,and $\phi_{s,rr,r}$ are the CES share coefficients derived from benchmark data. $\sigma_i^{IM} = 1/(1-\rho_i^{IM})$ and $\sigma_i^{DM} = 1/(1-\rho_i^{DM})$ are the implied elasticity of substitution across international and U.S. intra-national origins, respectively.

The corresponding CES cost functions of the final consumption are as follows:

$$\begin{cases} pa_{s,r} = [\theta_{s,r} pfx^{1-\sigma_i^{IM}} + \eta_{s,r} cfn_{s,r}^{1-\sigma_i^{IM}}]^{1/(10\sigma_i^{IM})} \\ cfn_{s,r} = [\pi_{s,r} p_{s,r}^{1-\sigma_i^{DM}} + \sum_{rr \neq r} \phi_{s,rr,r} pn_{s,rr}^{1-\sigma_i^{DM}}]^{1/(1-\sigma_i^{DM})}, \end{cases} \tag{4.2}$$

where $pa_{s,r}$, pfx, $cfn_{s,r}$, $p_{s,r}$ and $pn_{s,rr}$ represent Armington composite price, foreign exchange price, national composite price, local output price, and domestic bilateral trade flow price, respectively.

On the other hand, the gross output, which represents the total supply of good s in region r, is a CET composite of local output, domestic export and international export. The CET function of gross output and its corresponding price function are displayed as follows:

$$\begin{cases} Y_{s,r} = [\alpha_{s,r} LO_{s,r}^{-\rho_i^T} + \beta_{s,r} IE_{s,r}^{-\rho_i^T} + \gamma_{s,r} DE_{s,r}^{-\rho_i^{IM}}]^{-1/\rho_i^T} \\ py_{s,r} = [\alpha_{s,r} p_{s,r}^{1+\sigma_i^T} + \beta_{s,r} pfx^{1+\sigma_i^T} + \gamma_{s,r} pn_{s,r}^{1+\sigma_i^T}]^{1/(1+\sigma_i^T)}, \end{cases} \tag{4.3}$$

where $IE_{s,r}$ and $DE_{s,r}$ represent international export and domestic export, respectively. As in the previous CES function, $\alpha_{s,r}$,$\beta_{s,r}$,and $\gamma_{s,r}$ are the CET share coefficients derived from the benchmark data, and $\sigma_i^T = 1/(1-\rho_i^T)$ is the elasticity of substitution among international exports, U.S. intra-national exports, and local output.

The chapter adopts the double-constrained gravity model developed by Wilson (1967) and follows the procedures in Lindall et al. (2006) to construct commodity

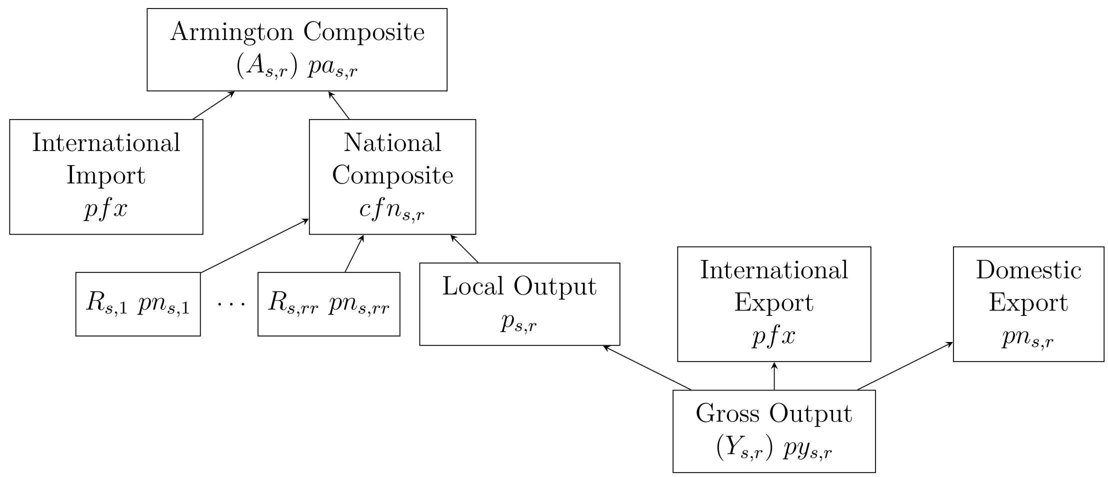


Figure 4.4: Structure for bilateral commodity trade flow

trade flows. Double constraints are applied to both domestic supply and domestic demand, so that domestic imports and exports could be canceled out: the total sum of domestic imports from all the states is equal to the sum of domestic imports of each commodity. The basic principle of the gravity model is based on the Newton's Law of Gravity, as shown in Equation (4.4):

$$\text{Gravity} = G \times \frac{(\text{Mass}_x \times \text{Mass}_y)}{\text{Distance}^2_{x-y}}, \tag{4.4}$$

where $Mass_x$ and $Mass_y$ represent the mass of two objects x and y. $Distance_{x-y}$ represents the distance between objects x and y. The gravitational constant is denoted by parameter G.

In a similar form, the commodity trade flow model in Eq. (4.5) is constructed so that the import and export flows between regions are proportional to the "size" or "attractiveness" of a region's economy, represented by the domestic supply and demand of the corresponding regions. At the same time, the import and export flows are inversely proportional to the "distance" or cost of moving goods and services between the regions:

$$T_{ij} = G(\frac{O_i D_j}{d_{ij}^b}), \tag{4.5}$$

where the left-hand side of the equation denotes the trade flow between regions i and j. For the right-hand side, O_i and D_j represent total commodity supply originating in region i and total commodity demand used in region j, respectively. Distance function is denoted by d_{ij}^b, while G represents gravity constant of trade.

Mathematically, the double-constrained gravity model is formulated in Equation (4.6).

$$T_{ij} = A_i B_j O_i D_j d_{ij}^{-b}, \tag{4.6}$$

where,

$$A_i = (\sum_j B_j D_j d_{ij}^{-b})^{-1} \tag{4.7}$$

$$B_i = (\sum_i A_i O_i d_{ij}^{-b})^{-1}. \tag{4.8}$$

A_i and B_j are defined variables to be solved. A closer look of their equation indicates that B_j is used to solve for A_i and A_i is used to solve for B_j. Therefore, an iterative search process is needed to calculate A_i and B_j iteratively, until the values for both A_i and B_j in two consecutive rounds of the iterative process remain unchanged. This formulation assures that the following two constraints (double-constraint model) are satisfied:

$$\sum_j T_{ij} = O_i \tag{4.9}$$

$$\sum_i T_{ij} = D_j. \tag{4.10}$$

When summing the trade flows over all origins and destinations, the following equation is satisfied:

$$\sum_i \sum_j T_{ij} = \sum_i O_i = \sum_j D_j. \tag{4.11}$$

Data from three sources are used to construct commodity bilateral trade flows: Oak Ridge National Labs (ORNL, 2011), Commodity Flows Survey (CFS, 2012), and IMPLAN (IMPLAN, 2013). The model requires commodity supply and demand data, as well as the impedance index indicating the distance and cost of transportation. The commodity supply and demand data are extracted from the IMPLAN social accounting matrix. ORNL's county-to-county distance database contains a matrix of distances and network impedances between each pair of county centroids by mode of transportation, including highway, railroad, water, and combined highway-rail paths. To combine the impedances of different modes of transportation into a single index, the CFS shipment characteristics by commodity and mode of transportation table are used to generate weights of each mode of transportation. The process for constructing the trade flow model is summarized in the following three steps:

1. Calculate distance (d_{ij}):

    - Calculate centroids of aggregated region and locate the centroid county using ArcGIS.
    - Use ORNL data to extract county-to-county impedance by mode of transportation.
    - Use CFS data to acquire weights for each mode of transportation by commodity.
    - Combine the above two datasets to calculate region-to-region impedance

indices by each commodity.

2. Extract supply and demand from IMPLAN data: $vxm(r, s, \text{“}dtrd'')$ and $vim(r, g, \text{“}dtrd'')$ [5].

3. Iterative over A_i and B_j until converge, and calculation of T_{ij} using R-CRAN (R Core Team, 2017).

4.4 Data

The benchmark data contain the social accounting matrices (SAMs) of all 50 U.S. states and 58 California counties in 2013, with 536 production sectors/commodities, and three factors for production, including labor, proprietary capital, and non-proprietary capital[6]. Nine household types are distinguished by their gross income level, and six types of government are represented at the federal, state or local levels. Next subsections introduce the data sources used for model specification and calibration, and data aggregation.

4.4.1 Data Sources

Table 4.4 summarizes the data sources and their usage in the CGE model. The IMPLAN data are the major source of data in the analysis. The IMPLAN data are developed by the Minnesota IMPLAN group (MIG), and include balanced yearly benchmark economic data of the U.S. at the national, state, or county levels. It provides consistent SAMs by reconciling the data from multiple sources,

[5] $vxm(r, s, \text{“}dtrd'')$ represents domestic exports of sector s in region r and $vim(r, g, \text{“}dtrd'')$ represents domestic imports of sector s in region r

[6] Proprietary capital is self-employment income, including capital consumption allowance, while non-proprietary capital consists of corporate profits, rent, interest, and capital consumption allowance.

including the Bureau of Economic Analysis (BEA), the Bureau of Labor Statistics, and U.S. census data (IMPLAN, 2013). The SAMs provide input-output data for 536 sectors/commodities, nine types of households, and six types of government agents. The data keep track of the monetary flows and commodity flows among and within production sectors and institutions. This chapter uses county-level SAMs data of California, and state-level SAMs data of the other U.S. states. By distinguishing county- and state-level data for different regions, the analysis can focus on northern California, the key study region at which the analysis models natural gas supply disruption induced by hazardous climate events. The chapter uses the ancillary tools provided by Rausch and Rutherford (2009), GAMS (General Algebraic Modeling System) programs to covert IMPLAN data files into GAMS readable format, translate IMPLAN data into GTAP format, aggregate regions and sectors, balance intra-national trade flows, and then formulate the model for calibration and equilibrium.[7]

[7] The ancillary tools also include programs to aggregate data by region and sector. However, the tools are subject to a number of limitations that prevent the work from directly using them. In particular, domestic trade flows are incorrectly aggregated by region in the tools because the program double-counts the trade flow between those two regions. In order to overcome this problem of double counting of domestic trade flows when aggregating regions, this study aggregates the regions in the IMPLAN software instead, wherein the correct trade flows are aggregated.

Table 4.4: Data sources and data usage in CGE model

Data Usage	Data Source	Data Type
Social Accounting Matrices	IMPLAN [i]	County / state level
Bilateral trade flow	ORNL [ii]	Oak Ridge National Labs county-to-county distances by mode of transportation
	CFS [iii]	Commodity Flow Survey shipment data
	IMPLAN	IMPLAN commodity supply and demand

[i] IMPLAN (2013)
[ii] Oak Ridge National Labs (2011)
[iii] U.S. Department of Transportation (2012)

4.4.2 Regional Aggregation

This chapter disaggregate the U.S. into 19 regions, as shown in Figure 4.5. The states other than California are aggregated into 10 regions, including Pacific, Arizona, Mountain, Central, Texas, Midwest, Southeast, Northeast, Hawaii and Alaska. California counties are aggregated into 9 regions, including Central Coast, Central Valley, North Bay, North Coast, Sacramento Valley, SoCal without P&GE territory, SoCal with PG&E territory, South Bay and Sierra Neveda.

The aggregation of states is determined based on electricity supply interconnections and natural gas supply networks. The bilateral commodity trade flows are constructed such that the domestic imports and exports between any two regions can be traced. Furthermore, regions are defined accounting for the physical system networks in the electricity sector. For example, regions in the western interconnections can trade only within the western interconnection, but not with the eastern or the Texas regions. This ensures that different electricity interconnections could not trade across interconnection borders in the U.S. electric

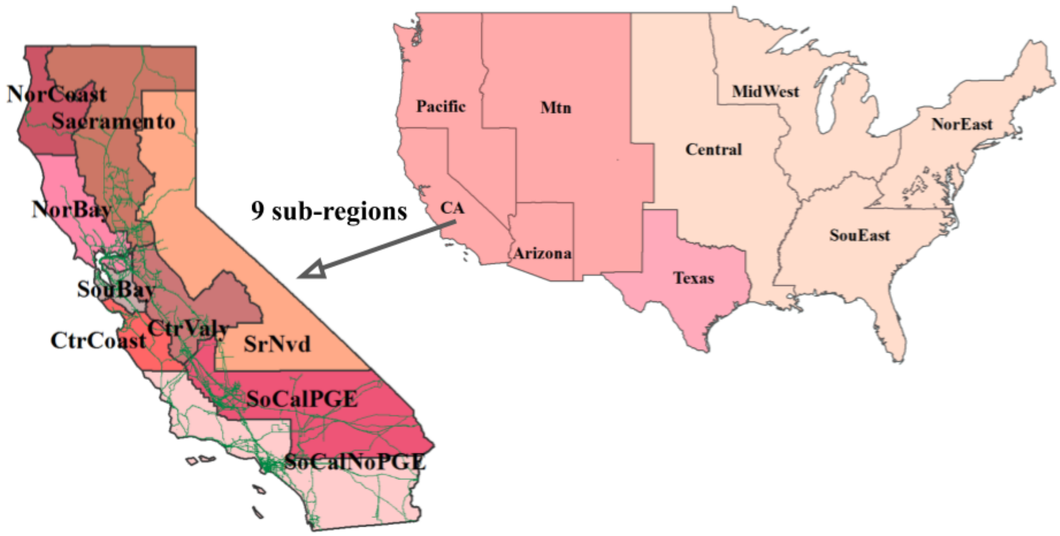


Figure 4.5: Regional aggregation in the CGE model

system.

4.4.3 Sectoral Aggregation

As in Rausch and Rutherford (2009), this model aggregates the 536 sectors in the IMPLAN data to ten sectors, as listed in Table 4.5, with five sectors as non-energy sectors and five sectors as energy sectors. Non-energy sectors include agriculture, services, transportation, energy-intensive industrial sectors, and other manufacturing sectors. Energy sectors include the primary fuel (i.e., coal, natural gas, and crude oil), refined oil, and electricity sectors. Different sectors are deployed different production structures in their nested CES production functions. Overall, the five non-energy sectors share the same production structure, while the energy sectors are more complicated. More specifically, coal, gas, and crude oil share a similar primary fuel production pattern, in which the only primary fuel input of each sector is its own primary fuel. For example, the fuel supply of the natural gas sector is gas, but not coal or crude oil. On the other hand, the refined oil and electricity sectors have distinctive production structures. The different production structures enable representing the production process of each sector in a more realistic way.

Table 4.5: Definition of sectoral aggregation

Aggregated Sector	Description
AGR	Agriculture
SRV	Services
TRN	Transportation
EIS	Energy intensive sector
MAN	Other manufacturing sectors
COL	Coal
GAS	Gas manufacture, distribution
COIL	Crude oil and natural gas
ROIL	Petroleum, refined oil
ELE	Electricity

4.5 Model Formulation

The model advances the simplified national economic model with state-level resolution developed by Rausch and Rutherford (2009) to include bilateral commodity trade flows. Each agent solves its optimization problem, including profit maximization for industries and utility maximization for representative agents. The model consists of three sets of equilibrium conditions, including zero-profit conditions, market clearance conditions, and income definitions to close the system, together defining the economy's equilibrium, including industry activity levels, commodity and good prices, and income levels. Each set of equilibrium equations determines one set of variables. More specifically, the zero-profit conditions determine the vector of activity levels; the market-clearance conditions determine the non-negative vector of prices; and the income definitions determine the income level of each market agent. The resulting problem is a mixed complementarity problem (MCP) (Mathiesen, 1985; Rutherford, 1995). The model is formulated using GAMS, and solved with the complementarity problem solver PATH (Dirkse and Ferris, 1995). Each set of conditions is elaborated in the following subsections.

4.5.1 Zero-profit Conditions

The economy is assumed to be perfectly competitive and populated with constant-returns-to-scale technologies, implying that profits will be driven to zero at equilibrium in the long run. In other words, the marginal cost of the inputs of an activity is equal to marginal price of output for each market participant at equilibrium (Mas-Colell et al., 1995). The cost and price equations associated with sectoral production, the Armington aggregation, investment, and public and private consumption variables are represented by zero-profit conditions.

- Sectoral production($Y_{s,r}$):

  The production functions are shown in Equation (4.12).

$$G_{s,r}(pk_{s,r}, pl_{s,r}, px_{1,s,r}, \cdots, px_{G,s,r}) = py_{s,r}, \tag{4.12}$$

  where

$$py_{s,r} = (\theta^{d}_{s,r} p^{1+\eta}_{s,r} + \theta^{fx}_{s,r} pfx^{1+\sigma^T_i} + \theta^{nt}_{s,r} pn^{1+\sigma^T_i}_{s,r})^{1/(1+\sigma^T_i)}.$$

  The left-hand side (LHS) of Equation (4.12) represents the marginal cost function of each production industry. The arguments to the cost function include intermediate goods ($px_{G,s,r}$), factor inputs, i.e., capital ($pk_{s,r}$) and labor ($pl_{s,r}$), and business taxes. The production function is represented by a general function $G(\cdot)$. However, the functional form and structure of the production function of each region r and of each sector s may vary. The right-hand side (RHS) of the equation is the output price, which is represented by a CET function that encompasses local output ($p_{s,r}$), international exports (pfx), and domestic exports ($pn_{s,r}$) with a substitution elasticity σ^T_i, where θ with different subscripts s, r represent value shares calibrated from the benchmark data. The model divides the ten aggregated sectors into four categories: electricity, refined oil, primary fuel (i.e., crude oil, gas, and coal), and other sectors (i.e., agriculture, manufacturing, transportation, service, and energy-intensive sector). The nested production function structures are depicted in Figure 4.2, as mentioned earlier.

- Armington aggregation ($A_{s,r}$):

  The Armington aggregation process is represented in the nested CES function:

$$(\theta^{ftrd}_{s,r} pfx^{1-\sigma_{df}} + \sum_{trd} \theta^{ar}_{trd,s,r} cfn^{1-\sigma_{df}}_{s,r})^{1/(1-\sigma_{df})} = pa_{s,r}, \tag{4.13}$$

where

$$cfn_{s,r} = (\theta_{s,r} p^{1-\sigma_{dm}}_{s,r} + \sum_{rr} \theta^{dtrd}_{s,rr,r} pn^{1-\sigma_{dm}}_{s,rr})^{1/(1-\sigma_{dm})}.$$

The Armington composite of each sector in each region is represented by a nested CES function. The first term of the LHS in Equation (4.13) represents the foreign exchange (international imports) price (pfx), and the second term ($cfn_{s,r}$) is a national cost indicator, which is further represented by a second-level CES function that combines local output ($p_{s,r}$) and intra-national imports ($pn_{s,rr}$) from all the other U.S. regions.

- Investment (INV_r) [8]:

$$\sum_{s} pa_{s,r} \overline{vinvd}_{s,r} = pinv_r \overline{vinv}_r. \tag{4.14}$$

Equation (4.14) indicates that, for each sector, the total value of investment in region r (LHS) equals the demand of the Armington composite for investment (RHS).

- Public consumption ($GOV_{pub,r}$):

$$\sum_{s} pa_{s,r} (\overline{vdgm}_{s,pub,r} + \sum_{trd} \overline{vigm}_{s,trd,pub,r}) = pgov_{pub,r} \overline{vgm}_{pub,r}. \tag{4.15}$$

The first term of LHS in Equation (4.15) represents the government consumption demand of local Armington goods, while the second term represents the government consumption demand of imported Armington goods.

[8] All expressions with an over-line represent the calibrated value for the baseline scenario.

For each sector, the demand of total government consumption in the LHS is equal to the total consumption level on the RHS of the equation.

- Private consumption ($C_{r,h}$):

$$L_{h,r}(pa_{ELE,r}, \ldots, pa_{SRV,r}) = pc_{h,r} \tag{4.16}$$

$L(\cdot)$ represents the cost function of private consumption, with a three-tier nested CES function as depicted in Figure 4.3. The inputs are the prices of Armington composite goods of all sectors except for crude oil (CRU), which is directly consumed by private households. The marginal compounded cost of the Armington good is equal to the RHS, which is the price of private consumption.

4.5.2 Market Clearance Conditions

At equilibrium, all market are cleared, meaning excess supply is non-negative for all goods and factors, thereby giving a positive price for each sector. In other words, the supply on LHS equates the demand in RHS for all the markets. These market clearance conditions are prerequisite for a CGE model, since market equilibrium can not be attained if excess supply or demand exists for any of the markets. Essentially, each market agent in the model maximizes its net benefit given its interconnections with other process or market agents, and those interconnections are represented by market clearance conditions.

- Market of domestic output ($p_{r,s}$):

$$Y_{s,r}(\frac{p_{s,r}}{py_{s,r}})^{\eta} = A_{s,r}(\frac{pa_{s,r}}{cfn_{s,r}})^{\sigma_{df}}(\frac{cfn_{s,r}}{p_{s,r}})^{\sigma_{dm}} \tag{4.17}$$

- Market of Armington aggregation ($pa_{r,s}$):

$$
\begin{aligned}
\overline{va}_{s,r}A_{s,r} &= \sum_{g}\overline{vdifm}_{g,s,r}Y_{s,r} \\
&+ \sum_{h}(\overline{vdpm}_{s,h,r} + \sum_{trd}\overline{vipm}_{s,trd,h,r}\frac{pc_{h,r}}{pa_{s,r}})C_{h,r} \\
&+ \overline{vinvd}_{s,r}INV_{r} \\
&+ \sum_{pub}(\overline{vdgm}_{s,r,pub} + \sum_{trd}\overline{vigm}_{s,r,trd,pub})GOV_{pub,r}
\end{aligned}
\tag{4.18}
$$

- Market of intra-national trade ($pn_{s,r}$):

$$
(\sum_{rr}\overline{trade}_{s,r,rr})Y_{s,r}(\frac{pn_{s,r}}{py_{s,r}})^{\eta} = \sum_{rr}A_{s,rr}\overline{trade}_{s,r,rr}(\frac{pa_{s,rr}}{cfn_{s,rr}})^{\sigma_{df}}(\frac{cfn_{s,rr}}{pn_{s,r}})^{\sigma_{dm}}
\tag{4.19}
$$

- Market of investment ($pinv_{r}$):

$$
\overline{vinv}_{r}INV_{r} = \sum\overline{vinvh}_{h,r}
\tag{4.20}
$$

- Market of public consumption ($pgov_{pub,r}$):

$$
\overline{vgm}_{pub,r}GOV_{pub,r}pgov_{pub,r} = GOVT_{pub,r}
\tag{4.21}
$$

- Market of primary factors ($pf_{fa,r}$):

$$
\sum_{h}evo_{h,fa,r} = \sum_{s}\overline{vfm}_{fa,s,r}Y_{s,r}\frac{cf_{s,r}}{pf_{fa,r}}
\tag{4.22}
$$

- Market of foreign exchange (pfx):

$$\sum_r \sum_h \overline{incadj}_{h,r} + \sum_{pub,r} \overline{vgm}_{pub,r} + \sum_r \sum_s \overline{vxm}_{s,ftrd,r} Y_{s,r} (\frac{pfx}{py_{s,r}})^{\eta}$$
$$= \sum_r \sum_s dfx_{s,r} + \sum_r \frac{TAXREV_r}{pfx} \qquad (4.23)$$

where

$$dfx_{s,r} = A_{s,r} \overline{vim}_{s,ftrd,r} (\frac{pa_{s,r}}{pfx})^{\sigma_{df}}$$

- Market of private consumption ($pc_{r,h}$):

$$\overline{vpm}_{h,r} C_{h,r} pc_{h,r} = rh_{h,r} \qquad (4.24)$$

- Market of price of business taxes ($ptax$):

$$\sum_s \overline{vfm}_{btax,s,r} = \sum_s \overline{vfm}_{btax,s,r} Y_{s,r} \qquad (4.25)$$

4.5.3 Income Definitions

The income levels of private households, government, and tax revenue agent are defined in such a way that the expenditure by each market agent can not exceed its income level.

- Private income ($RH_{h,r}$):

$$RH_{h,r} = \sum_{fa} pf_{fa,r} \overline{evo}_{h,fa,r} + pfx \overline{incadj}_{h,r} + pinv_r (-\overline{vinvh}_{h,r}) \qquad (4.26)$$

- Public income ($GOVT_{pub,r}$):

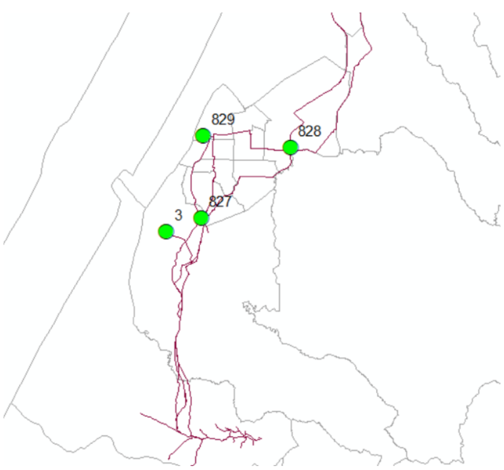
$$GOVT_{pub,r} = pfx\overline{vgm}_{pub,r} \tag{4.27}$$

- Income of tax revenue agent ($TAXREV_r$):

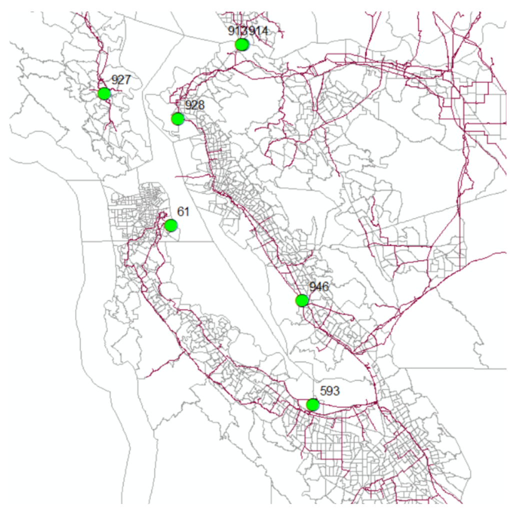
$$TAXREV_r = ptax_r \sum_s \overline{vfm}_{btax,s,r} \tag{4.28}$$

4.6 Scenarios

Among different climate-change-induced hazards that potentially disrupt natural gas system, this analysis focuses on quantifying the impact of sea-level rise. The first step in defining the scenarios for CGE modeling is to identify the key facilities, which are subject to the climate-change-induced sea-level rise, such as gas compression stations and gas regulation stations. More specifically, if the projected sea level exceeds the elevation of a facility, the facility will be submerged under sea water, and its operation is likely to be affected. Digital Elevation Model (DEM) Data of the gas facility network is compared to the sea-level rising data in order to identify the affected facilities. Figure 4.6 (a) represents facilities (No.3, 827, 828, 829) which are located fairly close to each other in Humboldt county in the North Coast region. As these facilities are clustered in a relatively small region, they are grouped into one clustered facility (a), with the assumption that the minimum elevation (208cm) of the four individual facilities is the elevation of the clustered facility. Therefore , if the sea level rise above 208cm, facility (a) is assumed to be subject to sea-level rising risk. Also, as the flow in a gas pipeline follows the direction of the pressure gradient, the gas supply downstream of an affected facility is assumed impacted. This is in contrast to the looped flows in the power sector, where different pathways can supply the same demand location. The assumption regarding the grouping of facilities is realistic because the nearby facilities share the same impacted regions. Key facilities in the Bay Area are identified in Figure 4.6 (b). As for the facilities in North Coast region, Facilities No.913 and 914 share the same impacted region and thus are grouped together to form clustered facility (d). The detailed information on facilities are described in Table 4.6, including facility ID number, county, and region. More importantly, it indicates the impacted population if that facility fails to function normally. Ideally, a gas operation model should be used to derive the extent of the impact. However, in absence of such a model, it is assumed that the extent of the impacted supply/demand is proportional to the fraction of the impacted population in the region (Percentage of Impact column in Table 4.6).



(a) Facilities in North Coast



(b) Facilities in North and South Bay Area

Figure 4.6: Facilities impacted by sea-level rising scenarios

Theoretically, a failing facility is not able to provide service to its local and

Table 4.6: Facility-level impact based on impacted population

Facility	Facility ID	Impacted Population	Minimum Elevation (cm)	County	Region	Total Population	Percentage of Impact
a	3/827/828/829	57,329	208	Humboldt	North Coast	175,969	0.3258
b	927	84,590	326	Marin	Northern Bay	2,613,013	0.0324
c	928	85,761	334	Contra Costa	Northern Bay	2,613,013	0.0328
d	913/914	27,206	264	Contra Costa & Solano	Northern Bay	2,613,013	0.0104
e	61	36,669	176	San Francisco	Southern Bay	5,168,554	0.0071
f	946	252,977	367	Alameda	Southern Bay	5,168,554	0.0489
g	593	1,440,109	329	Santa Clara	Southern Bay	5,168,555	0.2786

downstream regions where natural gas flows to. However, without explicit data allowing the simulation of gas flows, this analysis uses pipeline dimension to infer the direction of the flow near the facilities. Therefore, the analysis assumes the impact of service disruption of one facility is proportional to the impacted population served by that facility. Figure 4.7 illustrates how the impacted regions are determined in the analysis. Exemplified by 4.7 (a), dots represent the clustered facilities in the North Coast region. Nearby pipelines with different diameters are color marked and they are connected through the dots. The assumption is that if the facilities failed, the downstream regions served by the pipeline with smaller diameters will be impacted. With this assumption, the impacted regions are identified in geographic information tools, i.e. ArcGIS software (ESRI, 2019) and are denoted as polygons in Figure 4.7. The population residing in the polygon regions is then calculated based on census data. Of course, impacts are also linked to inputs the of industries in a region. However, because detailed gas supply and demand data are not available, this population-based approach is believed to be reasonable. After estimating the population impact for each facility, the analysis calculates the facility-level impact on natural gas supply by dividing the impacted population by the total population in each region. The results are summarized in the last column of Table 4.6.

Table 4.7 reports the facility status and aggregated regional impacts under different ranges of sea-level rise. At a certain sea level, a facility with an elevation lower than this level fails, as indicated by 'F' in Table 4.7. The Regional Impact is calculated based on the impacted population corresponding to the failed facilities. For example, assume the future sea-level for California rise, to $330cm$. This case corresponds to scenario 5 (range between 329 and $334cm$). Five facilities are expected to be inoperable because under sea water. Facility (a) is located in the North Coast region, and the impact is a reduction of 32.58% (or 0.3258) on gad supply. Facilities (b) and (d) are both located in the North Bay region. Since the impacted regions of the facilities are not overlapping, their aggregated impact can be estimated by summing the individual impacts, as shown in Table 4.6 ($0.0324 + 0.0104 = 0.0428$). By the same logic, the aggregated impact in the South Bay region is determined by adding the individual impacts of facility (e) and (h) ($0.0071 + 0.2786 = 0.2857$). Next, our analysis estimates the economic impacts of each scenario.

Table 4.7: Regional impacts of different sea-level rise ranges

Scenarios	Sea-level Rise Range (cm)	Facility Cluster							Regional Impact		
		a	b	c	d	e	f	g	North Coast	North Bay	South Bay
1	176<=E<208					F					0.0071
2	208<=E<264	F				F			0.3258		0.0071
3	264<=E<326	F			F	F			0.3258	0.0104	0.0071
4	326<=E<329	F	F		F	F			0.3258	0.0428	0.0071
5	329<=E<334	F	F		F	F		F	0.3258	0.0428	0.2857
6	334<=E<367	F	F	F	F	F		F	0.3258	0.0756	0.2857
7	367<=E	F	F	F	F	F	F	F	0.3258	0.0756	0.3347

* 'F' indicates a cluster of failing facilities under a given sea-level rise range. Facilities with a minimum elevation lower than the given sea level rise are assumed to fail to provide service to local customers.

In general, three major sources of natural gas supply are identified for each region: local gas supplied to the region, international gas imports, and the gas imports from other U.S. regions. The natural gas originating from all those sources constitutes the gas Armington composites in a CES cost function, and is consumed by representative agents through private consumption, government consumption, investment, and intermediate goods consumption. Seven scenarios are examined and simulated in this analysis, in addition to the baseline scenario, based on the different ranges of sea level rises in Table 4.7.

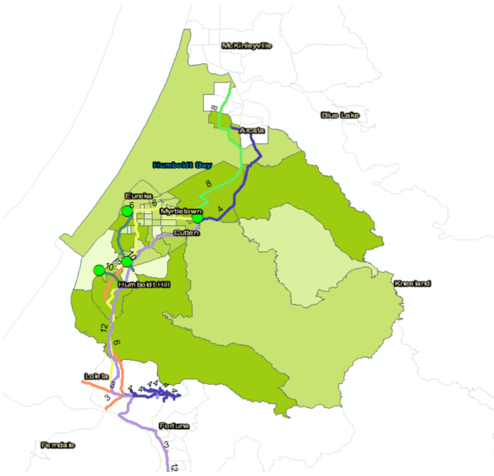
The analysis applied most of the elasticities of substitution commonly used in literature (Paltsev et al., 2005; Caron et al., 2015). As indicated earlier, one of the most important concept in CGE modeling is the Armington aggregation, which represents the imperfect substitution of goods produced domestically and imported from other regions. The elasticity of substitution in Armington aggregation helps quantify the extent of imperfect substitution. However, this is not the only place where the elasticity of substitution has an effect. The elasticity of substitution also plays an important role in production processes and final consumption. To be more specific, as illustrated in Figure 4.2, for any sector's production, commodities produced by all other sectors are inputs to produce that sector's output. For example, all non-energy commodities, including agriculture, service, transportation, energy-intensive and manufacturing commodities, as well as energy commodities such as coal, refined oil, natural gas, and electricity are used to produce electricity. However, not all commodities could be replaced or substituted equally. Some are better substitutes for each other, such as coal and oil, and some are not, such as agricultural and manufacturing commodities. Therefore, different elasticities of substitution are adopted for different commodities inputs. Similarly, another place where the elasticity of substitution plays a role lies in the private consumption as shown in Figure 4.3.

In summary, the analysis carefully adjusted three sets of elasticities of substitution in the model, including

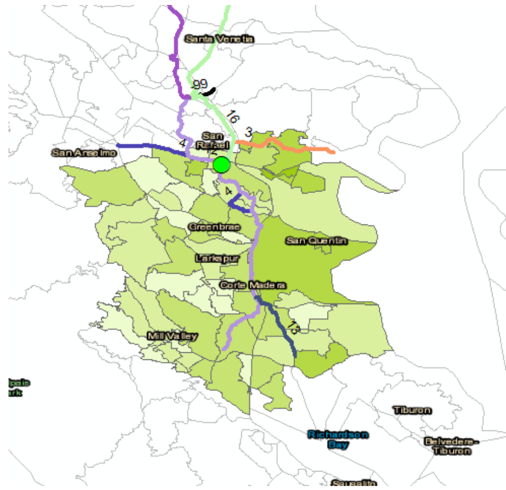
1. For Armington goods, to address the relationship between imports/exports and domestic goods.

2. For CES production functions, to change the substitution capability of different input factors.

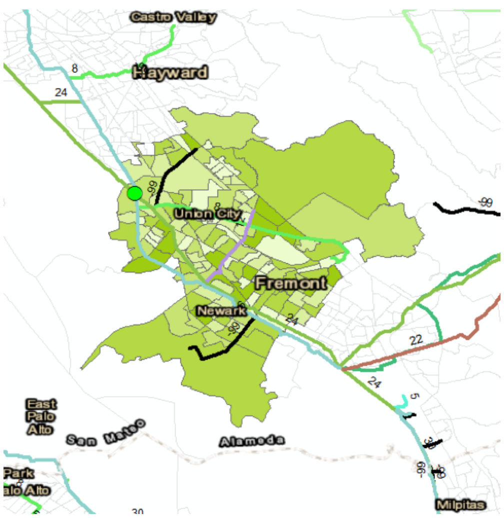
3. For private consumption, to change the commodity consumption structure in utility functions for households.



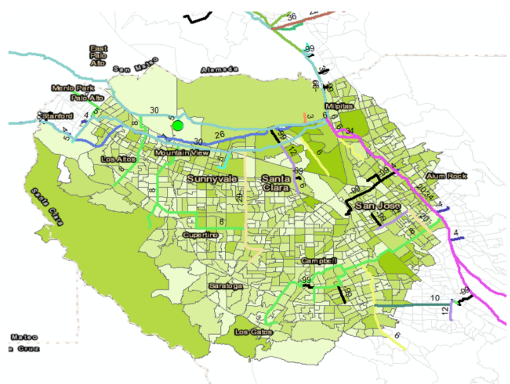
(a) Facility No.3, 827, 828, and 829 in North Coast



(b) Facility No.927 in North Bay



(c) Facility No.946 in South Bay



(d) Facility No.593 in South Bay

Figure 4.7: Impacted regions by facility: An illustration

4.7 Results

Seven scenarios, defined by different ranges of future sea level, are identified and simulated. These scenarios present a comprehensive list of economic impacts on the natural gas sector resulting from sea-level rising. Given the redundancy of going through all the results, this section uses scenario 5 as an example to illustrate the results. Understanding the results for scenario 5 makes it easy to understand the results of the other scenarios. The section further compares GDP results among different scenarios. The comparison allows an understanding of the magnitude of the impact resulting from different sea-level rising scenarios. The tables of comprehensive results of other scenarios are presented in Appendix A.4. All the results are displayed as relative changes, in a percentage term, from the baseline scenario. The results of regions within California are closely examined, as they are the main focus of the research[9]. Although results for states and regions outside California are not reported in this thesis, they are readily available from the simulations.

Tables 4.8–4.12 summarize the results of scenario 5. In this scenario, the decrease of gas supply to the three directly impacted regions causes changes in the outputs and prices of different economic sectors and regions. Table 4.8 reports the impacts on sectoral supply of the nine California regions. By scenario definition, when the sea level is within range of $329cm$ to $334cm$, the analysis introduces a supply shock to North Coast, North Bay and South Bay by 32.58%, 7.56% and 28.57%, respectively ('Natural gas' column of the Table 4.8). For the gas sector supply, the regions other than those three directly impacted regions increase their local gas supply accordingly. The logic behind this shift is that, when less

[9] California is impacted more significantly by a direct shock introduced to gas supply of North Coast, North Bay and South Bay.

gas is available to North Coast, North Bay, and South Bay, those regions are short of local energy supply. This shortage will incentivize the other regions to increase natural gas imports. As the table indicates, this results in the Central Valley and Sacramento regions to significantly increase their sectoral supply (by 5.5579% and 3.2681%, respectively), as compared to other regions, e.g., SoCal with PGE pipelines (by 0.2164%) and Sierra Nevada (by 0.8515%). These regions are neighboring regions with a relatively large economic size. To be more specific, the economic size of both the Central Valley and Sacramento regions is larger than the other nearby regions, and therefore they possess more resources to respond to the shock, thereby providing more natural gas to the whole system. Unlike Southern California regions, i.e., SoCal No PGE and SoCal PGE, these two regions are located closely to North Coast, North Bay and South Bay, and therefore the shock has a more direct impact on gas imports/exports between the three regions and the Central Valley/Sacramento regions.

Table 4.8 also indicates some important supply pattern changes in other non-gas sectors. For example, the supply of manufacturing sector in the North Coast and South Bay regions drops significantly (by -5.0781% and -3.9218%, respectively). A similar pattern is observed for the energy-intensive sector in these two regions (-3.2237% and -4.4854%). The North Bay region, however, appears to have a different supply pattern. While it is a directly shocked economy, just like the other two regions, its manufacturing and energy-intensive sectors are not negatively impacted as are the North Coast and South Bay regions. One possible reason for this divergent impact is that the South Bay and North Coast regions are more heavily reliant on natural gas as energy supply. The results can also be explained by the magnitude of the shock. The gas shock imposed on the North Coast and South Bay regions is around -30%, which is a fairly large shock to one sector, while the shock for the North Bay region is less than -5%. Although the gas supply from the North Bay region decrease, only a small part of the manufacturing and energy-intensive sector, which are reliant on gas supply, are negatively impacted. It may be relatively easy for them to seek alternative energy sources, and therefore their production activities will not necessarily be negatively impacted.

Table 4.8: Impacts on sectoral supply under scenario 5 (%)

Regions \ Sectors	Service	Transportation	Manufacturing	Energy-intensive	Agriculture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0688	-1.0049	-0.8035	0.5882	0.2054	1.0400		-0.4728	0.2574	0.8176
Central Valley	-0.1201	-0.5901	-0.0023	0.5311	0.2201	5.5579		-0.0930	0.0027	-4.0697
North Bay*	0.2144	-0.6097	0.4557	0.2673	0.2353	-4.2784		-0.2898	0.2462	-1.6083
North Coast*	0.6297	-2.9266	-5.0781	-3.2237	4.4817	-32.5790		5.6877	3.0192	-13.1567
Sacramento	-0.0807	0.0149	0.7323	0.5867	0.0003	3.2681	1.4241	-0.6298	-0.1219	-0.3581
SoCal No PGE	-0.0216	-0.2468	0.0626	0.1393	-0.1122	0.4877	0.0609	-0.1785	0.0633	0.4017
SoCal PGE	-0.0157	-0.2535	0.6487	0.1358	-0.2163	0.2164	-0.1100	-0.1086	-0.0023	0.3974
South Bay*	0.9193	3.6055	-3.9218	-3.4854	6.8948	-28.5724		7.1138	2.6628	-15.3642
Sierra Nevada	-0.0440	-0.2517	0.5133	0.1925	-0.0170	0.8515		-0.2008	0.0016	1.1519

* Directly impacted regions include North Bay, North Coast and South Bay regions.

Regarding the energy sectors, refined oil and electricity are the two sectors that also worth analyzing. Refined oil (petroleum) and natural gas are closely correlated sectors, since they share similar production processes, such as extraction. Therefore the supply changes in these two sectors are closely aligned. Table 4.8 reports that the supply of refined oil decreases by 1.6083%, 13.1567% and 15.3642% in the North Bay, North Coast and South Bay regions. The magnitude of refined oil supply reduction is around half the size of the reduction in gas supply, which is much larger than the supply change in any other sectors.

Regarding the electricity sector, Table 4.8 suggests that its supply increases in nearly all the regions. This increase, especially in the directly impacted regions (North Bay, North Coast and South Bay regions), may seem counterintuitive. Natural gas serves as an input to the electricity sector, and one might presume that a reduction in gas production will inevitably lead to a reduction in electricity output. However, this argument applies to the short-run, in which limited substitution is allowed between gas and electricity (i.e., complement effect). The analysis suggests that substitution is a dominant force in the long-term in determining the electricity output. The decrease in gas supply encourages more use of electricity as energy input into other production processes. In this sense, electricity is serving as a competitive energy source to natural gas sector. This substitution effect between electricity and natural gas sector outweighs the complementary effect, leading to an increase in electricity output. For example, an industrial facility that uses gas for heating may seek alternative heating processes when natural gas is not readily available or not economic to use. Some possible choices are to adopt electric heat pumps or solar heat pumps. Switching energy source from natural gas to electricity might encourage a greater supply of electricity when less natural gas is available.

Table 4.9: Impacts on Armington aggregate under scenario 5 (%)

Regions \ Sectors	Service	Transportation	Manufacturing	Energy-intensive	Agriculture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0517	-0.0459	-0.1142	0.0171	0.0901	0.2977	0.2763	0.1225	0.0296	-0.1890
Central Valley	-0.1241	-0.0364	-0.0538	0.0545	0.0867	-0.7774	0.1597	0.4284	-0.0465	-0.1148
North Bay*	0.0334	-0.2595	0.0256	-0.0303	0.0916	-1.4833	0.3905	-0.5876	0.0784	-0.2536
North Coast*	1.4053	0.4150	0.3407	-0.0065	2.5084	-10.3722	1.3608	-4.7185	1.6432	0.4086
Sacramento	-0.1449	-0.0268	0.0259	0.0196	-0.1273	0.1696	-0.0035	0.3258	-0.1342	-0.0892
SoCal No PGE	-0.0124	-0.0018	0.0003	0.0156	-0.0135	0.3107	0.0591	0.0654	0.0071	-0.0266
SoCal PGE	-0.0374	-0.0304	0.0306	0.0205	-0.1163	0.3296	0.0691	0.0628	-0.0186	-0.0570
South Bay*	1.4993	1.1794	-1.5064	-0.4410	3.1992	-10.6716	1.3272	-1.3690	1.4269	1.8621
Sierra Nevada	-0.0686	-0.0294	0.0509	0.0075	-0.0447	0.4142	0.0895	0.1078	-0.0397	-0.1020

* Directly impacted regions include North Bay, North Coast and South Bay regions.

Table 4.9 reports the impacts on Armington aggregates, which are used for households consumption, government consumption, investment or by other sectors as intermediate goods for their production processes. The change in Armington composites summarizes the joint effects of changes in local supply, international imports, and domestic imports, thereby serving as a good indicator of each commodity's overall consumption. Of particular interest, the overall magnitude of change of the Armington composite is much smaller than the magnitude of change in sectoral supply in Table 4.8. Consider the natural gas sector. The changes in the Armington aggregate are -1.4833%, -10.3722%, and -10.6717% for the North Bay, North Coast and South Bay regions, respectively, whereas the reductions in sectoral supply are -4.2784%, -32.5790% and -28.5724%, respectively. This result suggests that the economy is relatively elastic to imposed shocks. Although the gas sectoral supply of those three regions is reduced substantially, the economy responds to the shock by possibly reducing gas exports to other regions and by increasing gas imports to balance gas demands. While the overall demand of gas still decreases, the drop is much smaller than the original shock, due to the compensation resulting from increasing gas imports. A similar pattern is observed for the electricity sector. The increase of the electricity Armington aggregate is only 0.0784%, 1.6432%, and 1.4269% for North Bay, North Coast and South Bay regions, respectively, while the corresponding increases in the electricity supply, are 0.2462%, 3.0192%, and 2.6628%.

Although all sectors adjust their Armington aggregates downward because of the shock, the magnitude of the change is only marginal. Except for some sectors in the North Coast and South Bay regions, the magnitude of Armington aggregate change is always less than 2%. This outcome again indicates that the economy is relatively responsive and could well respond to the shock by adjusting substitution between different commodity sources. Less available local supply leads to more imports and less exports. This substitution helps stabilize the commodity market so that the overall demand will not dramatically change.

The changes in the supply prices of different sectors are reported in Table 4.10. A number of observations emerge. First, most of the sectors experience a price

Table 4.10: Impacts on supply price under scenario 5 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0934	0.1439	0.1655	0.1280	0.0609	0.1634		0.1406	0.2417	0.1704
Central Valley	0.0662	0.0599	0.0948	0.0688	0.0081	0.2922		0.1276	0.4781	0.9811
North Bay*	-0.0508	0.0382	0.0460	0.0593	-0.0041	2.7267		-0.0302	-0.0397	0.5171
North Coast*	0.4638	0.9563	1.0205	1.0897	-0.6508	10.1876		-2.2314	-5.0705	3.3225
Sacramento	0.0100	-0.0473	0.0215	-0.0080	0.0330	0.2831	-0.2178	0.1800	0.4839	0.3846
SoCal No PGE	0.0725	0.0711	0.1085	0.0784	0.0511	0.0773	0.0612	0.0774	0.0758	0.0457
SoCal PGE	0.0696	0.0631	0.0704	0.0664	0.0496	0.0833	0.0943	0.0705	0.1298	0.0659
South Bay*	0.2583	-0.7947	0.7057	0.9383	-1.0804	9.1549		-1.6749	-3.5967	3.7240
Sierra Nevada	0.0488	0.0564	0.0523	0.0402	0.0279	0.1043		0.1032	0.1502	0.0359

* Directly impacted regions include North Bay, North Coast and South Bay regions.

increase for nearly all the regions. For the natural gas sector, particularly, prices increase in all the regions. For the three directly impacted regions, the magnitudes of price increases are more drastic: 2.7267%, 10.1876% and 9.1549% for the North Bay, North Coast and South Bay regions, respectively. In contrast, the increase is milder (less than 0.3%) for the other regions. The increase in gas prices is intuitive. When there is a gas shortage, economics theory suggests that the market-created scarcity leads to a higher price. If only focusing on the gas market from a partial equilibrium framework, a shock on gas supply is equivalent to imposing a cap on the local supply quantity. This capping constraint incurs a positive dual variable, increasing the gas price. At the same time, the dual variable (price) also incurs an economic rent directly gained by gas providers/producers. However, in a general equilibrium model, the producers/firms are assumed to be zero-profit entities in the long-run. Therefore, the rent will need to be distributed to other entities, such as government, consumers, or as investment. The analysis assumes that the private consumers retain the rent in the long-term through monetary rebates (Burfisher, 2017). The results regarding private consumers are discussed in Table 4.11.

Household consumption is not restricted to a certain sector. Instead, it rep-

Table 4.11: Impacts on private consumption under scenario 5 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0604	-0.0584	-0.0575	-0.0538	-0.0476	-0.0447	-0.0499	-0.0549	-0.0953
Central Valley	-0.0768	-0.0842	-0.1036	-0.1246	-0.1524	-0.1817	-0.2130	-0.2413	-0.4688
North Bay*	-0.0020	-0.0025	-0.0106	-0.0154	-0.0229	-0.0258	-0.0415	-0.0717	-0.2614
North Coast*	0.0901	0.2471	0.7364	1.2746	2.0194	2.7253	3.3746	3.9880	6.7271
Sacramento	-0.0551	-0.0703	-0.1098	-0.1547	-0.2145	-0.2745	-0.3273	-0.3799	-0.6714
SoCal No PGE	-0.0526	-0.0488	-0.0378	-0.0254	-0.0086	0.0052	0.0080	0.0115	-0.0029
SoCal PGE	-0.0642	-0.0629	-0.0569	-0.0507	-0.0425	-0.0347	-0.0295	-0.0303	-0.0814
South Bay*	0.0430	0.1947	0.6111	1.0967	1.7346	2.3465	2.8363	3.2611	5.3299
Sierra Nevada	-0.0598	-0.0621	-0.0681	-0.0747	-0.0833	-0.0915	-0.0981	-0.1063	-0.2253

* Directly impacted regions include North Bay, North Coast and South Bay regions.

resents the purchasing power in general (for all sectors) of each household with different levels of income. For non-directly impacted regions, private consumption decreases for nearly all the household types. This is primarily driven by the price increase in most of the sectors and regions, as indicated in Table 4.10. The price increase further decreases the purchasing power of private consumers, leading to less private consumption. The private consumption results of the three directly impacted regions are different. In the North Bay region, private consumption decreases for all households, while the North Coast and South Bay regions experience an increase in their private consumption level. This is mainly due to the difference in magnitude of the shock. As explained earlier, the rent incurred from gas supply restriction will be distributed to private consumers. Therefore, consumers in the North Bay, North Coast and South Bay regions will all receive a payment representing this rent, thereby increasing their total income level and private consumption level. At the same time, they have a tendency to decrease their consumption, similar to consumers in any other regions, due to the increase in prices. The final result is a joint result of two counteracting forces. In the North Bay region, since the magnitude of the shock is relatively small, the rent is also relatively small, and therefore the increase in consumption due to rent retention is not sufficiently large to drive the final consumption level. However, the North Coast and South Bay regions have both experienced a large shock, so the rents incurred are much larger in magnitude, thereby leading to an increased consumption level.

Regarding distributional effects, if the impact on private consumption is positive, the higher-income households experience a higher level of consumption increase. However, if this impact is negative, the distributional effect is ambiguous. For example, in the Sacramento and Sierra Nevada regions, households with higher income experience more negative impacts, whereas in the Central Coast and SoCal regions with PG&E pipelines, lower-income households are worse off with larger negative impacts.

Table 4.12: Impacts on GDP under scenario 5

Regions	GDP (billion $)	GDP change (%)	GDP difference (million $)
National	19,846.40	-0.0001	-24.03
California	2,545.63	-0.0045	-115.79
Central Coast	37.40	-0.0020	-0.75
Central Valley	114.15	0.0180	20.54
North Bay*	150.61	0.0509	76.62
North Coast*	6.79	0.0076	0.52
Sacramento	137.46	0.0000	0.04
SoCal No PGE	1,376.25	0.0042	58.39
SoCal PGE	128.38	-0.0017	-2.21
South Bay*	536.03	-0.0501	-268.91
Sierra Nevada	58.56	0.0000	-0.02

* Directly impacted regions include North Bay, North Coast and South Bay regions.

Table 4.12 reports the impacts on the regional GDP. GDP(Gross Domestic Product) is a monetary measure of the market value of all the final goods and services produced annually, in all the sectors of an economy. To some extent, GDP reflects how active the economy is. Nominal GDP is calculated by summing private consumption, government consumption, investment, and net export (exports - imports). When the North Coast, North Bay and South Bay regions have limited gas supply capacity, the GDP of California and the U.S. as a whole both decrease (-115.79 and -24.03 million \$), indicating negative impacts overall on the California economy and the U.S. economy. A closer examination by region shows that nearly all of the GDP reduction comes from the South Bay region (-268.91 million \$). The North Bay and North Coast regions actually increase their GDP after the shock. This result, interestingly, highlights a property of the CGE model: even when the economy is at equilibrium in the baseline (BAU), it is not optimal at optimal GDP level for a given set of resources. In fact, the BAU equilibria for some regions (e.g. North Bay and North Coast) are likely to be less than optimal. As a result, when a negative shock takes place, the region actually becomes more active and produces a higher GDP. In a sense, the economy is all about allocation of resources. When imposing some negative shock, the economy attains a better and more efficient allocation of resources (for the North Bay and North Coast regions). For the South Bay region, a decrease in GDP is observed because of the large magnitude of the negative shock.

Finally, this analysis compares the GDP for all the seven sea-level-rise scenarios in Table 4.13, which presents the GDP difference for each scenario compared to the BAU. In general, Table 4.13 shows that with a higher level of sea rise induced by climate change, more regions are impacted, and the overall economy of California and the U.S. is more negatively impacted. When the shock is relatively small, it is easier for the local region and other related regions to overcome the negative shock in production capability by, for example, reducing consumption and shifting some local production to imports. However, when the shock becomes larger, it is much more difficult to compensate for the loss in production capability, especially in the case where substitutions among Armington goods, input factors or consumption factors are limited.

Table 4.13: GDP comparison for different sea levels

Difference(Million $)	SLR-1	SLR-2	SLR-3	SLR-4	SLR-5	SLR-6	SLR-7
National	0.8410	-6.1611	-1.0653	12.2055	-24.0254	-14.0115	-40.7668
California	-1.3624	-5.6540	-3.0088	3.5609	-115.7896	-112.1546	-150.7013
Central Coast	-0.0049	-0.0087	-0.0025	0.0138	-0.7509	-0.7451	-1.0027
Central Valley	0.3915	0.2293	1.0598	3.2878	20.5443	22.4917	25.1302
North Bay*	2.7757	1.1642	2.0505	4.0274	76.6212	76.6593	80.1021
North Coast*	0.0004	0.5370	0.5383	0.5419	0.5177	0.5192	0.5028
Sacramento	0.0395	-0.4831	-0.4545	-0.3795	0.0401	0.0780	-0.1074
SoCal No PGE	1.2723	-0.1919	1.6362	6.6736	58.3839	63.5374	71.4080
SoCal PGE	-0.0284	-0.0895	-0.1452	-0.3003	-2.2147	-2.3887	-2.8385
South Bay*	-5.8138	-6.8044	-7.6914	-10.3213	-268.9092	-272.2923	-323.8184
Sierra Nevada	0.0053	-0.0069	-0.0001	0.0174	-0.0221	-0.0142	-0.0775

* Directly impacted regions include North Bay, North Coast and South Bay regions.

4.8 Conclusions

A static Computable General Equilibrium (CGE) modeling is explicated in order to understand the impact of climate-change-induced sea-level rise on the northern California gas system. CGE modeling is capable of examining the complex interaction among various commodity and factor markets. It captures the interdependencies among markets by using macroeconomic data summarized in social accounting matrix. By explicitly considering market participants, including producers, consumers, government, CGE modeling specifies their economic relationships in mathematical terms and formulates the model so that it could predict the change in market outcomes, such as economic activity levels, prices, consumption levels, resulting from changes in current economic state.

This chapter develops a U.S. regional economic CGE model that accounts for bilateral trade flows of each commodity market. The model is a multi-sector, multi-region, multi-household and multi-government types model. It keeps track of the monetary flow of among all market participants. The model is capable of capturing the spillover effects of climate-change-induced sea level rise on the natural gas sectors. A set of critical natural gas facilities that are prone to sea-level rise risk in northern California are identified. The analysis approximates the magnitude of gas service disruption using affected population data. Several scenarios are simulated with different ranges of sea levels in this study.

The analysis in this chapter finds that a gas market shock induced by sea level rise will negatively impact U.S. economy by reducing the GDP level for both U.S. and California. The higher the sea level, the larger the negative overall economic impacts (from scenario 1 to scenario 7). With a sea level rise higher than 334cm, California GDP will be reduced by 150 million USD resulting from the shock on northern California gas system. The economy, although negatively impacted by the sea-level-rise-induced gas supply shock, will respond by seeking other energy resource alternatives to mitigate the negative impacts and stabilize markets. In a natural gas service disruption event, the impacted industries and consumers will quickly turn to other available fuel sources, like electricity, instead of stopping their economic activities. By this kind of substitution behavior, the economy is able to recover from the shock and find a new equilibrium with minimal impact on the current market outcomes.

CGE modeling distinguishes direct and indirect impact. Direct impacts are explicitly modeled impacts in the directly impacted regions. In this study, they represent the impacts on the natural gas sector in the North Bay, North Coast, and South Bay regions. Indirect impacts are implicitly derived from solving the model, representing the regional effects and cross-sectoral effects beyond the natural gas sector, also known as "ripple effects". Our outcomes indicate that the resulting direct impacts are usually relatively large in scale, and the indirect impact is often much smaller. The major reason for the small indirect impacts is due to the substitution effect in the Armington assumption, which recognizes the imperfect substitution between 1) input factors and commodities, 2) imports/exports and local goods, and 3) commodities preferences of consumers. An example of comparison between sectoral supply and Armington aggregate can help illustrate the effect of substitution. With a supply shock imposed on the gas sector, the direct impact on the sectoral supply are significantly higher than the indirect impacts on the resulting Armington aggregates. This is because Armington aggregates encompass the exports/imports other than sectoral output. It recognizes the imperfect substitution between goods supplied to export and local markets and between good imported and domestically produced. By adjusting the exports/imports, CGE model mitigates the negative direct impact on natural gas output and results in smaller magnitude of indirect change of Armington aggregate. Substitution effect also plays an important role in producer's technology choices. If one type of resource (e.g., natural gas) is limited, the complementary effect causes the output from gas-dependent industries (e.g. electricity) to drop. However, the electricity sector also serves as a competing energy source to natural gas, leading to an increase in electricity production. In this case, the counteracting substitution effect and complementary effect jointly determine the final direction of impact.

This chapter also highlights the fact that the baseline scenario might not represent optimal allocation of resources, but rather a representation of market outcomes in baseline general equilibrium based on market data. It is possible that the market could be further optimized to reach a more efficient allocation of resources. In this case, even a negative shock, might result in a more efficient market outcome when the economy is relatively responsive so that input substitution among factors can efficiently respond to exogenous shocks. For example, the North Bay and North Coast regions experience an increase in GDP and become economically more active when a minor negative gas shock is imposed. However, it does not necessarily suggest that the negative gas shock is “Pareto” efficient because not all the market participants experience a positive impact. Overall, with the analytical strength of CGE models, i.e., multiple sectors and regions, that allows considering regional and cross-sectoral effect, we have a more holistic view of the impacts of climate-change induced sea-level rise on the whole economy.

Chapter 5

Discussion on Linkage of Bottom-up and Top-down Models

5.1 Introduction

Energy system is a significant contributor to greenhouse gas and other local air pollutions. It plays a critical role in mitigating and adapting to climate change. Two contrasting types of models have been developed by researchers to identify cost-effective technological pathways. These pathways entail shifting energy systems toward more environmentally desired technology paths (Hourcade et al., 2006). Technology-rich "bottom-up" models or process-based models are built on detailed engineering and technological details. These models are typically partial equilibrium and focus exclusively on single sector, e.g., the energy sector. The representation of heterogeneous technologies in these models is made possible using piece-wise or step functions. With their richness in technology and engineering representation, these models are useful in examining implications of complex engineering systems, production technologies, and end users' demand. The solutions from bottom-up models predict future technologies to be employed in order to mitigate or adapt to climate change. However, a oftenly cited drawback is its lack of consideration of feedback or interaction between energy and other sectors.

On the other hand, economy-wide “top-down” models are useful in modeling different sectors’ economic activities through embedded production functions and supply-demand relationship. The strength of the top-down models lie on their ability to account for substitution among input factors through elasticities of substitution. Since the late 1980’s, the dominated top-down energy-economy model is CGE models, in part because their ability to capture the interaction between the energy system and the rest of the economy. (Hourcade et al., 2006). Although CGE models have an explicit representation of the microeconomic behavior of the economic agents, e.g., producers, consumers, and government, the technological details behind energy system are generally treated as a black box and are typically characterized by substitution functions with which the underlying elasticities describe the potential adjustment among various inputs and energy mix. More specifically, energy mix is adjusted and re-optimized based on relative prices among different fuel types. However, which technologies to be implemented in order to realize the optimal fuel or technologies are generally not answered, since the models do not have detailed representation of technological or engineering systems.

This chapter first discusses the strengths and weaknesses of aforementioned bottom-up and top-down models. The common approaches that link these two models are then discussed, including soft-linking, hard-linking, and hybrid approaches. The chapter concludes the thesis and discusses future work.

5.2 Bottom-up Models

Bottom-up models, particularly those that focus on the energy sector, are typically formulated as optimization problems that determine technology choices by minimizing investment costs while subject to projected future energy demand (Böhringer and Rutherford, 2008). Bottom-up models are flexible in representing energy systems, e.g., investment, operations, and consumption decisions, and are appropriate to answer different economic or policy questions, ranging from short-term operation scheduling to long-term investment planning problems. The outputs from bottom-up models include timing of introducing new technologies, phase-out of old technologies, etc.

However, bottom-up models tend to overestimate technological potentials, especially those with low costs (Wing, 2006) and, thus, ignores financial risk associated with new clean promising technologies (Fortes et al., 2014). Hence, bottom-up models have been criticized for misrepresenting a realistic micro-economic framework by underestimating the abatement costs (Bataille et al., 2006; Grubb et al., 1993; Wilson and Swisher, 1993). Other researchers also are concerned about them for not providing realistic portrayal of consumers' technological choices (Labriet et al., 2012). Moreover, the impact of long-term energy policies is not likely to be confined to the energy system alone. Thus, any partial equilibrium models that focus on one sector fails to include an economy-wide framework and consequently leads to unrealistic results. They also do not account for the macro-economic impact resulting from different energy pathways or policies because the changes in economic structure, productivity, and trade, which are crucially in affecting the rate, direction and distribution of the economic growth, are missing (Hourcade et al., 2006).

5.3 Top-down Models

On the other hand, top-down models explicitly consider interactions among energy systems and rest of the economy. CGE models, in particular, provide a consistent framework for analyzing those interactions through economics principles. By solving individual participants' problems through price-quality relationship, the models could be used to study not only the cross-sectoral and but also cross-regional spill-over economic impacts resulting from energy policies or other types of shocks. The models also account for the income/wealth endowment and expenditure associated with all market participants, thereby capable of addressing income distribution and other distributional implications among agents in an economy. (Frei et al., 2003). In summary, the strength of the models makes them particularly suitable for examining energy regulation and taxation problems that tend to affect the whole economy(Wing et al., 2008).

Although CGE models explicitly represent the microeconomic behavior of the market agents, they neglect the technological and engineering details, which are important in the energy sector. As indicated in Chapter 4, the energy sector in a CGE model can only be represented by production functions, describing substitution possibilities through elasticity of substitution. Different technologies within a sector are represented as competing resource inputs, i.e., intermediate goods; and production functions are constructed as neoclassical differentiable substitution. However, the structural changes of technologies (i.e., phasing out of a technology or the introduction of new technologies) are incompatible with the differentiable substitution (Frei et al., 2003). Therefore, production functions are not sufficient to represent the technologies in details.

Another drawback of CGE models is their lack of empirical evidence on elasticities, which determine the substitution among competing technologies. Those elasticities, usually derived from historical data, represent the technological flexibility now and, thus, with limited generalizability to the distant future (Grubb et al., 2002). Even with carefully designed nested production structures and carefully chosen elasticities of substitution, CGE models still can not capture the technological flexibility to a realistic extent. Another worth-noting caveat concerning the top-down models lies in their useage to evaluate energy- or climate-related policies. More specifically, because of lacking technological details in representing carbon emitting sectors in top-down models, it is difficult to assess the effect of commonly used price-based or fiscal policies, e.g., carbon tax, in presence of technology-specific regulation (Böhringer and Rutherford, 2009). The results are also believed to violate fundamental conservation principles of energy since top-down models represent commodity flow in terms of monetary values but not in physical units of commodity (Böhringer and Rutherford, 2009).

5.4 Linkage of Bottom-up and Top-down Models

Theoretically, the strengths and weaknesses of the bottom-up models and top-down models render an opportunity for these two types of models to forge together and to complement each other. Properly integrating them together and producing "hybrid" models might be able to compensate for the respective limitations possessed by each approach. In other words, the hybrid models not only contain engineering and technology details but also allow simulating impacts of energy policies or implication resulting from climate change events on the macroeconomy and feedbacks. However, integrating bottom-up and top-down models in a consistent way is challenging on several methodological fronts, including theoretical inconsistency, computational complexity, empirical validity, and policy relevance (Hourcade et al., 2006). Nevertheless, a number of researchers have attempted to combine the economic comprehensiveness of top-down models with the technological explicitness of bottom-up models.

Böhringer and Rutherford (2009) state that there are three types of different methods that have been proposed by researchers to integrate top-down and bottom-up models in the literature: (a) coupling existing large-scale bottom-up and top-down models, (b) explicitly building one model while applying a "reduced-form" approach to represent the other model, and (c) integrating two models by formulating them as a mixed complementarity problem (MCP). Wene (1996) groups the types of model links into informal (or soft-linking) and formal link (hard-linking) approaches. The processes, transfer, and communications of information or solutions between two models, which is directly controlled by researchers in the soft-linking approaches, are formalized and handled by computer programs in the hard-linking approaches. Helgesen and Tomasgard (2018) further extend the categories proposed by Wene (1996) to include "integrated models" in addition to the soft-linking and hard-linking approaches. The so-called "integrated models" actually correspond to the aforementioned (c) category in Böhringer and Rutherford (2009). The thesis next discusses these three approaches in details.

5.4.1 Soft-linking Approaches

Soft-linking approach, first developed by Hoffman and Jorgenson (1977), entails iteratively coupling existing large-scale bottom-up and top-down models by researchers. The approach combines the Brookhaven Energy System Optimisation Model (BESOM) with econometric macroeconomic model by first using macroeconomic model to derive changes in final demand and employment resulting from energy policy change. Then, the bottom-up models determine the optimal level of resources given scenarios associated with energy policy and the induced economic changes. Similar to Hoffman and Jorgenson (1977), a number of applications based on soft-linking approach focus on one specific sector or agent, e.g., the electricity sector (Martinsen, 2011), the transport sector (Schäfer and Jacoby, 2006), or demand functions of the consumers (Drouet et al., 2005). Overall, soft-linking approach is relatively transparent, and its complexity and computational time is manageable. However, due to inconsistencies in behavioral assumption and heterogeneity of the models, it is difficult to achieve overall consistencies and coherence (Böhringer and Rutherford, 2008). For instance, Lanz and Rausch (2011) find that the electricity technologies represented in the top-down models produce fuel substitution patterns that are inconsistent with bottom-up cost data. This inconsistency issue can not be addressed by iteratively applying the result of one model to the other. Thus, soft-linking approach has its limitation in providing consistent outcomes that are important in evaluating the performance of heterogeneous technologies across bottom-up and top-down models.

5.4.2 Hard-linking Approaches

Compared to the soft-linking approach, the ability to automating data transfer, processes, and computation is the key advantage of hard-linking approach. Using the hard-linking approach , processing information and transferring data are formalized and handled by computer programs without the need of users' intervention. One example of the hard-linking models is the MARKAL-Macro model Manne and Wene (1992), The long-term economic growth model in MARKAL-Macro is hard-linked to an economy-wide production function in order to estimate the energy demand. One well-known advantage of the hard-linking approach is its scalability and the uniqueness of solutions (Wene, 1996). When the model size becomes large and the number of model runs increases, the soft-linking approach typically needs more resources, in terms of labor and computational time, to implement, while the hard-linking approach consumes a compatible amount of resources. For each set of model assumptions and data, the hard-linking approach returns one unique solution (under some mild conditions), and the results can be properly documented so that researchers can review them latter. In summary, the hard-linking approach is much more efficient and productive compared to the soft-linking approach.

5.4.3 Integrated Approach

Recently, “integrated” or “hybrid” approach emerges as a promising tool. The approach applies a single integrated framework to represent both the bottom-up and the top-down models. The integrated framework formulates the market equilibrium as mixed complementarity problems (Rutherford, 1995). The resulting mixed complementarity problems allow researchers to capture both technological details and economic complexity in one single mathematical formulation. This approach is facilitated by the development of efficient solvers of solving large-scale complementarity problems, i.e., PATH (Dirkse and Ferris, 1995). One example is by Böhringer and Rutherford (2008) who explicitly models an energy-economic model based on an MCP formulation. A decomposition algorithm is further used to reduce computational time required to solve the resulting MCP (Böhringer and Rutherford, 2009). Moreover, Wing et al. (2008) recognizes the difficulty of constructing databases that integrate macroeconomic data with engineering information. His later work develops a method to address this issue and applies the approach to study the cost of carbon emission reduction (Wing, 2006). In a more recent paper, Helgesen and Tomasgard (2018) develops four formulations to compare the results from using hard-linking and integrated modeling approaches. The paper finds that being able to integrate bottom-up and top-down models in a coherent and consistent way is one of the biggest strength of the integrated approach. However, they acknowledge that the dimensionality and algebraic complexity remain the main limitations that prevent the hybrid models from having a real application.

5.5 Conclusions and Future Work

Climate change is a daunting challenge faced by our society today. Researchers have developed various quantitative energy models to identify cost-effective pathways to mitigate and to adapt to climate change. Bottom-up models that are built upon individual's optimization problem with detailed representation of engineering systems and heterogeneous technologies are popular computational tools when the focus is on one sector, e.g., the power electric sector or the natural gas sector. On the other hand, if the impacts on the whole economy spanning over multiple sectors and regions is of interest, top-down models based on supply-demand relationship of those sectors and regions is more appropriate. This chapter reviews three types of links that bridge the top-down and bottom-up models that the thesis develops in Chapters 3, and 4, including soft-linking, hard-linking, and integrated or hybrid approaches. The chapter concludes that the soft-linking approach is transparent and resource demanding, and its inconsistencies in behavioral assumption and heterogeneity of the models make the approach difficult to achieve overall consistencies and coherence. On the other hand, the hard-linking approach processes information and transfers data using computer programs so that the intervention by users is limited. The hard-linking approach also preserves the scale-of-economy as it can easily be scaled up to large problems without demanding more resources. Finally, the recent emerging integrated (or hybrid) approach provides an integrated framework that allows solving top-down and bottom-up models together by formulating them in a complementarity system. However, the dimensionality and algebraic complexity of the approach limits its real-life applications.

Among the three approaches, either the soft-linking approach or the integrated models could be applied to link the bottom-up model in Chapter 3, and the top-down model in Chapter 4. This is mainly because both of the bottom-up and top-down models in this thesis are already (or could be) formulated as MCPs. Thus, information on equilibrium prices and quantity demanded are readily to be extracted from the solutions and shared between the two models. However, a full deployment of these two approaches remains challenging for the following reasons:

1. The operation of power system is simulated by grouping hourly load into nine periods in Chapter 3. It is not consistent with the annual representation of the economy in the CGE model. Furthermore, the CGE focuses on short- and medium-run outcomes based on the solution concept of long-run equilibrium. This suggests that a capacity expansion model is needed in order to integrate the bottom-up model in Chapter 3, with the CGE model in Chapter 4.

2. To link the CGE model with a bottom-up model, the "link variables" between the two models should also be carefully evaluated. The link variables, which should be iteratively fed into these two models, include quantity de-

manded, equilibrium price, or even energy mixes.

3. Both of the bottom-up and CGE models developed in this thesis also encompass different regions. In particular, the CGE model in Chapter 4 considers the bilateral trade flows among all the regions in the U.S. while the bottom-up only studies mid-Atlantic region. This suggests that nesting the bottom-up (small region) within the top-down model based on either the soft-linking or integrated approach might be appropriate.

The implementation of integrating top-down and bottom-up model is beyond the scope of my current research. I will leave them for future work.

Appendix A

Appendix

A.1 Proof for propositions in Chapter 3

Proof 1. First, if there are only two firms with $x > 0$ holds for all states i so that (3.8) - (3.11) are all equality conditions. We can calculate that

$$\text{(3.8) - (3.9): } P_1 - P_2 + \lambda^+ - \lambda^- = -p_1^c(E_1 - E_a) + p_2^c(E_2 - E_a) \tag{A.1}$$

$$\text{(3.10) - (3.11): } P_1 - P_2 + \lambda^+ - \lambda^- = -p_1^c(E_1 - E_b) + p_2^c(E_2 - E_b) \tag{A.2}$$

From (A.1), (A.2), it yields

$$\begin{gathered} p_1^c[-(E_1 - E_a) + (E_1 - E_b)] = p_2^c[-(E_2 - E_a) + (E_2 - E_b)] \\ p_1^c(E_a - E_b) = p_2^c(E_a - E_b) \end{gathered} \tag{A.3}$$

We therefore conclude that $p_1^c = p_2^c$. The result holds for any number of firms, greater than two at any state. For example, we can add firm c at state 1 with x_{c11}, x_{c12} and assume they are both positive. Then we have the following additional equation:

$$P_1 - P_2 + \lambda^+ - \lambda^- = -p_1^c(E_1 - E_c) + p_2^c(E_2 - E_c). \tag{A.4}$$

Condition (A.4) together with either (A.1) or (A.2) would allow us conclude that $p_1^c = p_2^c$. We therefore extend our analysis beyond two-firm case in following analysis. On the other hand, we need to consider the case when $x > 0$ doesn't hold for all the firms. Suppose firms with $x_{fii} > 0$, $x_{fij} > 0$ or $x_{fii} = x_{fij} = 0$, i.e. "all or nothing scenario". Moreover, there exist at least two firms with $x_{fii} > 0$, $x_{fij} > 0$. For example, $x_{a11}, x_{a12} > 0$, $x_{b21}, x_{b22} > 0$ as before and $x_{c11} = x_{c12} = 0$. From (A.1), (A.2) we have $p_1^c = p_2^c$ as before and furthermore, we have additional conditions:

$$\begin{cases} P_1 - C_c' - \rho_c + p_1^c(E_1 - E_c) + \phi_{c1} = 0, \quad \phi_{c1} > 0 \\ P_2 - C_c' - \rho_c - \lambda^+ + \lambda^- + p_2^c(E_2 - E_c) + \phi_{c2} = 0, \quad \phi_{c2} > 0 \end{cases} \tag{A.5}$$

$$\longrightarrow \qquad P_1 - P_2 + \lambda^+ - \lambda^- = -p_1^c(E_1 - E_c) + p_2^c(E_2 - E_c) - \phi_{c1} + \phi_{c2} \tag{A.6}$$

In order to ensure $p_1^c = p_2^c$, $\phi_{c1} = \phi_{c2}$ needs to hold in this case. The same applies to the case of $x_{a11} > 0$, $x_{a12} > 0$, $x_{c11} > 0$, $x_{c12} > 0$ while $x_{b21} = x_{b22} = 0$. That is, state 1 has two firms with all positive output while state 2 has firms with no output.

Proof 2. Suppose that only one firm is with $x_{fij} > 0$ for all j, and other firms sell a positive quantity to some states but not to all the states. For example, $x_{a11}, x_{a12} > 0$, $x_{b21} = 0, x_{b22} > 0$ (or $x_{b21} > 0, x_{b22} = 0$). Then we have (A.1) and

(A.7)

$$P_1 - P_2 + \lambda^+ - \lambda^- = -p_1^c(E_1 - E_b) + p_2^c(E_2 - E_b) + \phi_b \tag{A.7}$$

, where ϕ_b can be either positive or negative. Subtracting (A.1) from (A.7) and collect terms would yield

$$(p_1^c - p_2^c)(E_a - E_b) = \phi_b \gtrless 0 \quad (\neq 0) \tag{A.8}$$

This concludes that $p_1^c \neq p_2^c$.

Proof 3. Suppose firms with $x_{fii} > 0, x_{fij} > 0$ do not exist. In this case some firms sell positive output at some states but not all. Some firms may sell nothing at states.

For example, firms a and b sell positive output at some of states.

$$p_1^c(E_a - E_b) + \phi_a = p_2^c(E_a - E_b) + \phi_b, \text{ slack } \phi_a \gtrless 0, \phi_b \gtrless 0 (\neq 0) \tag{A.9}$$

if $\phi_a = \phi_b$, then $p_1^c = p_2^c$, otherwise $p_1^c \neq p_2^c$.

Proof 4. If $p_1^c = p_2^c = p^c$ holds, A.1 can be written as,

$$\begin{aligned} P_1 - P_2 &= -\lambda^+ + \lambda^- + p^c[-(E_1 - E_a) + (E_2 - E_a)] \\ &= -\lambda^+ + \lambda^- + p^c(E_2 - E_1) \end{aligned} \tag{A.10}$$

When there is no transmission congestion, $\lambda^+ = \lambda^- = 0$. Therefore,

$$P_1 - P_2 = p^c(E_2 - E_1)$$

A.2 Data for Three-state Case Study

The data used in three-state example are presented in Tables A.1–A.3.

Table A.1: Intercepts of inverse demand function of the three-state example

Node	P_0	Q_0
1	228	1400
2	93.12	540
3	111.6	840

Table A.2: Generation profile of the three-state example

Plant	B_{0fih}	B_{1fih}	CO_2	Capacity	Firm	Node
1	38	0.02	0.58	250	3	1
2	35.72	0.03	0.545	200	1	1
3	36.8	0.04	0.6	450	2	1
4	15.52	0.01	0.5	150	1	2
5	16.2	0.02	0.5	200	2	2
6	0	0.001	0	200	3	2
7	17.6	0.02	1.216	400	1	3
8	16.64	0.01	0.249	400	1	3
9	19.4	0.01	1.171	450	1	3
10	18.6	0.02	0.924	200	3	3

Table A.3: Power transmission distribution factors of the three-state example

Node	1	2	3
1	0.3333	-0.3333	0
2	0.3333	0.6667	0
3	-0.6667	-0.3333	0

A.3 Data for PJM Market Simulation

(1) Loads: The simulation period is a full year in 2012, comprising 8784 h. The load is represented by nine blocks based on the season of the year and time of the day. We divide the year into three seasons: summer (May to Sep), winter (Dec to Feb), and spring&fall (Mar, Apr, Oct, and Nov); and divide each day into three time periods: midday (9 to 16), late night (1 to 5) and morning&evening (6 to 8, and 17 to 24). Each hour is then categorized into one of the nine blocks according to its season and time. The size of the blocks varies from 455 to 1683 h. Hourly load data for each node is obtained from the PJM website (PJM, 2017) and it serves as the basis to approximate the nodal inverse demand curves. We assume a short-run elasticity of 0.02, which is relatively inelastic (Chen, 2009).

(2) Emission standards: We base our five-year emission standards on the performance-based emission standards released by CPP. CPP publishes the performance-based emission baseline for 2012 and emission targets for 2030, upon which we linearly calculate the reduction percentage for a five-year time period. Although it's possible to include expansion planning for longer planning horizon, it's beyond our modeling scope because we focus on the efficiency implication between different policy scenarios, rather than making a long-term forecast. Then by running the baseline simulation and deriving the emission rate for each state, we impose the reduction percentage to simulated emission rate for each state to define the state-wise emission targets for state-by-state performance-based scenario. It further becomes the basis for emission targets for other scenarios as described in three-state case study.

(3) Generation characteristics: In total, 1623 generating units are included in our model. The generation capacity by fuel type for the simulated data are presented

Table A.4: Generation capacity by fuel type

Fuel Type	Capacity (GW)	Capacity Share
Coal	45.1	36.6%
Gas	38.8	31.5%
Nuclear	19.7	16.0%
Petroleum	10.4	8.5%
Renewables	4.0	3.3%
Other	5.1	4.1%

in Table A.4. The majority supply are provided by coal, gas and nuclear plants, while petroleum and renewable energy serve the peak load. Each unit's marginal cost is the sum of its fuel cost and non-fuel variable O&M cost. The required data come from multiple sources and were merged together. Capacity, prime mover, fuel type, capacity factor, and state are drawn from EIA datasets (EIA). Cost data such as fuel cost and O&M cost are derived from SNL dataset (SNL). Emission rate for each unit is from EPA Emissions & Generation Resource Integrated Database (eGrid) dataset (US EPA). The equivalent forced outage rate (EFOR) comes from NERC Generating Availability Data System (GADS) (NERC). For units without complete data, we estimate the values accounting for factors including their prime mover, fuel type, and capacity. In the model, other than capacity constraint and other balance constraints similar to three-state example, we further include forced outage constraint to account for unpredicted plant outages, and include capacity factor constraint to account for actual energy output.

(4) Transmission network: We follow the network data calculation by Ruth et al. (2008). Data including transmission thermal capacities and reactances required for deriving PTDFs, were obtained from the PowerWorld website. We expand the network so that each node is fully located within just one state.

A.4 Economic impacts of sea-level rising

A.4.1 SLR Scenario 1: $176cm \leq SL < 208cm$

Table A.5: Impacts on sectoral supply under scenario 1 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0014	-0.0240	-0.0229	0.0132	0.0048	0.0145		-0.0119	0.0068	0.0126
Central Valley	-0.0019	-0.0150	-0.0050	0.0112	0.0043	0.0654		-0.0051	0.0023	-0.0240
North Bay	-0.0037	-0.0029	0.0438	0.0221	-0.0170	0.1355		0.0137	-0.0037	-0.0269
North Coast	-0.0003	-0.0115	0.0105	0.0026	-0.0004	0.0031		0.0021	0.0030	0.0147
Sacramento	-0.0011	-0.0037	0.0134	0.0117	0.0014	0.0395	0.0230	-0.0121	-0.0011	0.0303
SoCal No PGE	-0.0004	-0.0062	0.0009	0.0029	-0.0015	0.0090	-0.0009	-0.0043	0.0015	0.0071
SoCal PGE	-0.0001	-0.0068	0.0150	0.0028	-0.0045	0.0029	-0.0021	-0.0032	0.0003	0.0066
South Bay	0.0230	0.0899	-0.0985	-0.0869	0.1640	-0.7095		0.1665	0.0641	-0.2864
Sierra Nevada	-0.0006	-0.0072	0.0098	0.0031	-0.0011	0.0114		-0.0024	0.0003	0.0184

Table A.6: Impacts on Armington aggregate under scenario 1 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0007	-0.0006	-0.0029	0.0004	0.0025	0.0054	0.0070	0.0014	0.0012	-0.0038
Central Valley	-0.0017	-0.0005	-0.0012	0.0011	0.0019	-0.0022	0.0040	0.0050	-0.0001	-0.0031
North Bay	-0.0081	-0.0077	-0.0024	-0.0009	-0.0128	-0.0228	0.0106	0.0187	-0.0074	-0.0056
North Coast	-0.0001	-0.0004	0.0005	-0.0002	0.0009	0.0080	0.0022	0.0006	0.0006	-0.0020
Sacramento	-0.0023	-0.0011	0.0006	0.0005	-0.0016	0.0071	0.0005	0.0028	-0.0020	-0.0026
SoCal No PGE	-0.0001	0.0000	-0.0001	0.0003	0.0001	0.0055	0.0012	0.0011	0.0003	-0.0006
SoCal PGE	-0.0006	-0.0007	0.0008	0.0005	-0.0023	0.0055	0.0015	0.0006	-0.0001	-0.0014
South Bay	0.0372	0.0291	-0.0380	-0.0111	0.0781	-0.2257	0.0278	-0.0344	0.0348	0.0460
Sierra Nevada	-0.0009	-0.0005	0.0011	0.0001	-0.0010	0.0062	0.0016	0.0015	-0.0004	-0.0020

Table A.7: Impacts on supply price under scenario 1 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0024	0.0031	0.0044	0.0034	0.0019	0.0033		0.0032	0.0040	0.0035
Central Valley	0.0017	0.0015	0.0028	0.0020	0.0006	0.0041		0.0027	0.0066	0.0085
North Bay	-0.0008	-0.0024	-0.0030	-0.0028	0.0037	0.0050		0.0014	0.0168	0.0091
North Coast	0.0015	0.0022	0.0020	0.0023	0.0009	0.0010		0.0007	-0.0002	0.0021
Sacramento	0.0004	-0.0005	0.0011	0.0003	0.0008	0.0034	-0.0032	0.0032	0.0070	0.0008
SoCal No PGE	0.0018	0.0017	0.0028	0.0020	0.0013	0.0017	0.0018	0.0019	0.0015	0.0010
SoCal PGE	0.0017	0.0016	0.0019	0.0017	0.0013	0.0018	0.0020	0.0017	0.0021	0.0015
South Bay	0.0063	-0.0205	0.0172	0.0228	-0.0263	0.1773		-0.0410	-0.0899	0.0651
Sierra Nevada	0.0012	0.0015	0.0017	0.0013	0.0010	0.0018		0.0018	0.0022	0.0011

Table A.8: Impacts on private consumption under scenario 1 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0014	-0.0013	-0.0011	-0.0009	-0.0005	-0.0003	-0.0002	-0.0002	-0.0004
Central Valley	-0.0016	-0.0016	-0.0017	-0.0019	-0.0021	-0.0023	-0.0026	-0.0029	-0.0063
North Bay	-0.0013	-0.0019	-0.0036	-0.0054	-0.0078	-0.0101	-0.0124	-0.0149	-0.0278
North Coast	-0.0012	-0.0011	-0.0007	-0.0004	0.0001	0.0006	0.0011	0.0016	-0.0006
Sacramento	-0.0011	-0.0013	-0.0019	-0.0026	-0.0034	-0.0043	-0.0051	-0.0059	-0.0110
SoCal No PGE	-0.0013	-0.0011	-0.0008	-0.0005	0.0000	0.0004	0.0006	0.0007	0.0007
SoCal PGE	-0.0015	-0.0014	-0.0012	-0.0009	-0.0006	-0.0003	-0.0001	0.0000	-0.0008
South Bay	0.0011	0.0049	0.0151	0.0270	0.0427	0.0577	0.0697	0.0801	0.1310
Sierra Nevada	-0.0013	-0.0013	-0.0013	-0.0012	-0.0012	-0.0011	-0.0011	-0.0011	-0.0029

Table A.9: Impacts on GDP under scenario 1

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.4212	0.0000	0.8410
California	2,545.7489	-0.0001	-1.3624
Central Coast	37.4057	0.0000	-0.0049
Central Valley	114.1269	0.0003	0.3915
North Bay	150.5312	0.0018	2.7757
North Coast	6.7920	0.0000	0.0004
Sacramento	137.4586	0.0000	0.0395
SoCal No PGE	1,376.1972	0.0001	1.2723
SoCal PGE	128.3845	0.0000	-0.0284
South Bay	536.2939	-0.0011	-5.8138
Sierra Nevada	58.5589	0.0000	0.0053

A.4.2 SLR Scenario 2: $208cm \leq SL < 264cm$

Table A.10: Impacts on sectoral supply under scenario 2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0006	-0.0264	-0.0207	0.0165	0.0000	0.0102		-0.0162	0.0043	0.0060
Central Valley	-0.0013	-0.0177	-0.0025	0.0148	0.0008	0.0662		-0.0078	0.0006	-0.0199
North Bay	-0.0032	-0.0149	0.0247	0.0142	-0.0246	0.1376		0.0069	-0.0006	-0.0100
North Coast	0.6364	-2.4374	-5.4636	-3.3158	4.5146	-32.5790		5.5572	2.8518	-13.8753
Sacramento	-0.0265	0.1057	0.1472	0.0879	-0.0226	1.2916	0.3505	-0.1199	-0.0837	-2.0506
SoCal No PGE	-0.0002	-0.0085	-0.0002	0.0028	-0.0085	0.0120	-0.0052	-0.0074	0.0008	0.0083
SoCal PGE	0.0000	-0.0074	0.0172	0.0044	-0.0095	0.0050	-0.0100	-0.0039	-0.0020	0.0102
South Bay	0.0239	0.0820	-0.1026	-0.0888	0.1533	-0.7095		0.1602	0.0635	-0.2825
Sierra Nevada	-0.0148	0.0260	0.0799	0.0392	0.0260	0.2787		-0.0632	-0.0213	0.0925

Table A.11: Impacts on Armington aggregate under scenario 2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0017	-0.0015	-0.0032	0.0001	0.0001	0.0037	0.0048	0.0008	0.0011	-0.0052
Central Valley	-0.0028	-0.0014	-0.0015	0.0012	-0.0001	-0.0019	0.0027	0.0050	-0.0004	-0.0044
North Bay	-0.0060	-0.0045	-0.0030	-0.0012	-0.0122	-0.0079	0.0088	0.0178	-0.0040	-0.0029
North Coast	1.4056	0.4337	0.3229	0.0010	2.4710	-10.7460	1.2294	-4.7269	1.6099	0.5032
Sacramento	-0.0386	0.0112	0.0019	0.0010	-0.0432	-0.2044	-0.0393	0.1357	-0.0464	0.0282
SoCal No PGE	-0.0004	-0.0003	-0.0004	0.0001	-0.0011	0.0064	0.0005	0.0014	0.0004	-0.0011
SoCal PGE	-0.0016	-0.0013	0.0005	0.0003	-0.0052	0.0083	0.0012	0.0013	-0.0009	-0.0019
South Bay	0.0377	0.0289	-0.0399	-0.0119	0.0782	-0.2244	0.0267	-0.0350	0.0356	0.0438
Sierra Nevada	-0.0192	-0.0035	0.0060	0.0022	0.0007	0.0756	-0.0025	0.0321	-0.0177	-0.0058

Table A.12: Impacts on supply price under scenario 2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0029	0.0037	0.0046	0.0035	0.0015	0.0057		0.0043	0.0081	0.0057
Central Valley	0.0023	0.0015	0.0030	0.0021	0.0002	0.0053		0.0036	0.0096	0.0089
North Bay	0.0018	-0.0001	0.0000	0.0003	0.0039	0.0066		0.0033	0.0145	0.0099
North Coast	0.4051	0.8505	0.9381	0.9916	-0.6779	10.0791		-2.2432	-5.0370	3.2022
Sacramento	-0.0039	-0.0230	-0.0167	-0.0181	0.0035	0.1318	-0.0683	0.0392	0.1646	0.3549
SoCal No PGE	0.0027	0.0025	0.0034	0.0027	0.0017	0.0030	0.0023	0.0028	0.0020	0.0019
SoCal PGE	0.0024	0.0019	0.0021	0.0020	0.0014	0.0029	0.0032	0.0023	0.0052	0.0021
South Bay	0.0079	-0.0190	0.0185	0.0242	-0.0259	0.1794		-0.0394	-0.0907	0.0663
Sierra Nevada	0.0014	-0.0077	-0.0071	-0.0085	-0.0051	0.0219		0.0216	0.0377	-0.0113

Table A.13: Impacts on private consumption under scenario 2 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0020	-0.0020	-0.0020	-0.0019	-0.0018	-0.0017	-0.0019	-0.0021	-0.0038
Central Valley	-0.0022	-0.0023	-0.0026	-0.0030	-0.0034	-0.0040	-0.0046	-0.0052	-0.0105
North Bay	-0.0022	-0.0025	-0.0034	-0.0044	-0.0057	-0.0070	-0.0082	-0.0097	-0.0178
North Coast	0.1350	0.2878	0.7622	1.2841	2.0064	2.6913	3.3191	3.9106	6.7260
Sacramento	-0.0084	-0.0133	-0.0253	-0.0392	-0.0578	-0.0762	-0.0922	-0.1065	-0.1758
SoCal No PGE	-0.0019	-0.0017	-0.0013	-0.0009	-0.0002	0.0003	0.0005	0.0007	0.0006
SoCal PGE	-0.0023	-0.0022	-0.0022	-0.0021	-0.0019	-0.0018	-0.0018	-0.0019	-0.0044
South Bay	0.0004	0.0043	0.0148	0.0271	0.0433	0.0588	0.0712	0.0819	0.1342
Sierra Nevada	-0.0054	-0.0068	-0.0111	-0.0158	-0.0220	-0.0280	-0.0334	-0.0390	-0.0674

Table A.14: Impacts on GDP under scenario 2

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.4142	0.0000	-6.1611
California	2,545.7446	-0.0002	-5.6540
Central Coast	37.4056	0.0000	-0.0087
Central Valley	114.1267	0.0002	0.2293
North Bay	150.5296	0.0008	1.1642
North Coast	6.7925	0.0079	0.5370
Sacramento	137.4581	-0.0004	-0.4831
SoCal No PGE	1,376.1958	0.0000	-0.1919
SoCal PGE	128.3844	-0.0001	-0.0895
South Bay	536.2929	-0.0013	-6.8044
Sierra Nevada	58.5589	0.0000	-0.0069

A.4.3 SLR Scenario 3: $264cm \leq SL < 326cm$

Table A.15: Impacts on sectoral supply under scenario 3 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0017	-0.0290	-0.0125	0.0214	0.0015	0.0427		-0.0151	0.0041	0.0472
Central Valley	-0.0057	-0.0152	0.0167	0.0227	0.0065	0.3668		0.0048	-0.0081	-0.3761
North Bay	0.0403	-0.0721	-0.1327	-0.0600	0.0893	-1.0412		-0.0941	0.0472	-0.0741
North Coast	0.6364	-2.4405	-5.4623	-3.3151	4.5119	-32.5790		5.5596	2.8560	-13.8481
Sacramento	-0.0277	0.1119	0.1521	0.0918	-0.0253	1.3316	0.3654	-0.1232	-0.0825	-1.9941
SoCal No PGE	-0.0009	-0.0076	0.0024	0.0054	-0.0125	0.0243	0.0053	-0.0077	0.0016	0.0208
SoCal PGE	-0.0012	-0.0048	0.0215	0.0065	-0.0124	0.0151	-0.0110	-0.0020	-0.0030	0.0239
South Bay	0.0249	0.0719	-0.1048	-0.0911	0.1553	-0.7095		0.1668	0.0649	-0.6851
Sierra Nevada	-0.0156	0.0267	0.0846	0.0423	0.0259	0.2909		-0.0670	-0.0199	0.1291

Table A.16: Impacts on Armington aggregate under scenario 3 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0034	-0.0033	-0.0032	0.0003	-0.0006	0.0104	0.0057	0.0060	-0.0003	-0.0081
Central Valley	-0.0081	-0.0029	-0.0021	0.0020	0.0012	-0.0816	0.0033	0.0282	-0.0044	-0.0030
North Bay	0.0375	0.0015	0.0118	-0.0003	0.0618	-0.0766	0.0041	-0.1446	0.0415	-0.0064
North Coast	1.4057	0.4331	0.3230	0.0010	2.4707	-10.7320	1.2336	-4.7264	1.6107	0.5016
Sacramento	-0.0400	0.0120	0.0020	0.0010	-0.0450	-0.1943	-0.0371	0.1441	-0.0470	0.0265
SoCal No PGE	-0.0011	-0.0005	-0.0001	0.0004	-0.0024	0.0158	0.0018	0.0035	-0.0001	-0.0011
SoCal PGE	-0.0028	-0.0013	0.0004	0.0005	-0.0074	0.0198	0.0022	0.0051	-0.0021	-0.0018
South Bay	0.0385	0.0269	-0.0409	-0.0127	0.0801	-0.3901	0.0402	-0.0353	0.0370	0.0415
Sierra Nevada	-0.0204	-0.0043	0.0063	0.0023	0.0001	0.0858	0.0011	0.0340	-0.0181	-0.0074

Table A.17: Impacts on supply price under scenario 3 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0026	0.0056	0.0038	0.0030	0.0004	0.0077		0.0049	0.0138	0.0077
Central Valley	0.0018	0.0015	0.0011	0.0009	-0.0015	0.0189		0.0052	0.0313	0.0792
North Bay	-0.0008	0.0160	0.0199	0.0209	-0.0149	0.2852		-0.0075	-0.0725	0.0263
North Coast	0.4051	0.8522	0.9381	0.9922	-0.6783	10.0820		-2.2438	-5.0377	3.2045
Sacramento	-0.0041	-0.0231	-0.0171	-0.0182	0.0033	0.1333	-0.0705	0.0406	0.1683	0.3546
SoCal No PGE	0.0027	0.0028	0.0032	0.0025	0.0017	0.0038	0.0012	0.0030	0.0035	0.0022
SoCal PGE	0.0025	0.0018	0.0017	0.0017	0.0010	0.0039	0.0044	0.0024	0.0090	0.0027
South Bay	0.0077	-0.0155	0.0191	0.0255	-0.0271	0.2296		-0.0410	-0.0873	0.1487
Sierra Nevada	0.0013	-0.0071	-0.0075	-0.0087	-0.0058	0.0231		0.0226	0.0399	-0.0108

Table A.18: Impacts on private consumption under scenario 3 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0023	-0.0024	-0.0029	-0.0033	-0.0037	-0.0043	-0.0050	-0.0057	-0.0100
Central Valley	-0.0036	-0.0042	-0.0060	-0.0079	-0.0104	-0.0129	-0.0153	-0.0175	-0.0321
North Bay	0.0042	0.0065	0.0128	0.0200	0.0297	0.0393	0.0473	0.0540	0.0859
North Coast	0.1349	0.2878	0.7622	1.2841	2.0066	2.6914	3.3194	3.9110	6.7262
Sacramento	-0.0087	-0.0137	-0.0262	-0.0405	-0.0598	-0.0788	-0.0953	-0.1100	-0.1814
SoCal No PGE	-0.0020	-0.0019	-0.0017	-0.0015	-0.0011	-0.0008	-0.0009	-0.0010	-0.0022
SoCal PGE	-0.0026	-0.0027	-0.0029	-0.0031	-0.0034	-0.0037	-0.0040	-0.0045	-0.0087
South Bay	0.0001	0.0040	0.0148	0.0273	0.0439	0.0596	0.0722	0.0831	0.1358
Sierra Nevada	-0.0056	-0.0071	-0.0117	-0.0167	-0.0233	-0.0296	-0.0354	-0.0413	-0.0716

Table A.19: Impacts on GDP under scenario 3

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.4193	0.0000	-1.0653
California	2,545.7472	-0.0001	-3.0088
Central Coast	37.4057	0.0000	-0.0025
Central Valley	114.1275	0.0009	1.0598
North Bay	150.5305	0.0014	2.0505
North Coast	6.7925	0.0079	0.5383
Sacramento	137.4581	-0.0003	-0.4545
SoCal No PGE	1,376.1976	0.0001	1.6362
SoCal PGE	128.3844	-0.0001	-0.1452
South Bay	536.2920	-0.0014	-7.6914
Sierra Nevada	58.5589	0.0000	-0.0001

A.4.4 SLR Scenario 4: $326cm \leq SL < 329cm$

Table A.20: Impacts on sectoral supply under scenario 4 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0048	-0.0360	0.0104	0.0353	0.0055	0.1336		-0.0118	0.0034	0.1607
Central Valley	-0.0179	-0.0081	0.0702	0.0446	0.0223	1.2042		0.0398	-0.0324	-1.3537
North Bay	0.1596	-0.2290	-0.5635	-0.2634	0.4032	-4.2784		-0.3720	0.1789	-0.2506
North Coast	0.6366	-2.4491	-5.4587	-3.3131	4.5046	-32.5790		5.5663	2.8674	-13.7733
Sacramento	-0.0310	0.1289	0.1660	0.1025	-0.0327	1.4424	0.4068	-0.1321	-0.0793	-1.8381
SoCal No PGE	-0.0027	-0.0052	0.0095	0.0126	-0.0234	0.0581	0.0343	-0.0086	0.0037	0.0552
SoCal PGE	-0.0046	0.0025	0.0334	0.0122	-0.0205	0.0431	-0.0139	0.0031	-0.0060	0.0618
South Bay	0.0279	0.0441	-0.1108	-0.0975	0.1608	-0.7095		0.1854	0.0687	-1.7938
Sierra Nevada	-0.0176	0.0288	0.0975	0.0510	0.0255	0.3247		-0.0777	-0.0158	0.2300

Table A.21: Impacts on Armington aggregate under scenario 4 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0081	-0.0082	-0.0031	0.0010	-0.0025	0.0290	0.0081	0.0204	-0.0044	-0.0162
Central Valley	-0.0231	-0.0070	-0.0037	0.0044	0.0048	-0.3002	0.0049	0.0928	-0.0157	0.0011
North Bay	0.1567	0.0180	0.0524	0.0020	0.2651	-0.2656	-0.0084	-0.5906	0.1660	-0.0160
North Coast	1.4059	0.4316	0.3234	0.0008	2.4697	-10.6934	1.2451	-4.7252	1.6127	0.4972
Sacramento	-0.0437	0.0140	0.0023	0.0008	-0.0499	-0.1665	-0.0312	0.1673	-0.0486	0.0217
SoCal No PGE	-0.0031	-0.0011	0.0009	0.0014	-0.0061	0.0417	0.0052	0.0092	-0.0014	-0.0010
SoCal PGE	-0.0060	-0.0012	0.0002	0.0009	-0.0134	0.0513	0.0052	0.0157	-0.0053	-0.0014
South Bay	0.0407	0.0214	-0.0437	-0.0149	0.0855	-0.8468	0.0775	-0.0361	0.0406	0.0351
Sierra Nevada	-0.0235	-0.0064	0.0073	0.0026	-0.0018	0.1138	0.0110	0.0391	-0.0192	-0.0121

Table A.22: Impacts on supply price under scenario 4 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0016	0.0107	0.0017	0.0016	-0.0027	0.0131		0.0065	0.0294	0.0132
Central Valley	0.0005	0.0016	-0.0042	-0.0023	-0.0060	0.0566		0.0097	0.0918	0.2738
North Bay	-0.0080	0.0600	0.0745	0.0774	-0.0665	1.0708		-0.0371	-0.3117	0.0716
North Coast	0.4049	0.8569	0.9383	0.9939	-0.6795	10.0899		-2.2453	-5.0395	3.2110
Sacramento	-0.0045	-0.0233	-0.0184	-0.0186	0.0027	0.1375	-0.0767	0.0445	0.1785	0.3538
SoCal No PGE	0.0027	0.0037	0.0025	0.0018	0.0015	0.0061	-0.0020	0.0035	0.0074	0.0031
SoCal PGE	0.0028	0.0017	0.0004	0.0009	0.0000	0.0064	0.0076	0.0024	0.0196	0.0043
South Bay	0.0072	-0.0057	0.0206	0.0290	-0.0306	0.3692		-0.0457	-0.0777	0.3777
Sierra Nevada	0.0009	-0.0054	-0.0087	-0.0094	-0.0076	0.0264		0.0253	0.0459	-0.0092

Table A.23: Impacts on private consumption under scenario 4 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0032	-0.0037	-0.0053	-0.0070	-0.0092	-0.0114	-0.0135	-0.0156	-0.0271
Central Valley	-0.0075	-0.0096	-0.0152	-0.0214	-0.0297	-0.0376	-0.0450	-0.0518	-0.0924
North Bay	0.0217	0.0313	0.0572	0.0872	0.1269	0.1666	0.1997	0.2292	0.3707
North Coast	0.1349	0.2878	0.7623	1.2844	2.0069	2.6920	3.3202	3.9121	6.7267
Sacramento	-0.0096	-0.0150	-0.0286	-0.0442	-0.0652	-0.0859	-0.1037	-0.1197	-0.1971
SoCal No PGE	-0.0024	-0.0025	-0.0028	-0.0031	-0.0035	-0.0040	-0.0048	-0.0054	-0.0100
SoCal PGE	-0.0037	-0.0041	-0.0050	-0.0061	-0.0076	-0.0090	-0.0102	-0.0116	-0.0207
South Bay	-0.0007	0.0032	0.0146	0.0280	0.0453	0.0620	0.0750	0.0863	0.1401
Sierra Nevada	-0.0063	-0.0081	-0.0135	-0.0193	-0.0269	-0.0343	-0.0410	-0.0478	-0.0831

Table A.24: Impacts on GDP under scenario 4

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.4326	0.0001	12.2055
California	2,545.7538	0.0001	3.5609
Central Coast	37.4057	0.0000	0.0138
Central Valley	114.1298	0.0029	3.2878
North Bay	150.5325	0.0027	4.0274
North Coast	6.7925	0.0080	0.5419
Sacramento	137.4582	-0.0003	-0.3795
SoCal No PGE	1,376.2027	0.0005	6.6736
SoCal PGE	128.3842	-0.0002	-0.3003
South Bay	536.2894	-0.0019	-10.3213
Sierra Nevada	58.5589	0.0000	0.0174

A.4.5 SLR Scenario 6: $334cm \leq SL < 367cm$

Table A.25: Impacts on sectoral supply under scenario 6 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0728	-1.0121	-0.7763	0.6042	0.2114	1.1621		-0.4679	0.2552	0.9262
Central Valley	-0.1335	-0.5816	0.0546	0.5549	0.2369	6.4624		-0.0555	-0.0230	-5.0152
North Bay	0.3351	-0.7681	0.0148	0.0595	0.5547	-7.5605		-0.5724	0.3805	-1.7830
North Coast	0.6299	-2.9353	-5.0745	-3.2217	4.4741	-32.5790		5.6948	3.0308	-13.0806
Sacramento	-0.0842	0.0327	0.7470	0.5979	-0.0075	3.3859	1.4682	-0.6389	-0.1189	-0.1967
SoCal No PGE	-0.0236	-0.2443	0.0703	0.1469	-0.1236	0.5235	0.0912	-0.1792	0.0654	0.4370
SoCal PGE	-0.0193	-0.2461	0.6613	0.1418	-0.2246	0.2454	-0.1132	-0.1030	-0.0054	0.4363
South Bay	0.9223	3.5760	-3.9279	-3.4925	6.9012	-28.5724		7.1369	2.6654	-16.4805
Sierra Nevada	-0.0461	-0.2493	0.5271	0.2017	-0.0172	0.8878		-0.2120	0.0056	1.2552

Table A.26: Impacts on Armington aggregate under scenario 6 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0574	-0.0513	-0.1141	0.0180	0.0882	0.3208	0.2775	0.1408	0.0244	-0.1978
Central Valley	-0.1400	-0.0404	-0.0555	0.0573	0.0905	-0.9866	0.1606	0.4987	-0.0587	-0.1105
North Bay	0.1539	-0.2422	0.0663	-0.0281	0.2976	-1.6712	0.3777	-1.0398	0.2040	-0.2628
North Coast	1.4055	0.4134	0.3411	-0.0066	2.5074	-10.3330	1.3725	-4.7173	1.6453	0.4042
Sacramento	-0.1488	-0.0247	0.0263	0.0194	-0.1325	0.1985	0.0024	0.3500	-0.1360	-0.0940
SoCal No PGE	-0.0145	-0.0024	0.0013	0.0166	-0.0173	0.3372	0.0626	0.0714	0.0057	-0.0264
SoCal PGE	-0.0408	-0.0303	0.0304	0.0210	-0.1226	0.3619	0.0721	0.0738	-0.0220	-0.0566
South Bay	1.5014	1.1736	-1.5093	-0.4433	3.2047	-11.1364	1.3688	-1.3694	1.4304	1.8569
Sierra Nevada	-0.0719	-0.0315	0.0520	0.0078	-0.0466	0.4433	0.0995	0.1132	-0.0409	-0.1066

Table A.27: Impacts on supply price under scenario 6 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0924	0.1491	0.1629	0.1262	0.0573	0.1701		0.1426	0.2608	0.1773
Central Valley	0.0650	0.0596	0.0891	0.0652	0.0032	0.3314		0.1326	0.5419	1.1793
North Bay	-0.0581	0.0829	0.1015	0.1168	-0.0566	3.5881		-0.0604	-0.2830	0.5634
North Coast	0.4636	0.9610	1.0206	1.0914	-0.6521	10.1957		-2.2330	-5.0725	3.3291
Sacramento	0.0095	-0.0477	0.0200	-0.0085	0.0323	0.2875	-0.2243	0.1841	0.4947	0.3837
SoCal No PGE	0.0724	0.0719	0.1077	0.0776	0.0510	0.0797	0.0577	0.0779	0.0799	0.0466
SoCal PGE	0.0699	0.0629	0.0691	0.0655	0.0484	0.0859	0.0975	0.0705	0.1408	0.0675
South Bay	0.2576	-0.7849	0.7072	0.9421	-1.0841	9.3381		-1.6801	-3.5842	4.0031
Sierra Nevada	0.0484	0.0580	0.0510	0.0394	0.0259	0.1078		0.1061	0.1565	0.0373

Table A.28: Impacts on private consumption under scenario 6 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0614	-0.0599	-0.0605	-0.0583	-0.0542	-0.0532	-0.0601	-0.0668	-0.1158
Central Valley	-0.0810	-0.0900	-0.1134	-0.1390	-0.1730	-0.2081	-0.2446	-0.2778	-0.5327
North Bay	0.0161	0.0230	0.0348	0.0531	0.0761	0.1039	0.1137	0.1067	0.0289
North Coast	0.0901	0.2471	0.7365	1.2749	2.0199	2.7259	3.3754	3.9891	6.7278
Sacramento	-0.0560	-0.0715	-0.1123	-0.1586	-0.2202	-0.2820	-0.3363	-0.3901	-0.6880
SoCal No PGE	-0.0530	-0.0493	-0.0389	-0.0271	-0.0112	0.0018	0.0039	0.0068	-0.0112
SoCal PGE	-0.0652	-0.0642	-0.0590	-0.0537	-0.0468	-0.0402	-0.0359	-0.0377	-0.0938
South Bay	0.0422	0.1939	0.6109	1.0974	1.7361	2.3488	2.8391	3.2643	5.3340
Sierra Nevada	-0.0605	-0.0630	-0.0699	-0.0774	-0.0871	-0.0964	-0.1040	-0.1131	-0.2375

Table A.29: Impacts on GDP under scenario 6

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.4063	-0.0001	-14.0115
California	2,545.6381	-0.0044	-112.1546
Central Coast	37.4049	-0.0020	-0.7451
Central Valley	114.1490	0.0197	22.4917
North Bay	150.6051	0.0509	76.6593
North Coast	6.7925	0.0076	0.5192
Sacramento	137.4587	0.0001	0.0780
SoCal No PGE	1,376.2595	0.0046	63.5374
SoCal PGE	128.3821	-0.0019	-2.3887
South Bay	536.0274	-0.0508	-272.2923
Sierra Nevada	58.5589	0.0000	-0.0142

A.4.6 SLR Scenario 7: $SL \geq 367cm$

Table A.30: Impacts on sectoral supply under scenario 7 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0852	-1.1859	-0.9078	0.7045	0.2485	1.3718		-0.5480	0.2963	1.0356
Central Valley	-0.1528	-0.6845	0.0501	0.6431	0.2729	7.3301		-0.0755	-0.0201	-5.5361
North Bay	0.3453	-0.8364	0.1975	0.1523	0.5218	-7.5605		-0.5580	0.3917	-2.0252
North Coast	0.6289	-3.0216	-5.0089	-3.2072	4.4684	-32.5790		5.7174	3.0580	-12.9680
Sacramento	-0.0933	0.0139	0.8503	0.6843	-0.0037	3.7272	1.6564	-0.7282	-0.1276	0.0774
SoCal No PGE	-0.0271	-0.2876	0.0809	0.1697	-0.1418	0.6041	0.0996	-0.2088	0.0756	0.5009
SoCal PGE	-0.0215	-0.2909	0.7707	0.1641	-0.2601	0.2788	-0.1317	-0.1212	-0.0056	0.4987
South Bay	1.0757	4.2169	-4.5837	-4.0803	8.1437	-33.4669		8.4307	3.1352	-18.9756
Sierra Nevada	-0.0511	-0.2985	0.6024	0.2276	-0.0246	0.9866		-0.2360	0.0080	1.4248

Table A.31: Impacts on Armington aggregate under scenario 7 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0669	-0.0590	-0.1333	0.0211	0.1039	0.3750	0.3220	0.1650	0.0282	-0.2302
Central Valley	-0.1596	-0.0460	-0.0643	0.0665	0.1050	-1.0785	0.1868	0.5660	-0.0657	-0.1312
North Bay	0.1322	-0.2918	0.0615	-0.0341	0.2662	-1.8885	0.4491	-1.0392	0.1886	-0.3050
North Coast	1.4056	0.4103	0.3441	-0.0080	2.5138	-10.2745	1.3932	-4.7160	1.6507	0.3880
Sacramento	-0.1674	-0.0319	0.0306	0.0227	-0.1475	0.2608	0.0065	0.3804	-0.1522	-0.1141
SoCal No PGE	-0.0165	-0.0028	0.0014	0.0191	-0.0195	0.3868	0.0719	0.0821	0.0068	-0.0311
SoCal PGE	-0.0469	-0.0356	0.0356	0.0245	-0.1416	0.4137	0.0834	0.0833	-0.0250	-0.0665
South Bay	1.7561	1.3814	-1.7596	-0.5152	3.7587	-12.9104	1.6098	-1.5992	1.6761	2.1839
Sierra Nevada	-0.0805	-0.0358	0.0598	0.0087	-0.0545	0.4987	0.1136	0.1261	-0.0451	-0.1230

Table A.32: Impacts on supply price under scenario 7 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.1085	0.1727	0.1905	0.1475	0.0673	0.1992		0.1671	0.3052	0.2078
Central Valley	0.0765	0.0693	0.1055	0.0769	0.0048	0.3763		0.1541	0.6168	1.3167
North Bay	-0.0659	0.0789	0.0959	0.1135	-0.0457	3.9297		-0.0593	-0.2338	0.6448
North Coast	0.4739	0.9788	1.0350	1.1083	-0.6474	10.2134		-2.2310	-5.0786	3.3493
Sacramento	0.0118	-0.0525	0.0263	-0.0073	0.0373	0.3141	-0.2508	0.2086	0.5510	0.3891
SoCal No PGE	0.0846	0.0837	0.1259	0.0907	0.0595	0.0926	0.0681	0.0909	0.0927	0.0541
SoCal PGE	0.0815	0.0733	0.0809	0.0766	0.0567	0.0997	0.1130	0.0823	0.1621	0.0785
South Bay	0.3024	-0.9238	0.8286	1.1037	-1.2706	11.3112		-1.9691	-4.2018	4.6906
Sierra Nevada	0.0566	0.0686	0.0611	0.0476	0.0316	0.1221		0.1203	0.1762	0.0452

Table A.33: Impacts on private consumption under scenario 7 (%)

Regions \ Income	Households <5k	Households 5-10k	Households 10-15k	Households 15-20k	Households 20-30k	Households 30-40k	Households 40-50k	Households 50-70k	Households 70k+
Central Coast	-0.0718	-0.0699	-0.0706	-0.0680	-0.0630	-0.0618	-0.0698	-0.0774	-0.1341
Central Valley	-0.0936	-0.1037	-0.1301	-0.1589	-0.1970	-0.2366	-0.2779	-0.3154	-0.6061
North Bay	0.0120	0.0171	0.0227	0.0347	0.0492	0.0692	0.0703	0.0525	-0.0848
North Coast	0.0823	0.2401	0.7321	1.2734	2.0223	2.7321	3.3854	4.0029	6.7289
Sacramento	-0.0640	-0.0814	-0.1271	-0.1788	-0.2478	-0.3169	-0.3776	-0.4383	-0.7751
SoCal No PGE	-0.0618	-0.0575	-0.0452	-0.0314	-0.0126	0.0027	0.0054	0.0088	-0.0114
SoCal PGE	-0.0759	-0.0747	-0.0684	-0.0621	-0.0537	-0.0458	-0.0406	-0.0425	-0.1070
South Bay	0.0500	0.2278	0.7165	1.2866	2.0351	2.7532	3.3278	3.8263	6.2525
Sierra Nevada	-0.0699	-0.0726	-0.0798	-0.0876	-0.0978	-0.1075	-0.1153	-0.1249	-0.2649

Table A.34: Impacts on GDP under scenario 7

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19,846.3796	-0.0002	-40.7668
California	2,545.5995	-0.0059	-150.7013
Central Coast	37.4047	-0.0027	-1.0027
Central Valley	114.1516	0.0220	25.1302
North Bay	150.6085	0.0532	80.1021
North Coast	6.7925	0.0074	0.5028
Sacramento	137.4585	-0.0001	-0.1074
SoCal No PGE	1,376.2674	0.0052	71.4080
SoCal PGE	128.3817	-0.0022	-2.8385
South Bay	535.9759	-0.0604	-323.8184
Sierra Nevada	58.5588	-0.0001	-0.0775

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