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FINAL PROJECT REPORT

Increasing the Resiliency of the Northern California Natural Gas System to Reduce Vulnerability to Climate Change

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PREPARED BY:
Primary Authors:
Yihsu Chen (University of California, Santa Cruz)
Andrew L. Liu (Purdue University)
Chi-hao Wang (California State University Fresno))
Na Chen (University of Cincinnati)
Jean-Michel Guldmann (The Ohio State University)

University of California, Santa Cruz
1156 High Street, Santa Cruz, CA 95064
(831) 502-7184
https://ucsc.edu/

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PREPARED FOR:
California Energy Commission

Joseph O'Hagan
Project Manager

Alex Horangic
Acting Office Manager
ENERGY GENERATION RESEARCH OFFICE

Jonah Steinbuck
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Drew Bohan
Executive Director

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation and bring ideas from the lab to the marketplace. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas & Electric Company and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Increasing the Resiliency of the Northern California Natural Gas System to Reduce Vulnerability to Climate Change is the final report for the Investigating Climate-change-induced Vulnerability of the Northern California Natural Gas Energy System and Identifying Resilience Options project (Contract Number: 500-2015-007) conducted by the University of California, Santa Cruz. The information from this project contributes to the Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

This project developed a system-level risk-analysis framework that builds upon regional economic models coupled with a decision-support tool that addresses the vulnerability of the Northern California natural gas system to climate-change-induced weather events, specifically sea-level rise and wildfire. The tool also identifies resilience options and the timing of their implementation to these events. Researchers identified gas facilities located either at relatively low elevation along the coastline at risk for sea-level rise, or in the northern part of the study region near a major segment of the gas system at risk for wildfire. The project showed that the economic loss induced by climate-change events is not necessarily limited to Northern California but will also likely affect the rest of the California economy. The extent of economic loss depends on the magnitude of a gas-service disruption, which is difficult to quantify due to a lack of publicly available data. Nevertheless, the project showed that the economy could recover by using an alternative supply of gas from Southern California together with reallocation of resources in the economy in the medium and long terms. Through simulation and stochastic modeling, this analysis finds that the Northern California natural gas system is generally robust against sea-level rise hazards prior to 2060 due to facility elevations. The probability of complete facility burn-down due to wildfire hazard is also minimal before 2080. However, toward the end of the century when natural-hazard risks are very likely to increase, considering the impacts of service interruptions to the California economy may lead to different decisions regarding hardening at-risk facilities. This project also provided a risk analysis framework that is suitable for the analysis of other types of infrastructures that are subject to climate-induced risks.

Keywords: Natural Gas, Climate-Change-Induced Hazards, Computational General Equilibrium, Models, Wildfire, Sea-Level Rise, Resilience Option

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EXECUTIVE SUMMARY

Introduction

The Northern California natural gas system encompasses a service territory of more than 70,000 square miles that stretches from Eureka in the north to Bakersfield in the south, and from the Pacific Ocean in the west to the Sierra Nevada in the east. This system provides gas services to more than 15 million customers through roughly 50,000 miles of pipelines. The network is laid out over different types of terrain and vegetation and is subject to different climate conditions and climate-induced risks. In particular, facilities in coastal areas are subject to flooding or storm surges that could be exacerbated by sea-level rise caused by warming temperatures and facilities in some inland regions are vulnerable to wildfire risks under extremely dry conditions.

The core location of natural gas facilities in Northern California is in the San Francisco-Oakland-Fremont area, which represents a gross domestic product of $412 billion. Within this area, the San Jose-Sunnyvale-Santa Clara area accounts for 50 percent of this regional value. The highly interconnected radial-gas network means that any damage to a facility is likely to affect the gas supply to customers downstream from that facility. The dense population around cities and highly developed economy can be viewed as vulnerabilities for this region, with significant economic losses likely when catastrophic natural-disaster events cause gas-service disruptions.

One possibility for preventing gas-service disruptions is for utilities to invest in resilience options to harden their gas systems. This investment choice entails a trade-off between the opportunity cost of up-front capital and future avoided damage costs. However, this damage is difficult to quantify and can be grossly underestimated if there is a failure to incorporate impacts from other affected sectors and regions. A lack of understanding of these climate-change-induced hazards and vulnerabilities combined with, the lack of analytical tools to evaluate resilience options, put the San Francisco-Oakland-Fremont area at great risk.

Project Purpose

This project developed a system-level risk-analysis framework built upon regional economic models and a decision-support tool that addresses the vulnerability of the Northern California natural gas system to climate-change-induced weather events. The framework identifies resilience options and implementation timing. The project addresses two types of climate-change-induced risk: sea-level rise and wildfire. The results from this project provide decision-makers and natural gas utilities with useful tools to evaluate the costs, benefits, and timing of various resilience investment options, as well as much-needed system vulnerability information. In particular, the project's conclusions benefit the natural gas sector as well as other economic sectors that could be adversely affected by gas shortages. In general, California's consumers will benefit from a more resilient natural gas system.

Project Approach

Research for this project was conducted in three steps and supported by a technical committee comprised of experts from academia and industry in the areas of risk assessment, natural gas modeling, and economic-impact assessment. The first step was a vulnerability assessment, which assessed the risk to the natural gas system by considering the probability and magnitude of a given hazard. The Scripps Institution of Oceanography at the University of California, San Diego, and the University of California, Merced, processed global-circulation models for both future sea-level rise and wildfire. This assessment was mapped with detailed information on the Northern California natural gas system to identify natural gas facilities vulnerable to climate-change-induced hazards. A population-based approach was then applied to approximate the magnitude of a natural gas-service disruption at each facility, for both sea-level rise and wildfire scenarios.

The magnitude of service disruption was subsequently fed into a multiple-regional computable general equilibrium model developed to quantify the economic impacts from natural gas service disruptions, including those beyond the natural gas sector. In the last step of the project, a stochastic decision-supporting tool was developed to optimize the types and implementation timing of resilience options while balancing the up-front costs of resilience options with the future benefits of avoided economic losses.

Project Results

The project successfully achieved its intended goal and objectives. A summary of results from each step follows.

The vulnerability assessment identified a total of 38 facilities that are likely at risk for either sea-level rise or wildfire. Sixteen of those facilities are clustered mainly around the San Francisco Bay Area and near Crescent City. The 22 remaining facilities are mainly located close to the northern boundary of the study region and along the western ridge of the Central Valley. The corresponding risk of sea-level rise and wildfire for each facility (or for a cluster of nearby facilities) over the next 80 years, expressed in 20-year time increments, was then calculated based on data from the Scripps Institution of Oceanography and the University of California, Merced. Data on the affected facilities were used in the next step of the analysis to quantify the extent of economic costs. The estimated risks of sea-level rise and wildfire were also used in the stochastic-resilience option analyses to evaluate investment timing.

The economic modeling results suggest that the disruption of natural gas supplies caused by climate-change induced hazardous events could drastically change the supply patterns of different energy sources and lead to multiple energy commodities' price increase (not limited to natural gas). Sea-level rise and wildfire can negatively impact the natural gas supply in regions with gas facilities that are vulnerable to climate-change risk. In response to gas supply shortages, impacted regions would reduce consumption, increase imports, and reduce exports to maintain their natural gas supplies. The economic sector would seek alternative energy resources to compensate for its natural gas shortages. This chain of events shows how the U.S. economy, and Northern California in particular, could be negatively impacted by climate-change-induced events.

A range of options is available to improve natural gas-system resilience and mitigate the potential risks and costs of future climate-change-induced events. Project researchers developed a stochastic dynamic programming-based model to help decision-makers choose the most cost-effective options. The modeling results depend heavily on assumptions made without access to investor-owned utility data, so should not be taken as either direct investment or policy recommendations. They nonetheless provide insights into how trade-offs between cost and potential future risk can be balanced in a systematic and scientific approach. Based on the simulation of future sea-level rises and the results from the stochastic dynamic programming model, researchers concluded that the Northern California natural gas system is generally resilient to sea-level rise until 2060, even under the most extreme projection (99-percent quantile). After 2060, the most vulnerable facilities are gas-regulating stations in Humboldt County. After 2080, no additional facilities will be subject to substantial flooding risk under a modest projection of sea-level rise.

However, various gas facilities in seven counties (Humboldt, Marin, Contra Costa, Solano, San Francisco, Alameda, and Santa Clara) will be subject to considerable flooding risk under the extreme projection of sea-level rise. As the cost of relocating will likely be much higher, the choice for all at-risk facilities will be to build a flood barrier in the 2080 period under the extreme sea-level projection scenario. Researchers identified three clustered natural gas facilities (a metering station in the North Coast region and regulating and pressure-limiting stations in the Sacramento Valley) that are subject to the potential risk of burning down from wildfire hazards, particularly in the later years of this century when wildfire risk is expected to intensify. However, if only repair and recovery costs are considered, the probability of total destruction by wildfire does not justify costly measures to mitigate those risks. As calculated in the computational general equilibrium model if costs to the entire Northern California economy are considered due to service interruptions, then certainly mitigation methods should be chosen in the 2080-2099 period despite their hefty investment costs.

This analysis has several caveats. First, the population-based approach to quantify the extent of gas service disruption is the second-best approach in the absence of private utility data needed to build a bottom-up engineering gas-system model. Second, some assumptions were made in defining damage states, that is, the possibilities of damage at a particular facility and in estimating resilience costs. These resilience costs are generic values based on published reports or other public sources. These values, some of which are inferred from other types of hazards that occurred outside of California, are likely to be either overestimated or underestimated. The general conclusion, however, is still robust. Overall, project results should be treated cautiously since their contribution is based on providing an evidence-based scientific approach that balances incurred costs and potential risks while considering the economic loss of the region caused by climate-change hazards to the natural gas system.

Knowledge and Technology Transfer

The research team analyzed the impact of climate-change-induced hazards, specifically sea-level rising and wildfire, on the natural gas infrastructure in Northern California. This analysis is primarily informative to policymakers and decision-makers in the energy sector, though its approach could also be of interest to other researchers. The research framework and findings have been accepted or presented at several international conferences including the Institute for Operations Research and Management Sciences and the Association of Collegiate Schools of Planning. The overall findings of the project will be submitted to scientific journals to highlight the role of the analytical framework in addressing the impacts of climate-induced hazards on a network infrastructure.

Benefits to California

This study is important to utility ratepayers because it provides a general understanding of how resilient Northern California's natural gas-system is in the face of future sea-level rise and wildfire risks. Since the study found that the system is resilient to these dual risks until the end of this century, the impacts of rate increase specifically related to hardening natural gas-systems in response to both sea-level rise and wildfire hazards may be insignificant in the near-term. The computational general equilibrium model can additionally help state government and policy makers understand the system-wide economic impacts from natural gas-service interruptions, while the developed stochastic model can help decision-makers identify and assess tradeoffs between the costs and benefits of hardening systems under uncertain conditions. This study lays the groundwork on how to best consider system-wide system costs and decision-making with more detailed modeling of interdependent sectors including natural gas, electricity, and water conveyance.

CHAPTER 1: Introduction

Resilience options in the face of effects from climate change are becoming important components of regional planning. Energy-sector vulnerability is a key issue among many climate-change issues in California. Without critical information on the vulnerability of the natural gas system, neither the government nor industry will be prepared to implement cost-effective resilience options to avoid potentially catastrophic future events.

The purpose of this report is to document research efforts to develop a system-level risk-analysis framework that builds upon state-wide or regional economic models coupled with a decision-support tool. This framework addresses the vulnerability of Northern California's natural gas system to climate-change-induced weather events (specifically storms, sea-level rise, and wildfire) and identifies resilience options and timing to counter their potentially destructive effects.

Climate-change-induced hazards and facility vulnerabilities are the two primary components of the risk to Northern California's natural gas system. Climate-change-induced hazards such as sea-level rise, wildfire, and other extreme future events are likely to increase risks to the natural gas system, either due to physical conditions (such as subsidence) or location, such as along the coast. The economic consequences could be widespread, not only in the natural gas sector but from spillover effects to other industries, such as manufacturing and heavy industry, that rely on natural gas, as well as downstream activities from these industries. The research utilized downscaled data from a global circulation model to identify facilities likely to be impacted by climate-change-induced risks and examined the implementation and timing of resilience options. This analysis was based on three steps:

1. Identify Northern California's natural gas system vulnerabilities (Chapter 2).
2. Estimate economic impacts, using regional economic models (Chapter 3).
3. Create resilience options and the timing of their implementation (Chapter 4).

The framework is scalable to larger systems and sufficiently flexible to incorporate other climate-change risks and extreme events including inland flooding, mudslides, and drought, which could also affect the natural gas system in the study region.

CHAPTER 2: Hazard Identification

2.1 Introduction

The climate-change-induced hazard analysis for Northern California aims primarily to provide decision-makers with assessment methods and relevant information on the risks of natural gas pipelines and stations to be exposed to sea-level rising (SLR) and wildfire hazards (WH). Using the projected outcomes on SLR and WH from previous California Energy Commission (CEC) funded projects, the project team explored different approaches and selected the most appropriate and feasible ones to better understand their likely frequency and intensity. In addition, the spatial characteristics of natural gas pipelines and stations and their surrounding geographical features (such as elevation) were obtained for further analysis to identity which parts of the natural gas system are most vulnerable to SLR or WH. This hazard assessment method converted projected outcomes into probabilities of inundation or burn events most likely to occur during certain periods (between 2020 and 2100) under given climate-change scenarios.

The objectives of this hazard analysis provided a sense of risk for decision-makers, and identified hazardous areas where natural gas pipelines and stations are located. The 80 years from 2020 to 2100 were divided into 4-time intervals of 20 years each. The hazard risk within each interval was calculated as the probability of inundation or wildfire events for a given facility due to climate change. The spatial distributions of these exposed natural gas facilities and SLR and WH areas are presented and discussed in this chapter. Identified hazard results were then input into a regional economic model that measured direct and indirect effects from the failure of a part of the natural gas system.

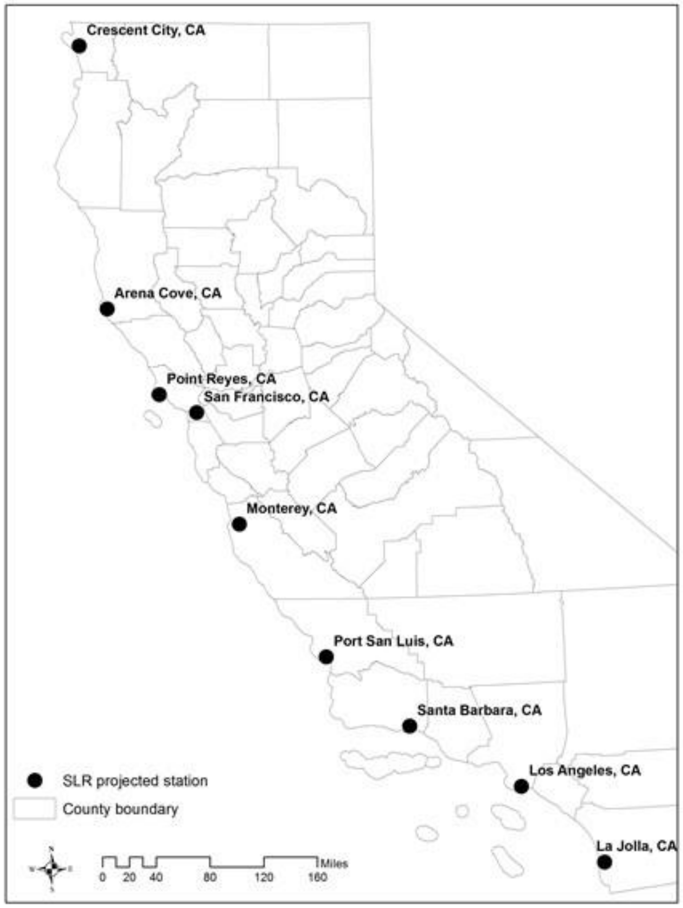
2.2 Data

2.2.1 Climate-Change-Induced Hazard Scenario Projections

2.2.1.1 Sea-Level Rise Scenario Projections

The risk analysis of sea-level rising over the natural gas system in Northern California was conducted using hourly sea-level (SL) projection data instead of pre-selected SLR values (Radke et al., 2017). This SLR scenario projection dataset was developed from 1950 to 2100 for nine coastal stations in California (Figure 1) by researchers from the Scripps Institution of Oceanography at the University of California, San Diego (Pierce, Kalansky, & Cayan, 2018). According to this dataset, the SL projections considered astronomical tides, regional and local weather influences, shorter-period climate fluctuations (for example, El Nino and other climate patterns), and long-term changes in regional sea levels generated by a subset of global climate models (GCM) and representative concentration pathways (RCP)-based sea-level rising (SLR) scenarios. The researchers selected the CNRM-CM5 (Centre National de Recherches Meteorologiques) global circulation model (GCM) output at three percentiles (50th, 90th, 99.9th) and two representative concentration pathway (RCP) scenarios (4.5 and 8.5) for the hazard analysis from 1950 to 2099. (There is no SL projection for the San Francisco station in 2100.)

Figure 1: Sea-Level Rising Projection Stations in California



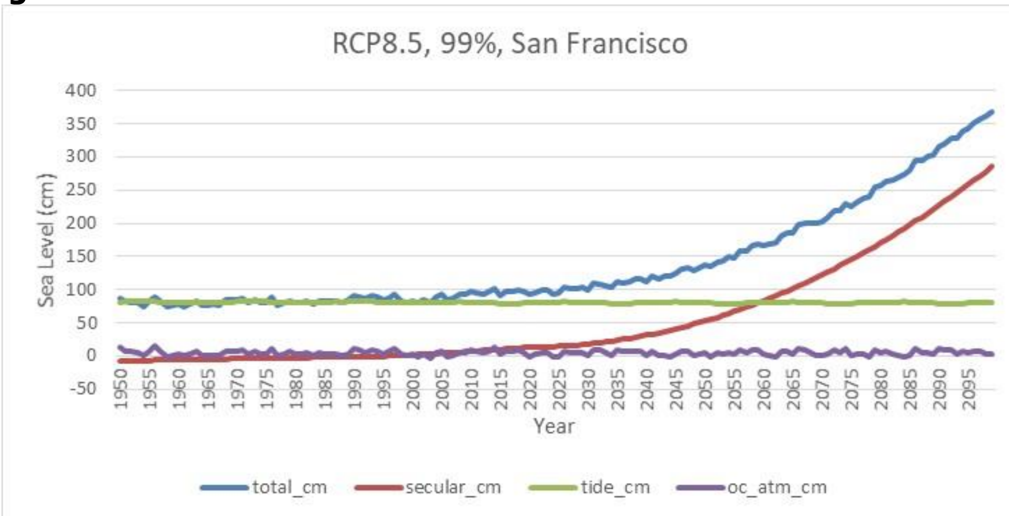
Source: University of California, Santa Cruz.

The hourly SL output under each scenario includes four variables, expressed in centimeters: total SL, secular SL, tides, and ocean/atmosphere effect. Total SL is the sum of the other three variables. Secular SL is the same for all GCM models for a given station and RCP scenario. Tides are the same for a given station. The ocean/atmosphere effect component, defined in terms of wind, low pressure, ocean temperature, and El Niño Southern Oscillation, is the same for all percentiles at a given station but changes across different RCP scenarios.

In Figure 2, the team used the San Francisco (SF) station at the 99.9th percentile under the RCP 8.5 scenario to illustrate the calculation of the extreme case of total SL with these three oceanic variables. It shows that the average values of the yearly maximum total SL from 1950 to 2099 is the sum of secular SL, daily maximum tide, and daily maximum ocean/atmosphere effect. The secular SL displays a steady, exponentially increasing trend over 1950–2099 and does not vary within a day. The average values of tides and ocean/atmosphere effects are close to zero. Therefore, the average daily maximum tide and ocean/atmosphere effects for each year over 1950 – 2099 were used for this analysis. The yearly average value of daily maximum tides is 80.6 centimeters (cm), which is close to the secular SL value in 2060 (83.3 cm). The average maximum ocean/atmosphere effect value is 3.2 cm. Secular SL reaches

285.3 cm in 2099. As a result, by 2099, the total SL is 369.1 cm (285.3+80.6+3.2) at the SF station.

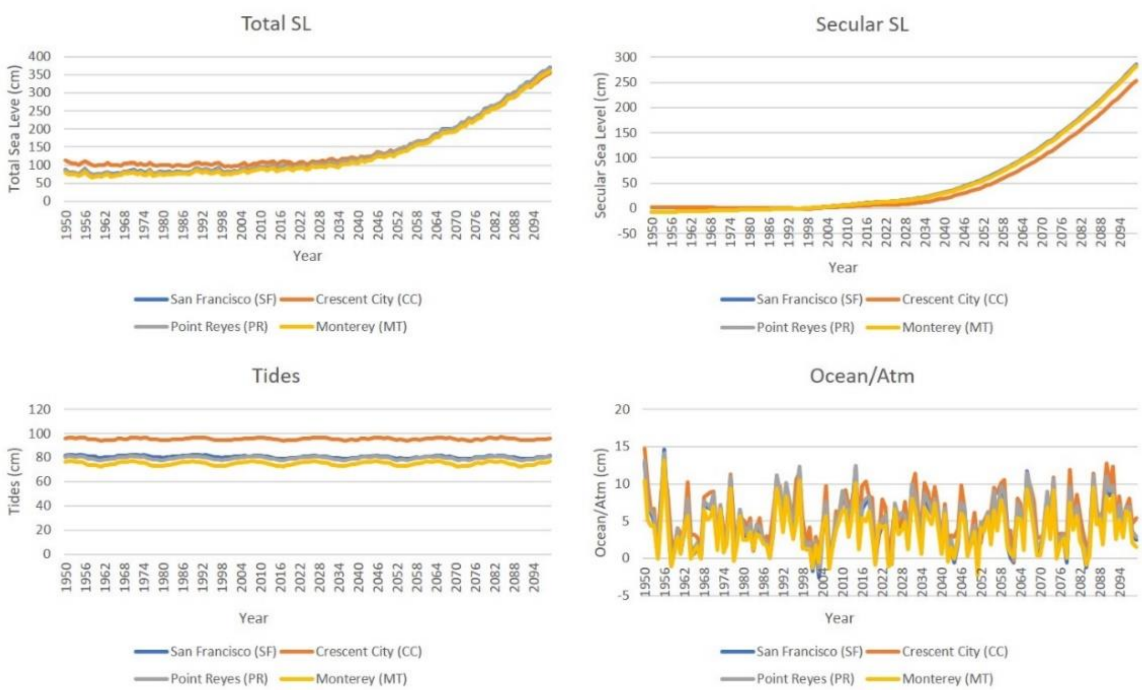
Figure 2: Extreme Case of Total Sea Level at San Francisco Station



Source: University of California, Santa Cruz.

Based on the spatial locations of natural gas pipelines and stations in Northern California, three other stations (in addition to SF) were selected for hazard analysis: Crescent City (CC), Point Reyes (PR), and Monterey (MT). The values of the four variables (total SL, secular SL, tides, and ocean/atmosphere effect) are displayed in Figure 3 to compare these four stations over 1950-2099 under RCP 8.5 at the 99.9th percentile. Overall, there is a similar trend in total SL across the four stations after 2060, but CC has a higher daily maximum tide and a slower SLR trend.

Figure 3: Sea-Level Comparisons Among Four Selected Stations



Source: University of California, Santa Cruz.

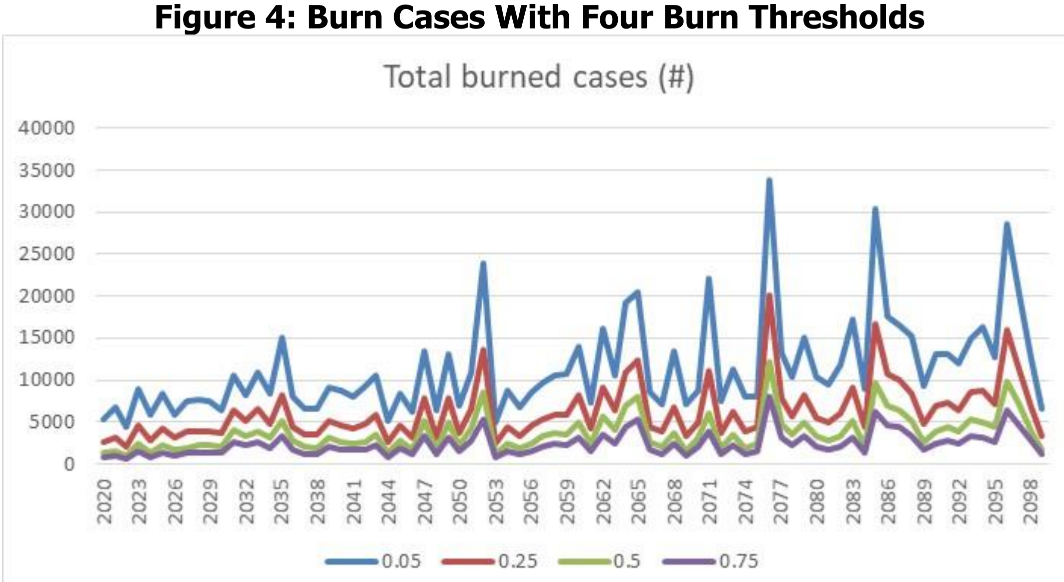
2.2.1.2 Wildfire Scenario Projections

The projection data for the wildfire assessment was provided by Dr. Westerling at the University of California, Merced (Westerling, 2018). Dr. Westerling developed simulations based on the statistical modeling of (1) large fire presence and absence, (2) the number of large fires, (3) the area burned in a grid cell given a fire, (4) high-severity burned area given a fire, and (5) emissions of smoke, under scenarios of four GCM models (CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5), two RCPs (8.5 and 4.5), population and development footprints based on low-, medium-, and high-growth scenarios for California, and three fuel-treatment scenarios (0 percent, 50 percent and 90 percent) (Westerling, 2018). One hundred simulations were conducted for each combination of climate, population, development footprint, and fuel-management scenarios to produce a fire-initiated (Boolean) variable, area burned (hectares), and fire severity at a 1/16° (6 kilometers [km] by 6 km) spatial resolution at the monthly level. These variables were then annualized for the years 1953 to 2099.

Wildfire projections under the RCP 8.5 scenario in a grid-cell format were selected for analysis. The total number of grid cells in Northern California was 14,892, and each grid cell was subject to 100 wildfire simulations, which yielded the value of burned-area-per-year from 1953 to 2099. In other words, there are 1,489,200 simulated burn cases for any given year. In addition, the 100 simulations for a year were also conducted for 10 different land-use and land-cover (LULC) scenarios. After comparing the simulated results among the 10 LULC scenarios, the researchers used the results of LULC Scenario #8 for analysis because the results of the 10 LULC scenarios were very similar though the values of Scenario 8 were slightly higher.

To facilitate this analysis, four thresholds (5 percent, 25 percent, 50 percent, and 75 percent) were set up to define burned cases (versus not burned). When using the 50-percent threshold, a given grid cell would be defined as a burned case if its burned area is larger than 50 percent of its total area, or 3,290 hectares. The total number of burned cases with these four thresholds and from 2020 to 2099 is shown in Figure 4. While the overall time-series patterns under the four thresholds are similar, the intensity levels of burned cases vary.

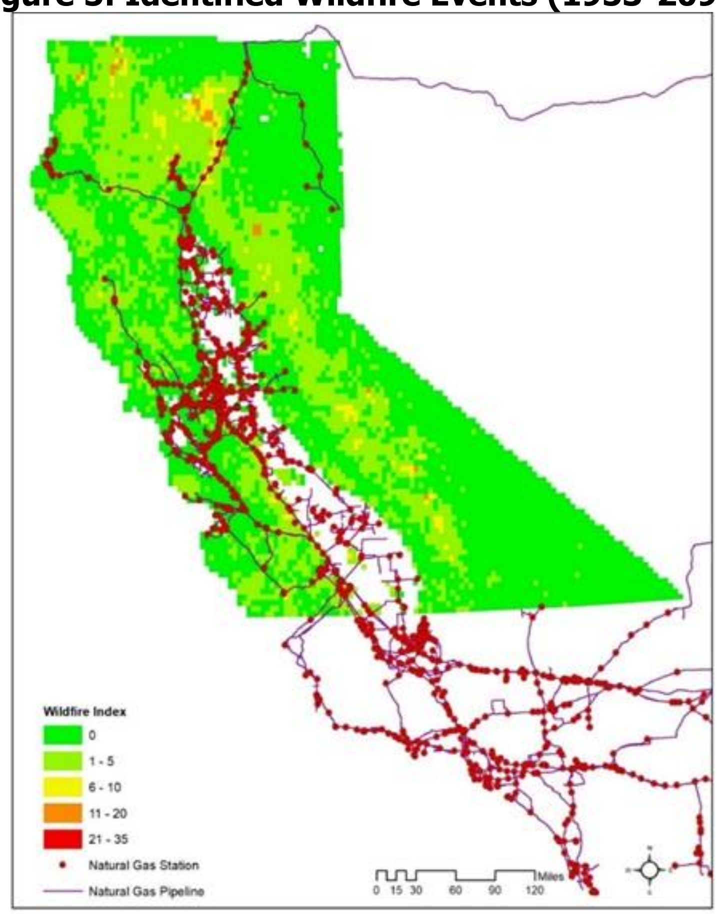
Figure 4: Burn Cases With Four Burn Thresholds



Source: University of California, Santa Cruz.

Based on this comparison of the four thresholds, overall wildfire simulated results were geographically presented in a three-step approach. In the first step, a cell was defined as a burned case if the simulated burned area was larger than 50 percent of the total area of that cell. For the 100 simulations in a given cell for a given year, the simulated result was identified as "1" if it was defined as a burned case over the 50-percent threshold. Then, the count of burned cases out of the 100 simulations was divided by 100. The result was the probability of burned cases in a given cell each year. The second step applied a 5-percent threshold to define a burned event in a grid cell for a given year based on the calculated probabilities in the first step. Specifically, a grid cell was identified as "1" if it had a burned event each year (if the calculated probability was larger than 5 percent). Finally, the numbers of annual burned events were aggregated over 147 years (1953-2099) for each grid cell in the study region, with a possible maximum value of 147. The results are mapped in Figure 5 for Northern California. Figure 5 shows several hot spots of annual wildfire events, such as the border between Siskiyou and Shasta counties and the Sierra mountain area. The top four worst cases (2076, 2096, 2085, and 2052) over the 147 years (Appendix A: Figure A-1) illustrate the wildfire hazard in a different way, showing the distribution of annual burn cases expressed in percentages across the study region. Using the same approach, the wildfire-hazard analysis was conducted by dividing the 147 years into three time periods to see how WH would increase over time: (1) BC: the first 50 years, (2) MC: the middle 50 years, and (3) EC: the last 47 years. The results are displayed in Appendix A Figure A-2.

Figure 5: Identified Wildfire Events (1953-2099)

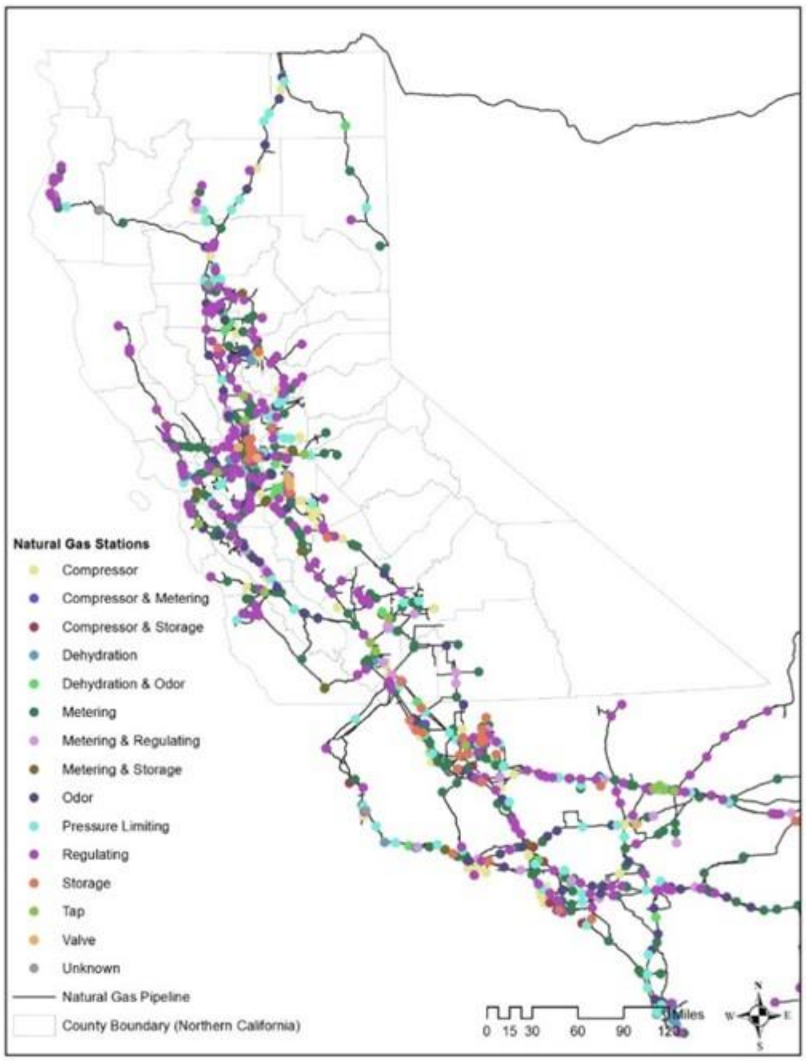


Source: University of California, Santa Cruz.

2.2.2 Natural Gas System in Northern California

The datasets on the natural gas system include pipelines and stations in a geographic information system (GIS) format (shapefiles), as provided by the Energy Commission and the National Pipeline Mapping System (NPMS). Figure 6 and Table 1 present the spatial and frequency distributions of these facilities, respectively. The pipelines cross 39 counties, with 3,229 segments owned by 40 utilities. Table 1 shows that 6,487 miles (out of a total of 13,562 miles in California) are in Northern California. Compressors, metering stations, and regulating stations make up the largest share. This natural gas system dataset also includes information on pipeline dimensions, which are used to estimate economic impacts.

Figure 6: Natural Gas Pipelines and Stations



Source: University of California, Santa Cruz.

Table 1: Summary of California's Natural Gas System

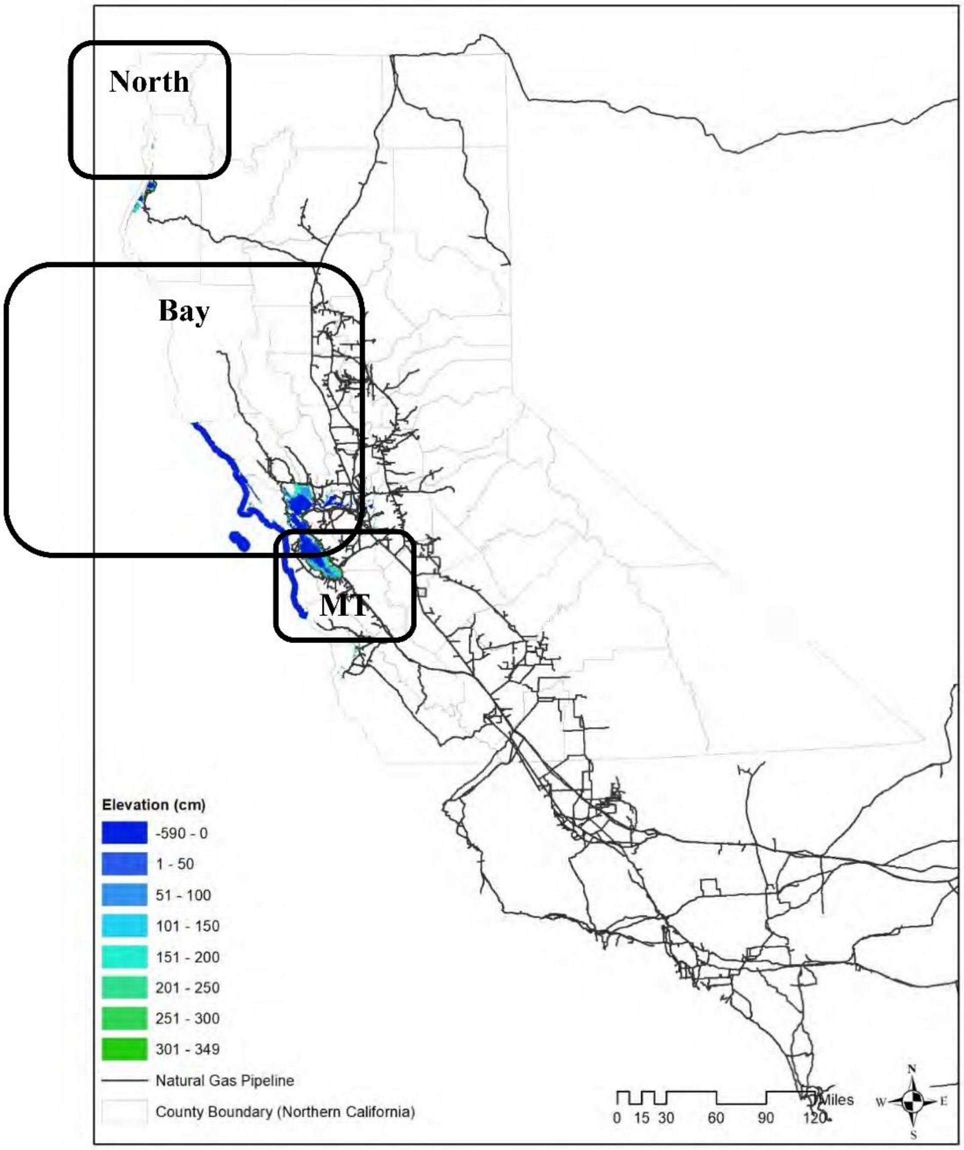
Station Type	Frequency	%
Compressor	145	12.95
Compressor & Metering Station	1	0.09
Compressor & Storage Station	12	1.07
Dehydration Station	33	2.95
Dehydration & Odor Station	41	3.66
Metering Station	346	30.89
Metering & Regulating Station	42	3.75
Metering & Storage Station	8	0.71
Odor Station	97	8.66
Pressure Limiting Station	97	8.66
Regulating Station	240	21.43
Storage	35	3.13
Tap	14	1.25
Valve	6	0.54
Unknown	3	0.27
Pipeline	**Length (miles)**	
All California	13,562.07	
North California	6,486.72	

Source: University of California, Santa Cruz.

2.2.3 Elevation Data for Sea-Level-Rising Hazard Analysis

Project researchers extracted the 1/3 arc resolution (around 6 meters) elevation data from the U.S. Geological Survey's (USGS) 3D Elevation Program (3DEP) to identify current sea level elevations of the pipelines and stations in the study region. As an initial analysis, the elevation data were spatially overlaid with the pipelines (Figure 7), which then identified three areas where pipelines could potentially be impacted by increasing SLR: a region in Northern California (North), a region around the Bay Area (Bay), and a region close to Monterey (MT). Table 2 shows these potentially inundated areas in 50-cm SLR increments for each region (North, Bay, and MT), percentage changes across SLR levels, and the potentially inundated pipeline length under different elevations.

Figure 7: Distribution of Pipelines and Elevations (< 350 cm)



Source: University of California, Santa Cruz.

Table 2: Potentially Inundated Areas and Pipeline Length Under Different Elevations

SLR Scenario	< 0 cm	< 50 cm	< 100 cm	< 150 cm	< 200 cm	< 250 cm	< 300 cm	< 350 cm
	Potentially inundated area (acre)							
North	47	20983	21057	27642	34059	37867	42917	48212
Bay	28257	757954	792831	820895	864312	896532	911424	926350
MT	181	4580	5092	6127.8	7728.0	9924.9	12171.8	14981.1
	% change							
North	N/A	44355	0.4	31.3	23.2	11.2	13.3	12.3
Bay	N/A	2582.4	4.6	3.5	5.3	3.7	1.7	1.6
MT	N/A	2433.4	11.2	20.4	26.1	28.4	22.6	23.1
	Potentially Inundated Pipeline Length (mile)							
North	0.000	0.000	0.000	0.266	4.560	5.890	7.457	12.395
Bay	1.197	14.199	16.420	19.922	27.498	41.384	56.570	75.743
MT	0.000	0.000	0.036	0.049	0.341	1.022	1.516	2.136
	% change							
North	N/A	N/A	N/A	N/A	1614	29	27	66
Bay	N/A	1086	16	21	38	50	37	34
MT	N/A	N/A	N/A	36	596	200	48	41

Source: University of California, Santa Cruz.

2.3 Method

2.3.1 Method for Sea-Level-Rise Risk Analysis

The approach for analyzing SLR risk assumes that the inundation of a natural gas facility occurs when the water depth caused by SLR is greater than the ground level of that facility. Based on the three identified regions (Figure 7) and the elevation data described above, the analysis focuses on the SLR projection results at the four stations (CC, PR, SF, and MT). The potentially inundated areas in 50-cm SL increments (0 cm, 50 cm, 100 cm, 150 cm, 200 cm, 250 cm, 300 cm, and 350 cm) for each region (North, Bay, and Monterey). The natural gas pipelines were mapped and are presented in Appendix B, Figures B1-B3. Table 3 displays the secular SL, maximum tides, and total SL for these stations in 2060 and 2099 under different scenarios, which show that the SL projections vary from 0 cm to 369.13 cm. The SLs and total SLs increase over time, together with more extreme percentiles and more severe climate-change scenarios.

A six-step approach was developed to convert projected SLs into water-depth risks (by percent) for the two RCP scenarios and all the stations with nearby natural gas facilities to help decision-makers identify the risk of sea-level rising:

1. Use the maximum SL of 370 cm (based on the maximum SL in Table 3) to identify possible inundated areas where the elevation is below this value.
2. Use the identified inundated areas to capture all-natural gas facilities that fall within these areas.

3. Calculate the water depth for each identified facility by deducting the elevation of that facility from the projected SL at the station closest to that facility.
4. Divide the calculated water depths into four intervals: <0, 0-50, 50-100, and >100 cm.
5. Divide the 80 years from 2020 to 2099 into four time periods: 2020-2040, 2040-2060, 2060-2080, and 2080-2099.
6. Calculate the percentage of water depth that falls into each of the four water-depth intervals for each period.

Table 3: Average Sea-Level-Rising Predictions in 2060 and 2099 (in centimeters)

Scenario/ Station	Secular SL in 2060	Secular SL in 2099	Max tide in 2060	Max tide in 2099	Total SL in 2060	Total SL in 2099
RCP 8.5 (99.9%)						
CC	65.53 [a]	253.85 [c]	95.39 [a]	96.14 [a]	164.75 [b]	355.32 [d]
PR	82.84 [a]	284.33 [c]	80.11 [a]	81.04 [a]	165.84 [b]	368.29 [d]
SF	83.31 [a]	285.33 [c]	80.54 [a]	81.32 [a]	165.69 [b]	369.13 [d]
MT	80.66 [a]	280.96 [c]	75.97 [a]	76.92 [a]	158.40 [b]	359.42 [d]
RCP 8.5 (50%)						
CC	19.41 [a]	106.37 [b]	95.39 [a]	96.14 [a]	118.64 [b]	207.85 [c]
PR	36.01 [a]	134.22 [b]	80.11 [a]	81.04 [a]	119.01 [b]	218.18 [c]
SF	36.57 [a]	135.06 [b]	80.54 [a]	81.32 [a]	118.95 [b]	218.86 [c]
MT	33.39 [a]	129.33 [b]	75.97 [a]	76.92 [a]	111.13 [b]	207.79 [c]
RCP 4.5 (99.9%)						
CC		148.22 [b]		96.14 [a]		247.70 [c]
PR		176.24 [b]		81.04 [a]		264.71 [c]
SF		176.09 [b]		81.32 [a]		261.20 [c]
MT		172.15 [b]		76.92 [a]		252.62 [c]
RCP 4.5 (50%)						
CC		45.96 [a]		96.14 [a]		145.44 [b]
PR		72.30 [a]		81.04 [a]		157.77 [b]
SF		73.13 [a]		81.32 [a]		158.23 [b]
MT		67.66 [a]		76.92 [a]		148.13 [b]

[a]: 0-100 cm; [b]: 100-200 cm; [c]: 200-300 cm; [d]: > 300 cm

Source: University of California, Santa Cruz.

2.3.2 Method for Wildfire Risk Analysis

The risk for natural gas facilities to be burned by wildfire is identified using the following steps to help decision-making on hazard mitigation:

1. Use the 100 simulated burned areas of a cell per year from 2021 to 2099 for the RCP 8.5 scenario.
2. Convert the simulated burned area of a cell into a percentage of burned area in a cell.
3. Allocate the burned percentages into four bins, including 0-25, 25-50, 50-75, and 75-100 percent.
4. Divide the 80 years from 2020 to 2099 into four time periods: 2021-2040, 2041-2060, 2061-2080, and 2081-2099.
5. Identify a burn case when the burned percentage matches the corresponding bin.
6. Count the number of burn cases in each bin for each period.
7. Convert the count of burn cases into a percentage for each bin in a period, so that the sum of the percentages in the four bins equals 1.

2.4 Results

2.4.1 Sea-Level-Rise Risk

Using the maximum SL of 370 cm described, the project team identified possible inundated areas, capturing 14 natural gas facilities (including compressor, metering station, and regulating stations) within the inundated areas in Northern California. The identified stations are shown in Figure 8 and described in Table 4, showing that CC and SF are the two closest SLR projection stations.

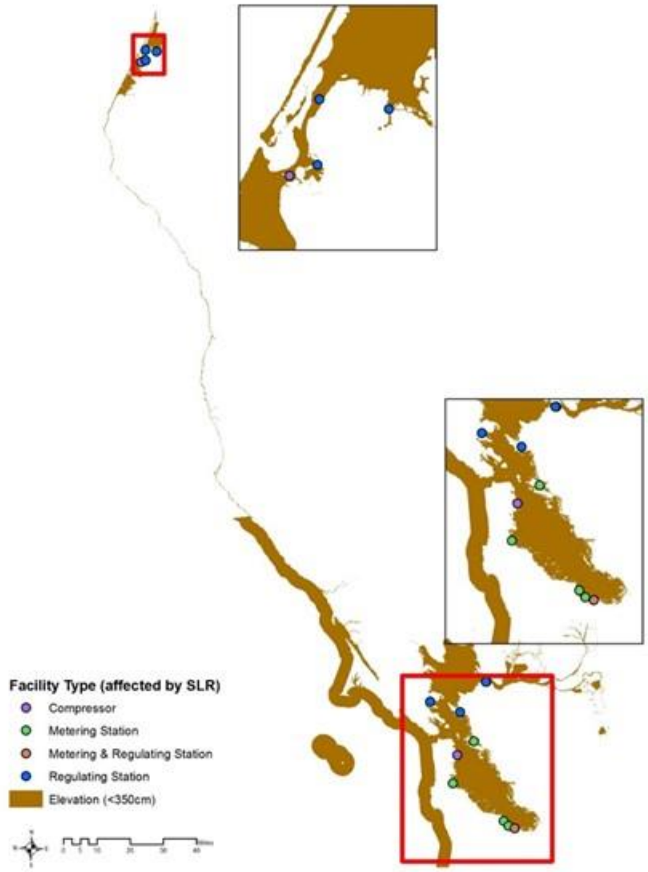
The SLR risk was calculated for these 14 facilities under the RCP 8.5 and 4.5 at the 99.9th and 50th percentiles. First, the water depth for each identified facility was calculated by deducting the elevation of that facility from the projected SL at the station closest to that facility. Then the probability of water depths falling in the ranges of four intervals described in Section 2.3.1 for the years 2021-2040, 2041-2060, 2061-2080, and 2081-2099 were calculated, as presented in Table 5a. For instance, under RCP 8.5 at the 99.9th percentile, the probability for facility #387 to be inundated by a 50-cm water depth is 7.11 percent between 2021 and 2040. The calculated results for the years 2081-2099 are presented in Table 5 and 6. The results for the other time periods are presented in Appendix C. These results show that facility #387 is the only one likely to be inundated with a probability greater than 5 percent within a 50-cm water depth from 2021 to 2060. From 2061 to 2080, this probability increases to around 30 percent in a 50-cm water depth and 28 percent in a 100-cm water depth under a severe scenario (RCP 8.5 and 99.9 percentile). These values suggest that facility #387 is an SLR mitigation target from now on. Between 2081 and 2099, 10 of the 14 facilities have at least a 5 percent probability of being inundated within a 50-cm or higher water depth under the scenario RCP 8.5 and 99.9 percentile. The results in these tables indicate that the year 2080 could be a key period when many natural gas facilities in Northern California might suffer from extremely high SLR risk.

Table 4: Natural Gas Stations Affected by Sea-Level Rise

NG Station ID	Station Type	Elevation (cm)	Closest SLR Station
3	Compressor	208	Crescent City, CA (CC)
61	Compressor	176	San Francisco, CA (SF)
172	dehydration station	365	San Francisco, CA (SF)
357	metering station	334	San Francisco, CA (SF)
376	metering station	176	San Francisco, CA (SF)
386	metering station	213	San Francisco, CA (SF)
387	metering station	96	San Francisco, CA (SF)
593	metering & regulating station	329	San Francisco, CA (SF)
827	regulating station	256	Crescent City, CA (CC)
828	regulating station	344	Crescent City, CA (CC)
829	regulating station	220	Crescent City, CA (CC)
913	regulating station	264	San Francisco, CA (SF)
914	regulating station	342	San Francisco, CA (SF)
927	regulating station	326	San Francisco, CA (SF)
928	regulating station	334	San Francisco, CA (SF)
946	regulating station	367	San Francisco, CA (SF)

Source: University of California, Santa Cruz.

Figure 8: Natural Gas Facilities Affected by Sea-Level Rise



Source: University of California, Santa Cruz.

Table 5: Probabilities (%) for Natural Gas Facilities to be Inundated Within Given Water Depths (2081-2099) (RCP 8.5)

Scenario	NG Station ID (CM)	Water depth (cm)<=0	Water depth (cm) 0-50	Water depth (cm) 50-100	Water depth (cm)>100
RCP 8.5 (99.9%)					
CC	3 (208)	51.58	24.78*	17.26*	6.38*
CC	827 (256)	75.45	17.75*	6.02*	0.78
CC	828 (344)	98.54	1.39	0.07	0.00
CC	829 (220)	57.54	24.04*	14.24*	4.19
SF	61 (176)	36.78	28.12*	24.04*	11.07*
SF	357 (334)	95.72	4.11	0.17	0.00
SF	376 (176)	36.78	28.12*	24.04*	11.07*
SF	386 (213)	39.52	28.18*	22.93*	9.38*
SF	387 (96)	2.36	8.55*	19.43*	69.66*
SF	593 (329)	94.72	5.01*	0.27	0.00
SF	913 (264)	68.23	22.68*	8.21*	0.88
SF	914 (342)	96.99	2.92	0.09	0.00
SF	927 (326)	94.07	5.58*	0.35	0.00
SF	928 (334)	95.72	4.11	0.17	0.00
RCP 8.5 (50%)					
CC	3 (208)	98.49	1.44	0.06	0.00
CC	827 (256)	99.93	0.07	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.24	0.74	0.02	0.00
SF	61 (176)	97.59	2.39	0.03	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	97.59	2.39	0.03	0.00
SF	386 (213)	98.27	1.71	0.02	0.00
SF	387 (96)	40.05	32.28*	23.03*	4.63
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	99.98	0.02	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates a percentage larger than 5 percent for inundation**

Source: University of California, Santa Cruz.

Table 6: Probabilities (%) for Natural Gas Facilities to be Inundated Within Given Water Depths (2081-2099) (RCP 4.5)

Scenario	NG Station ID (CM)	Water depth (cm) <=0	Water depth (cm) 0-50	Water depth (cm) 50-100	Water depth (cm) >100
RCP 4.5 (99.9%)					
CC	3 (208)	90.67	8.51*	0.79	0.02
CC	827 (256)	99.07	0.91	0.02	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	94.09	5.54*	0.37	0.01
SF	61 (176)	85.19	13.54*	1.27	0.01
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	85.19	13.54*	1.27	0.01
SF	386 (213)	87.56	11.55*	0.88	0.00
SF	387 (96)	20.52	26.20*	31.94*	21.34*
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	99.17	0.82	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 4.5 (50%)					
CC	3 (208)	99.97	0.03	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.99	0.01	0.00	0.00
SF	61 (176)	99.99	0.01	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	99.99	0.01	0.00	0.00
SF	386 (213)	99.99	0.01	0.00	0.00
SF	387 (96)	70.06	25.14*	4.75	0.05
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

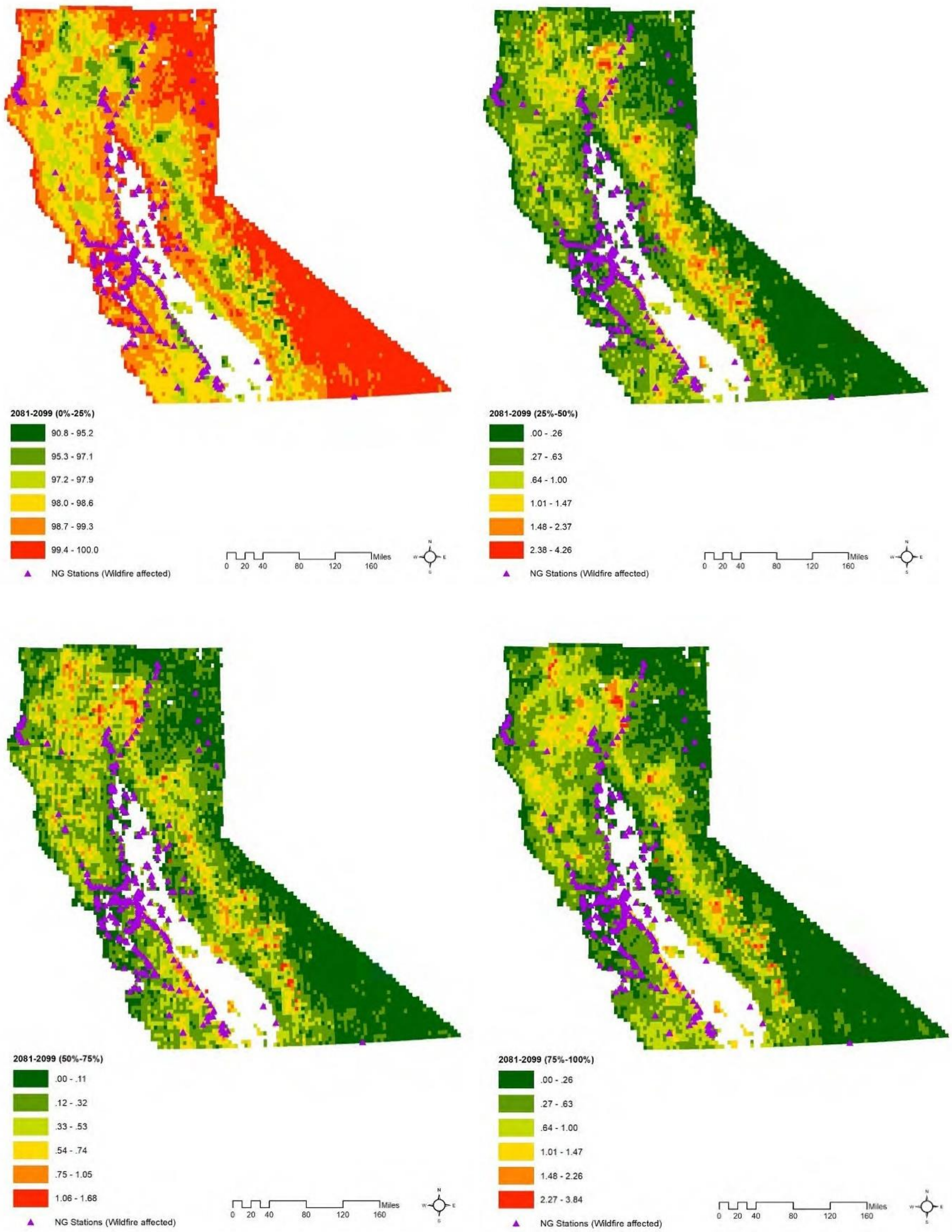
***: Indicates that the percentage larger than 5 percent for inundation**

Source: University of California, Santa Cruz.

2.4.2 Wildfire Risk

Using the approach described in Section 2.3.2, wildfire risks were calculated for four burn probability bins (0-25, 25-50, 50-75, 75-100 percent) in four time periods (2021-2040, 2041-2060, 2061-2080, and 2081-2099). Figure 9 shows the calculated wildfire risks for 2081-2099.

Figure 9: Calculated Wildfire Risk: 2081-2099



Source: University of California, Santa Cruz.

The results for other probability bins and time periods are presented in Appendix D. The highest values of wildfire risks always appear in the first bin (0-25 percent) among the four time periods. This means that most simulated wildfire results in the future 80 years have burned areas below 25 percent in a grid cell. The values in the other three probability bins also slightly increase, inferring that more simulation cases result in larger burned areas (> 25 percent) over time.

Since the sum of the percentages in the four bins in a grid cell equals 1 (100 percent), a low value in the first (0-25 percent) or second bin (25-50 percent) essentially implies a high value in the third (50-75 percent) or fourth bins (75-100 percent). It is therefore more illuminating to examine maps in the third and fourth bins for wildfire hazards. For instance, Figures D-2, D-3, D-6, and D-7 in Appendix D indicate that high wildfire risks from 2021 to 2060 are mostly concentrated in areas west of the Central Valley, particularly in the counties of San Benito, Monterey, Mariposa, Madera, and Tuolumne. The Bay to the north (including Trinity, Shasta, and Tehama counties) shows high wildfire hazards for the years 2041 to 2060. From 2061 to 2099, high wildfire hazards appear in Siskiyou and Shasta counties and along the Sierra Nevada mountain area (Figures D-10, D-11, D-14, D-15). In summary, counties in Northern California, such as Siskiyou and Shasta, can be identified as the hot spots for wildfire hazards for the next 80 years. Another hot spot would be from the west edge of the Central Valley to the east side from 2021-2060 to 2061-2099.

Wildfire simulated results were spatially overlaid with the natural gas system to identify grid cells where at least one gas facility is located. As a result, 34 grid cells were identified. The wildfire risk results just explained were then attached to these 34 grid cells for natural gas-system wildfire risk assessments. For instance, a compressor located close to Siskiyou County and Shasta County would have an above 5 percent chance of being burned, as indicated by summing up the burned percentages in the third (1.68 percent) and fourth (3.84 percent) bins.

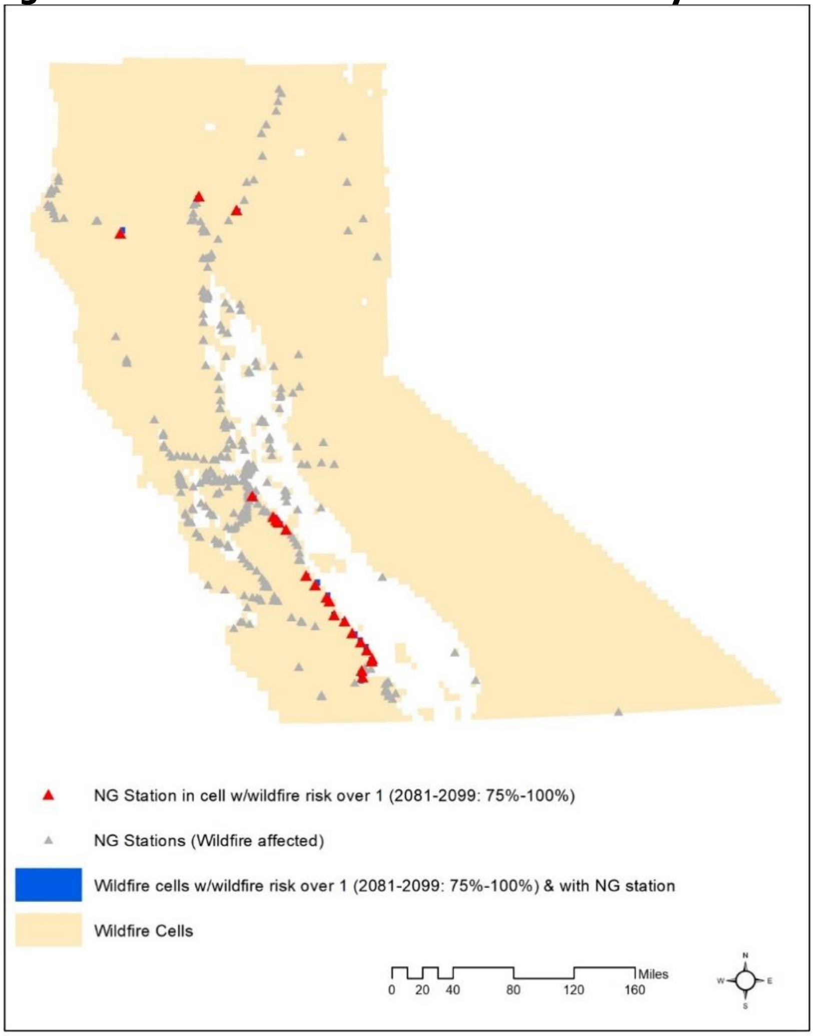
The wildfire risks calculated for 2081-2099 in the fourth bin were used to extract 19 grid cells with a value over 1 (representing the percentage that the burned probability falls into the bin 75 percent-100 percent over 2081-2099 in a cell). This helped to identify 22 facilities in these cells, presented in Table 7 and Figure 10. These results, along with the spatial distribution of average areas burned (obtained from Westerling, 2018), helped in selecting focal areas in Northern California for further economic-impact analysis.

Table 7: Natural Gas Stations Affected by Wildfire

Facility ID	Station Type	Owner	Zip Code	County
74	Compressor	PG&E	93640	Fresno
78	Compressor	Chevron	93210	Fresno
236	Metering Station	PG&E	00039	Trinity
359	Metering Station	PG&E	95304	San Joaquin
360	Metering Station	PG&E	95304	San Joaquin
368	Metering Station	PG&E	95377	San Joaquin
377	Metering Station	PG&E	95363	Stanislaus
402	Metering Station	PG&E	93622	Merced
407	Metering Station	PG&E	93622	Fresno
411	Metering Station	PG&E	93640	Fresno
421	Metering Station	PG&E	93210	Fresno
660	Odor Station	PG&E	94514	Contra Costa
730	Pressure Limiting Station	PG&E	96096	Shasta
830	Regulating Station	Private	96003	Shasta
933	Regulating Station	PG&E	95304	San Joaquin
956	Regulating Station	PG&E	95322	Merced
958	Regulating Station	PG&E	93635	Merced
963	Regulating Station	PG&E	93622	Fresno
970	Regulating Station	PG&E	93640	Fresno
977	Regulating Station	Chevron	93210	Fresno
1105	Tap	PG&E	93210	Fresno
1106	Tap	PG&E	93210	Fresno

Source: University of California, Santa Cruz.

Figure 10: Natural Gas Stations Affected by Wildfire



Source: University of California, Santa Cruz.

CHAPTER 3: Regional Economic Analysis on Climate-Induced Hazards

3.1 Background

Understanding the economic impacts of climate change is becoming an increasingly important component of managing critical infrastructures like the gas system, which is essential to nearly every area of modern society. This understanding helps industry identify key components of the infrastructure that are both susceptible to climate-change-related risks and critical to the overall system's recovery. It will also allow the industry to prioritize its resources when choosing resilience options to adapt to climate change. Among all the climate-change issues in California, the energy sector's vulnerability is important to address, particularly within the natural gas system. Without information on this system's vulnerability and the economic consequences of its disruption, neither government nor industry will be able to implement timely, cost-effective resilience options that harden the system to avoid damage from catastrophic events including sea-level rising, coastal flooding, wildfires, droughts, storm events, and other extreme events (Office of Environmental Health Hazard Assessment, 2018). These events would likely increase risks for natural gas systems when natural gas pipelines or compressor stations are located in impacted hazard areas. The consequences of gas system disruptions due to climate-change-induced hazards could be extensive since many industries and households in California rely heavily on natural gas as their primary energy source.

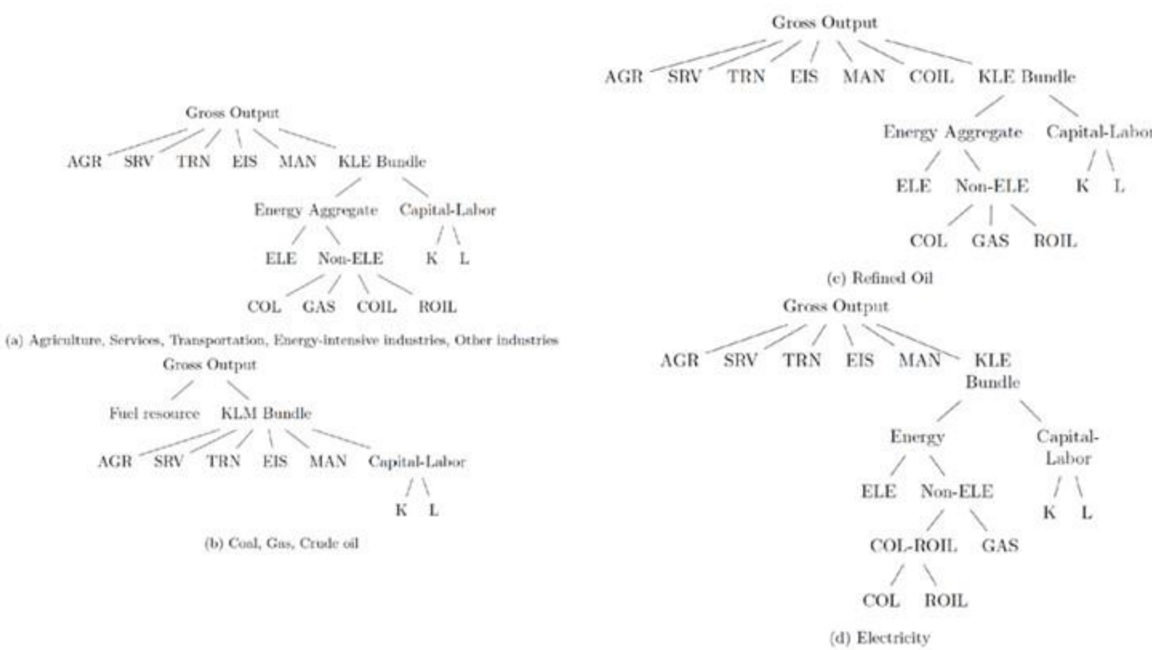
This chapter describes the development of a multiple-regional economic computational general equilibrium (CGE) model that addresses the vulnerability of Northern California's natural gas system to climate-change-induced events. The model is a static U.S. state-level CGE model and accounts for bilateral-trade flows among regions to quantify the spillover effects of service disruptions onto other sectors and regions. CGE models are systems of simultaneous equations from first-order conditions of agents' optimization problems, as well as from market clearance conditions for each commodity and factor market. Economic agents, such as households and companies, make economic decisions based largely on price, which is included within the CGE model. One of the most important features in CGE modeling is the Armington assumption (Armington, 1969), which models the imperfect substitution of goods produced either domestically or 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, which account for their differences (McFadden, 1963). The analysis focuses primarily on short- to medium-run scenarios.

3.2 Method

3.2.1 Model Description

The structure of a typical CGE model is illustrated in Figure 11. Each representative household contains primary factors such as labor or capital. The households apply these factors to various sectors in exchange for their revenue. To increase their utility, households spend their revenue for either private consumption of goods or savings and investments. Each industry or sector produces goods or services with primary inputs, including value-added labor and capital, natural resources, and intermediate goods. A production function then links 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 those functions. The gross output from the production process is then assigned to local goods, domestic exports, and international exports through a CET function. As described earlier, this is because, in an Armington assumption, local goods, domestic goods, and international export goods are slightly different goods. The local goods are then combined with domestic imports and international imports through a bi-level nested CES function to form Armington composite goods, which are used for final consumption including household consumption, investment, government consumption, and intermediate good consumption. In short-run and medium-run analyses, limited substitution in production and demand processes is allowed and outcomes from analyses represent the relatively worst case. The extreme short-run case requires an input-output (IO) approach where no substitution is allowed. With the model represented in a complementary format, it can be solved for the equilibrium activity levels and prices to gauge regional economic impacts.

Figure 11: Structure of Monetary and Commodity Flows in Computational General Equilibrium Model



Source: University of California, Santa Cruz.

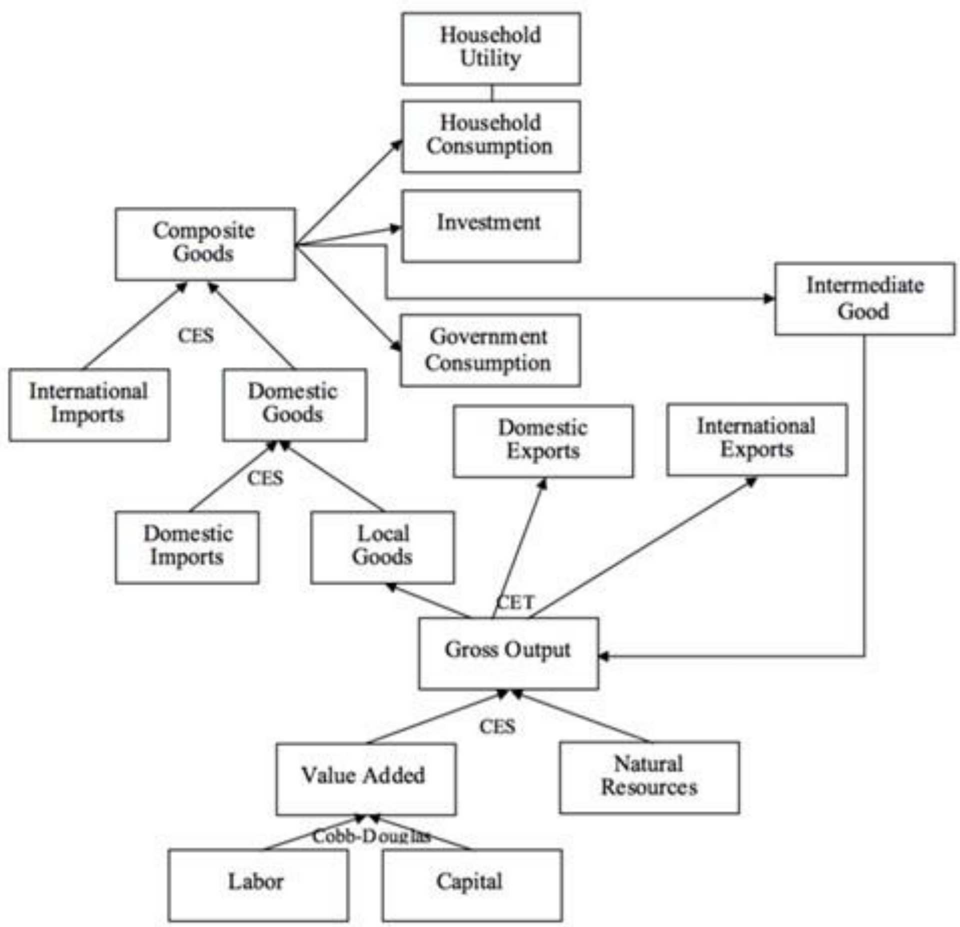
The researchers constructed a U.S. CGE model that accounted for multiple-sector, multiple-region, and multiple-household types. The model closely follows the formulation by Rausch & Rutherford (2009), with improvement in the production structures and construction of bilateral trade flows. The model aggregates sectors and regions into the desired resolution. The elasticities used in CES functions are mainly from existing literature (Paltsev et al., 2005; Rausch, Metcalf, Reilly, & Paltsev, 2011). A detailed description of the model appears in

Appendix G. This model can analyze various climate-change-related events and policies as well as climate-change impacts on the natural gas system from sea-level rising and wildfire.

3.2.2 Model Assumptions

Each production sector or industry is assumed to minimize its cost with a production function assumed to apply a constant-returns-to-scale technology. The production function of each sector may use a combination of Leontief-type, Cobb-Douglas-type, and CES-type technologies. This study uses the calibrated share form, which is based on the benchmark price-quantity pair of the model to represent production functions and demand preferences (Böhringer, Rutherford, & Wiegard, 2003). The calibrated share form simplifies the calculation of free parameters (share coefficients for production or demand functions) as compared with the conventional coefficient form where the computationally intensive inversion of production (or demand) functions is required. The nested structure of production functions is shown in Figure 12. By differentiating the production structure of different sectors and applying a nested CES structure, the model can flexibly account for different elasticities of substitution for different inputs. The elasticities of substitution between capital and labor and between coal and natural gas can be assigned different values. This specification of elasticities allows for a more realistic representation of production functions.

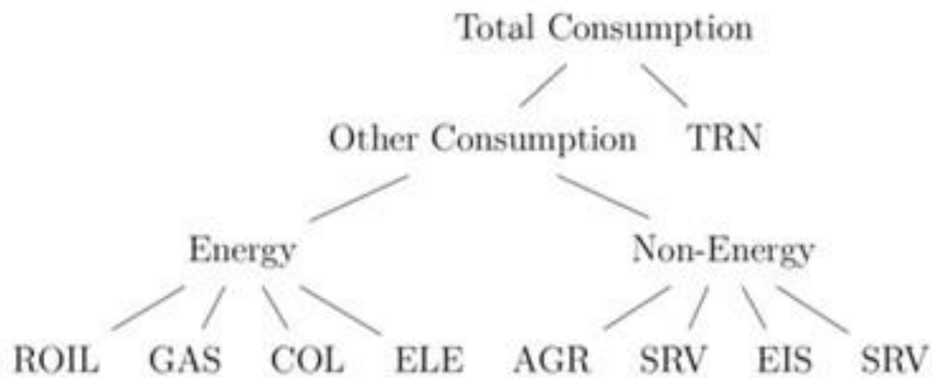
Figure 12: Structure of Production Sectors



Source: University of California, Santa Cruz.

From the consumer perspective, the model differentiates nine different representative households, defined by levels of household income, in each region. The consumer is modeled as an agent who maximizes his or her utility from consuming goods. Labor and capital, proprietary and non-proprietary, are then applied to consumers so that they receive income from producers for providing their labor and capital. They then use the income received to consume commodities that increase their utility. Household income is allocated between investment savings and private consumption. The model assumes a constant level of total investment 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 shown in Figure 13.

Figure 13: Nested Structure of Private Consumption and Households



Source: University of California, Santa Cruz.

Government activity is represented at three levels: federal, state, and local. Government is the entity that purchases commodities for 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.

The supply of final goods and intermediate and final consumption are all differentiated following the Armington assumption, where goods imported and exported are considered to be imperfect substitutes for those produced or consumed locally. The degree of this difference can be measured by a parameter, or the elasticity of substitution. The model distinguishes goods by local (within a region), domestic (within the U.S.), or international origins and destinations, using a two-tier nest for the Armington composite CES function, and a one-tier nest for the gross output CET function.

The chapter adopts the double-constrained gravity model (Wilson, 1967) and follows the procedures in reference (Lindall, Olson, & Alward, 2006) to construct commodity trade flows. Double constraints are applied to domestic supply and domestic demand so that domestic imports and exports can be canceled out: the total sum of domestic imports from all the states is equal to the sum of domestic imports of each commodity.

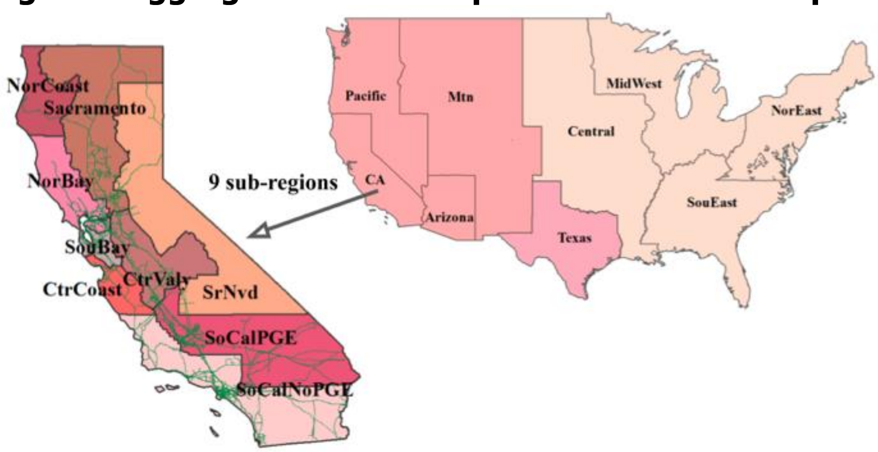
3.2.3 Data

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 and commodities, and three factors of production, including labor and capital. Nine household types are distinguished by their gross income level, and six types of government are represented at the federal, state, and local levels.

The CGE model utilizes data from three sources: Oak Ridge National Labs (ORNL, 2011), Commodity Flows Survey (CFS) (U.S. Department of Transportation, 2012), and IMPLAN (IMPLAN, 2013). The IMPLAN data are the major source of data in this analysis and were developed by the Minnesota IMPLAN group (MIG). The data include annual benchmark economic data of the U.S. at the national, state, and county levels, and provide consistent SAMs by reconciling the data from multiple sources including the Bureau of Economic Analysis (BEA), the Bureau of Labor Statistics, and the U.S. Census Bureau. The data track monetary flows and commodity flows among and within production sectors and institutions. This chapter uses county-level SAMs data for California, and state-level SAMs data for other U.S. states. By distinguishing county- and state-level data for different regions, this analysis can focus on Northern California, which is the study region where natural gas supply disruptions from hazardous climate events are modeled. ORNL and CFS data are used to construct bilateral trade flow.

This chapter disaggregates the U.S. into 19 regions, as shown in Figure 14. 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: Central Coast, Central Valley, North Bay, North Coast, Sacramento Valley, Southern California (SoCal) without PG&E territory, SoCal with PG&E territory, South Bay, and the Sierra Nevada.

Figure 14: Regional Aggregation in a Computational General Equilibrium Model



Source: University of California, Santa Cruz.

The aggregation of states is determined based on electricity supply interconnections and natural gas supply networks. The bilateral commodity trade flows are constructed so that domestic imports and exports between any two regions can be traced. Furthermore, regions are also defined according to their electricity physical-system networks. Regions in the western interconnections can trade only within the western interconnection, but not with eastern or Texas regions. This means that different electricity interconnections cannot trade across interconnection borders in the U.S. electric system.

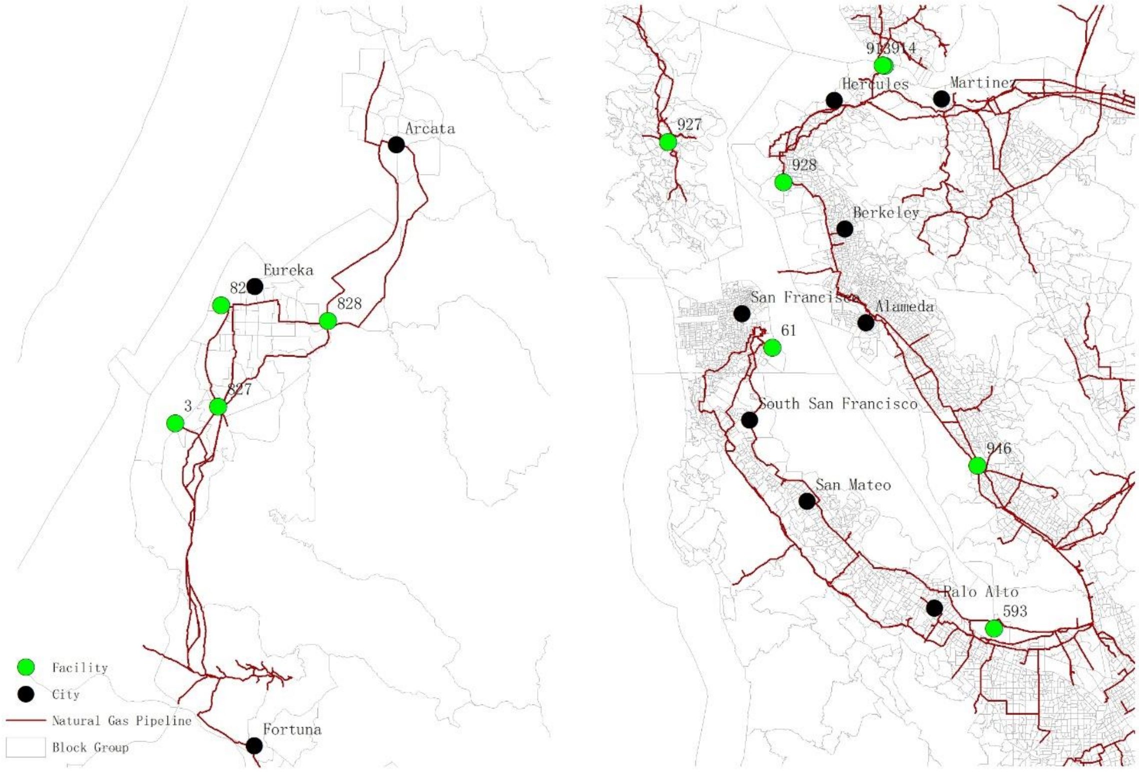
The model aggregates the 536 sectors in the IMPLAN data to ten sectors, with five sectors as non-energy sectors and five sectors as energy sectors. Non-energy sectors include agriculture, services, transportation, energy-intensive industrial sectors, and other manufacturing sectors. Energy sectors include primary fuels (that is, coal, natural gas, and crude oil), refined oil, and electricity. Different sectors deploy different production structures in their nested CES production functions. Overall, the five non-energy sectors share the same production structure whereas the energy sectors are more complicated. More specifically, coal, gas, and crude oil share a similar primary fuel-production pattern where the only primary fuel input of each sector is its own primary fuel. The fuel supply of the natural gas sector is natural 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 reveal more realistic representations of production processes in each sector.

3.3 Scenarios

3.3.1 Sea-Level Rise

Among different climate-change-induced hazards that could potentially disrupt Northern California's natural gas system, this analysis focuses on quantifying the impacts of sea-level rise. The first step in defining the scenarios for CGE modeling is to identify the key facilities that are subject to climate-change-induced sea-level rise such as gas compressor 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. Digital Elevation Model (DEM) data of the gas facility network are compared with sea-level rising data to identify affected facilities. The left map in Figure 15 represents facilities (3, 827, 828, and 829) located fairly close to one another in Humboldt County in the North Coast region. Because these facilities are clustered in a relatively small region, they are grouped into one clustered facility (a), with the assumption that the minimum elevation (208 cm) of the four individual facilities is the elevation of the clustered facility. Therefore, if the sea level rises above 208 cm, the 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 to be impacted. This contrasts with 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 also appear in the right-hand map in Figure 15. As for the facilities in the North Coast region, facilities 913 and 914 share the same impacted region and thus are grouped together to form clustered facility (d). Detailed information on these facilities is shown in Table 8 including facility ID number, county, and region, which show the size of the impacted population if that facility stops its operation. Ideally, a gas-operation model should derive from the extent of the impact. However, in the absence of such a model, it is assumed that the extent of the impacted supply and demand is proportional to the fraction of the impacted population in the region (as shown in the Percentage of Impact column in Table 8).

Figure 15: Facilities Affected by Sea-Level Rise Scenarios: North Coast (left), North and South Bay Area (right)



Source: University of California, Santa Cruz.

Table 8: 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

Source: University of California, Santa Cruz.

Theoretically, a failing natural gas facility is unable to provide service to its local and downstream regions. However, without explicit data that allows gas-flow simulations, this analysis used pipeline dimensions to estimate gas-flow direction near facilities. An existence of looped flows in the gas system might bias the impacts based on the population-based approach upward. This is because the gas demand in the impacted region can then be met by alternative routes of gas supply. It is therefore assumed here that the impact of a service disruption to one facility is proportionate to the population served by that facility. If one facility fails, downstream regions served by pipelines with smaller diameters will also be impacted.

Using this assumption, impacted regions were identified with ArcGIS tools (Esri, 2019). The population residing in identified regions was then calculated based on 2019 U.S Census data. Impacts were also linked to the natural gas inputs to industries in a given region. However, because detailed gas supply-and-demand data were not available, this population-based approach is a reasonable alternative. After estimating the population impact for each facility, the facility-level impact on natural gas supply was calculated by dividing the impacted population by the total population in each region. These results are summarized in the last three columns of Table 9.

Table 9: 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.

Source: University of California, Santa Cruz.

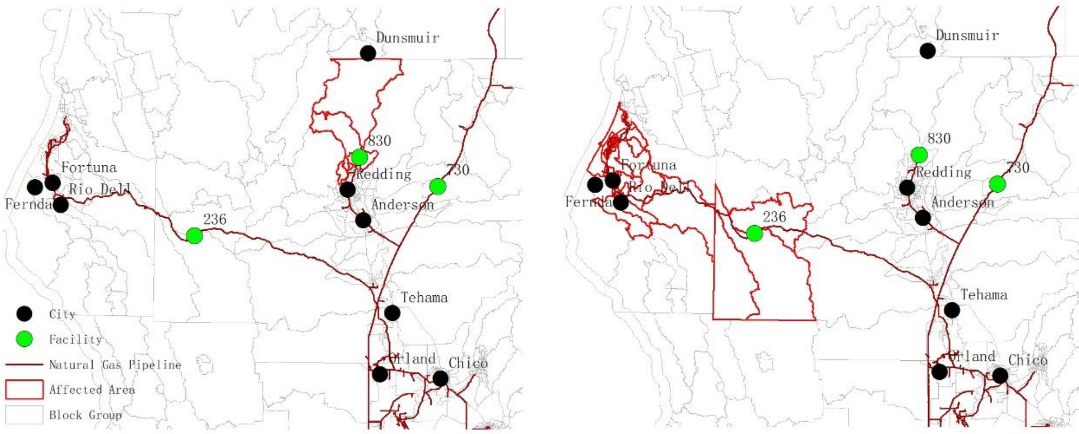
The facility status and aggregated regional impacts under different ranges of sea-level rise were reported. At a certain sea level, a facility with an elevation lower than that level will fail, as indicated by 'F' in Table . The regional impact was calculated based on the impacted population that corresponded to the failed facilities. Assuming that the future sea-level for California rises to 330 cm (Scenario 5 (329-334cm), five facilities are expected to be under sea water. Facility (a) is in the North Coast region and its impact is a reduction of 32.58 percent (or 0.3258) of gas supply. Facilities (b) and (d) are located in the North Bay region. Since the impacted regions of the facilities do not overlap, their aggregated impact was estimated by adding their individual impacts, as shown in Table (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 facilities (e) and (h) (0.0071 + 0.2786 = 0.2857). The economic impacts of each scenario were then estimated.

3.3.2 Wildfire

The regional economic impacts of wildfires in Northern California were also evaluated. Three facilities (236, 830, and 730) were identified to be at risk of wildfire, as shown in Figure 16. Using methods like those used to estimate the impacts of SLR, the impacts of facilities 830 and 236 were drawn from the impacted population. More specifically, the downstream regions served by smaller-diameter pipelines were impacted if facilities 830 and 236 failed. The identified regions are marked in Figure 16. Gas supply in the Sacramento Valley and North Coast regions were assumed to be impacted by facilities 830 and 236, respectively, and their impacts calculated by dividing the impacted population by the total regional population. On the other hand, Facility 730 was treated differently because it is located on the transmission backbone of the natural gas system while facilities 830 and 236 are located on the local transmission and distribution pipeline systems. The backbone gas system transports gas through interstate pipelines into the Pacific Gas and Electric Company (PG&E) and Southern California Gas Company (SoCalGas) intrastate gas-transmission pipeline systems. If Facility

730 is impacted by wildfire, its impact is likely to be more severe and widespread. Since Facility 730 is in the Sacramento Valley region, it is assumed that gas supply to this region will be reduced. At the same time, gas flows from the Sacramento Valley region to downstream regions including the North Coast, North Bay, Central Valley, and Sierra Nevada regions are also assumed to be reduced. The analysis adopts three levels of impacts: 10 percent, 30 percent, and 50 percent, as shown in Table 10. Case C3 represents a high-impact scenario in which gas supply in the Sacramento Valley region and gas flows from that region to downstream regions decrease by 50 percent. Once these percentages were calculated, the CGE models were run for cases A, B, C1, C2 and C3. The results are discussed in the following section.

Figure 16: Wildfire Impacted Facilities and Regions: North Coast (left) and the Sacramento Valley (right)



Source: University of California, Santa Cruz.

Table 10: Regional Impacts of Different Wildfire Cases

Case	Facility ID	Region	Impacted Population	Total Population	Percentage of Impact
A	830	North Coast	117,232	175,969	0.6662
B	236	Sacramento Valley	11,257	2,447,566	0.0046
C1		Sacramento Valley,			0.1000
C2	730	North Coast, North Bay,			0.3000
C3		Central Valley, Sierra Nevada			0.5000

Source: University of California, Santa Cruz.

3.4 Results

3.4.1 Sea-Level Rise

Seven scenarios, defined by different ranges of future sea level, were both identified and simulated. These scenarios reveal a comprehensive view of economic impacts in the natural gas sector. Given the redundancy of going through all these results, this section used Scenario 5 as an illustrative example. Understanding the results for Scenario 5 makes it easier to understand the results for the other scenarios. This section further compares gross domestic product (GDP) results among the different scenarios. This comparison provides an understanding of the magnitude of impacts from different scenarios. The comprehensive results for the other scenarios are presented in Appendix E. All the results are displayed as relative changes, in percentage terms, from the baseline scenario. The results of regions within California were closely examined since they are the primary focus of this research project. Results for states and regions outside California are readily available from the simulations.

Tables 11 through 15 summarize Scenario 5 results. Gas supply decreases to the three directly impacted regions would lead to changes in the outputs and prices of the different economic sectors and regions. Table 11 shows the impacts on the sectoral supply of the nine California regions. When the sea-level rise is between 329 cm and 334 cm, there would be a gas supply shock to the North Coast, North Bay, and South Bay regions of 32.58 percent, 4.28 percent, and 28.57 percent, respectively, as shown in Table 10. All other regions would increase their local gas supplies accordingly. The logic behind this shift is that, when less gas is available to the North Coast, North Bay, and South Bay regions, the shortage would incentivize other regions to increase their natural gas imports. This would cause the Central Valley and Sacramento regions to significantly increase their sectoral supplies by 5.56 percent and 3.27 percent, respectively, as would other regions, for example SoCal-PG&E region pipelines by 0.22 percent and Sierra Nevada by 0.85 percent. These regions are neighboring regions of relatively large economic size. The economic sizes of the Central Valley and Sacramento regions are larger than those of other nearby regions so have more resources to respond to a gas supply shock. Unlike Southern California regions, i.e., SoCal-No-PGE and SoCal PGE, the Central Valley and Sacramento regions are located closer to North Coast, North Bay and South Bay regions, and therefore the gas supply shock has a more direct impact on gas imports/exports in these two regions.

Table 11: Impacts on Sectoral Gas Supply Under Scenario 5 (percent)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	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.

Source: University of California, Santa Cruz.

This also shows important supply-pattern changes in non-gas sectors. The gas supply to manufacturing in the North Coast and South Bay regions drops significantly by -5.0781 percent and -3.9218 percent, respectively. A similar pattern is observed for the energy-intensive sector in these two regions (-3.22 percent and -4.49 percent). The North Bay region, however, appears to have a different supply pattern. While it is likely to be directly impacted by a gas supply shock, like the other two regions, its manufacturing and energy-intensive sectors are not likely to be negatively impacted, as compared with 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 for energy supply. These results can also be explained by the magnitude of the gas supply shock. The gas supply shock imposed on the North Coast and South Bay regions is around 30 percent, which is a large shock to one sector, while the shock for the North Bay region is less than 5 percent. Although the gas supply in the North Bay region decreases, only a small part of the manufacturing and energy-intensive sectors, which are reliant on gas supply, are negatively impacted. It may be relatively easy for that region to secure alternative energy sources, so that its production activities are not necessarily negatively impacted.

Regarding the energy sectors, refined oil and electricity are two additional sectors worth analyzing. Refined oil (or petroleum) and natural gas are closely related since they share similar extraction processes. Supply changes in these two sectors are therefore closely aligned. Table 11 shows that the supply to refined oil decreases by 1.61 percent, 13.16 percent and 15.36 percent in the North Bay, North Coast, and South Bay regions, respectively. 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 sector.

Regarding electricity, this 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), may seem counterintuitive since natural gas is an input to the electricity sector. However, this applies only in the short term where limited substitution is allowed between gas and electricity. This analysis suggests that substitution is a dominant force in the long term when determining electricity output. A decrease in gas supply encourages greater use of electricity as energy input into other production processes. In this sense, electricity serves as a competitive energy source to the natural gas sector. This substitution effect between the electricity and natural gas sector outweighs the complementary effect, leading to an increase in electricity output. An industrial facility that uses gas for heating may seek alternative heating processes when natural gas is not readily available or not economical to consume. Some possible choices could include adopting electric or solar heat pumps. Switching energy sources from natural gas to electricity might also encourage a greater supply of electricity when less natural gas is available.

Table 12 shows the impacts on Armington aggregates, which are used for household consumption, government consumption, and investment, or by other sectors as intermediate goods for their production processes.

Table 12: Impacts on Armington Aggregates Under Scenario 5 (%)

Sectors / Regions	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	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.

Source: University of California, Santa Cruz.

The change in Armington composites summarizes the joint effects of changes in local supply, international imports, and domestic imports, so served as a good indicator of each commodity's overall consumption. Of particular interest, the overall magnitude of change of the Armington composite was much smaller than the magnitude of change in sectoral supply. The natural gas sector, where changes in the Armington aggregate were -1.48 percent, -10.37 percent, and -10.67 percent for the North Bay, North Coast, and South Bay regions, respectively, while reductions in sectoral supply were -4.28 percent, -32.58 percent, and -28.57 percent respectively exemplify this. This discrepancy suggests that the economy was relatively elastic in response to imposed natural gas supply reductions. Although the gas sectoral supply of those three regions was reduced substantially, the economy responded to the shock by reducing gas exports to other regions and increasing gas imports thus alternatively meet gas demand. While the overall demand for gas still decreased, the drop was much smaller than the initial gas supply shock due to this compensation from increased gas imports. A similar pattern was observed for the electricity sector. The increase of the electricity Armington aggregate was only 0.08 percent, 1.64 percent, and 1.43 percent for the North Bay, North Coast, and South Bay regions, respectively, while corresponding increases in the electricity supply were 0.25 percent, 3.02 percent, and 2.66 percent. Although all sectors adjusted their Armington aggregates downward because of the shock, the magnitude of the change was only marginal. Except for some sectors in the North Coast and South Bay regions, the magnitude of Armington aggregate change was always less than 2 percent. This outcome again indicates that the economy responded well to the shock by adjusting substitutions between different commodity sources: less available local supply led to more imports and fewer exports. This substitution helped stabilize the commodity market so that overall demand did not appreciably change.

Changes in the supply prices of the different sectors are explained in Table 13.

Table 13: 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.

Source: University of California, Santa Cruz.

Several observations emerged. First, most of the sectors experienced a price increase in nearly all regions. For the natural gas sector, particularly, prices increased in all the regions. For the three directly impacted regions, the magnitude of price increases were more drastic: 2.73 percent, 10.19 percent and 9.15 percent for the North Bay, North Coast, and South Bay regions, respectively. In contrast, the increase was milder (less than 0.3 percent) for the other regions. The increase in gas prices can be explained intuitively. When there is a gas shortage, economics theory suggests that the market-created scarcity leads to higher prices. If the focus is only on the gas market in a partial-equilibrium framework, a shock to gas supply is equivalent to imposing a cap on the local supply. This capping constraint incurs a positive dual variable: reducing the gas price. At the same time, the dual variable (or price) also incurs an economic rent directly gained by gas providers and producers. However, in a general equilibrium model, the producers and 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 investments. Researchers assumed that private consumers retain the rent in the long term through monetary rebates (Burfisher, 2017). The results for private consumers are discussed in Table 14.

Table 6: 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.

Source: University of California, Santa Cruz.

Household consumption was not restricted to a certain sector. Instead, it represents the purchasing power in general (for all sectors) of each household, with different levels of income. For non-directly impacted regions, private consumption decreased for nearly all household types. This was primarily driven by price increases in most of the sectors and regions, as previously indicated. The price increase further decreased the purchasing power of private consumers, which led to less private consumption. Private consumption in the three directly impacted regions varied. In the North Bay region, private consumption decreased for all households, while the North Coast and South Bay regions experienced an increase in their respective private-consumption levels. This was due mainly to different magnitudes of shock. As explained earlier, the rent incurred from gas supply restrictions will be distributed to private consumers. Therefore, consumers in the North Bay, North Coast and South Bay regions will all receive payments representing this rent, increasing their total incomes and private consumption. At the same time, they tended to decrease their consumption, like consumers in other regions, because of the increase in price. The result was two counteracting forces. In the North Bay region, since the magnitude of the shock was relatively small, the rent was also relatively small. The increase in consumption due to rent retention was therefore not large enough to drive the final consumption level. However, the North Coast and South Bay regions both experienced a large shock, so the rents incurred were much larger in magnitude, thereby leading to increased consumption.

Regarding distribution: if the impact on private consumption is positive, higher-income households experience higher consumption. However, if this impact is negative, the distributional effect is ambiguous. In the Sacramento and Sierra Nevada regions, households with higher incomes experienced more negative impacts, while in the Central Coast and SoCal regions with PG&E pipelines lower-income households were worse off, with larger negative impacts.

Table 15 reports the impacts on regional GDP or Gross Domestic Product. It is a monetary measure of the market value of all the final goods and services produced annually, in all the sectors of an economy.

Table 15: Impacts on Gross Domestic Product 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.

Source: University of California, Santa Cruz.

To some extent, GDP reflects activity in an economy. Nominal GDP was calculated by adding private consumption, government consumption, investment, and net exports (exports minus imports). When the North Coast, North Bay, and South Bay regions had limited gas-supply capacity, the GDP of California, and the U.S. decreased by $115.79 and $24.03 million, respectively, indicating negative impacts overall for both the California and U.S economies. A closer examination by region shows that nearly all of the GDP reduction came from the South Bay region ($268.91 million). The North Bay and North Coast regions actually increased 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 at optimal GDP level for a given set of resources. In fact, the BAU equilibria for some regions (such as the North Bay and North Coast) were likely to be suboptimal. As a result, when a negative shock takes place, the region becomes more active and produces a higher GDP. In a sense, the economy allocates resources where they are most needed. When some negative shock is introduced, an economy attains a better and more efficient allocation of resources, as shown for the North Bay and North Coast regions. For the South Bay region, a decrease in GDP was observed because of the large magnitude of the negative shock.

Finally, the GDP was compared for all seven SLR scenarios in Table 16 which shows the GDP difference for each scenario when compared with the BAU. In general, this shows that with a higher level of sea rise more regions are impacted and the overall economies of California and the U.S. are negatively impacted. When the sea level rise is relatively small, it is easier for a local region and other related regions to overcome the negative shock in production capability by 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 a case where substitutions are limited among Armington goods, input factors or consumption factors.

Table 7: Gross Domestic Product 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.

Source: University of California, Santa Cruz.

3.4.2 Wildfire

In this section, the results of cases A, B, and C2 are discussed in greater detail. The results for cases C1 and C3 have patterns similar to case C2 but with different magnitudes. Some patterns resemble those of sea-level rising so are not the areas of focus. A comprehensive list of results is shown in Appendix F.

First, Case A imposes a gas-supply reduction in the North Coast region by 66.62 percent, as shown in Table 17.

Table 8: Impacts on Sectoral Supply Under Case A (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0016	-0.0059	0.0053	0.0069	-0.0097	-0.0082		-0.0078	-0.0052	-0.0122
Central Valley	0.0013	-0.0065	0.0060	0.0075	-0.0070	0.0025		-0.0044	-0.0034	0.0099
North Bay	0.0010	-0.0262	-0.0391	-0.0168	-0.0158	0.0055		-0.0127	0.0060	0.0361
North Coast	1.2497	-4.8809	-10.6647	-6.6170	9.4359	-66.6200		11.5700	6.0452	-28.7037
Sacramento	-0.0561	0.2408	0.2969	0.1677	-0.0537	2.7547	0.7256	-0.2287	-0.1821	-4.3749
SoCal No PGE	0.0003	-0.0054	-0.0017	0.0002	-0.0147	0.0081	-0.0079	-0.0051	-0.0014	0.0029
SoCal PGE	0.0001	-0.0015	0.0048	0.0034	-0.0101	0.0048	-0.0165	-0.0002	-0.0048	0.0075
South Bay	0.0017	-0.0178	-0.0077	-0.0036	-0.0225	0.0048		-0.0119	-0.0013	0.0109
Sierra Nevada	-0.0314	0.0723	0.1534	0.0787	0.0601	0.5860		-0.1316	-0.0474	0.1624

Source: University of California, Santa Cruz.

Gas supplies for other regions increased to compensate for this supply shortage. Particularly, the Sacramento Valley region increased its gas supply by 2.75 percent since it is the major gas supplier of the North Coast region. By increasing its gas output, it increased its gas exports to the North Coast region. In the North Coast region, due to the substitution effect among different energy sources, the crude oil and electricity sectors both increased their supply. Supply of refined oil decreased because refined oil and gas are closely related. For non-energy sectors, since gas supply was significantly reduced in the North Coast region, more energy-reliant sectors experienced a decrease in sectoral supply including the manufacturing, energy-intensive, and transportation sectors. Across all regions, the Sacramento Valley was the most impacted region. As mentioned earlier, this is because this region is a major gas supplier to North Coast. When North Coast experienced a gas disruption, Sacramento responded more actively to the change.

The results for Armington aggregate and supply price-share patterns similar to those related to SLR, and therefore results are not displayed here. In summary, a milder change to Armington aggregate was observed when compared to sectoral supply. This is because the Armington aggregate adjusts imports and exports to compensate for the adverse effects of gas reductions. Regarding supply price, the shortage of gas supply within the system caused gas price in all regions to increase; North Coast region increased by 29.67 percent. At the same time, crude oil and electricity prices in the North Coast region decreased by 4.58 percent and 10.25 percent, respectively.

Table 18 shows consumption impacts on households. Households in the North Coast region increased consumption, which is aligned with the assumption that the rent incurred by the limitation of gas supply was distributed to local customers, increasing their welfare. Other than the North Coast region, most regions had decreased household consumption across all household-income types. Another observation is that households with higher income levels experienced higher impacts in consumption.

Table 9: Impacts on Private Consumption Under Case A (%)

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	-0.0011	-0.0012	-0.0016	-0.0020	-0.0025	-0.0030	-0.0035	-0.0041	-0.0074
Central Valley	-0.0011	-0.0012	-0.0017	-0.0022	-0.0028	-0.0035	-0.0041	-0.0047	-0.0087
North Bay	-0.0015	-0.0010	0.0005	0.0022	0.0045	0.0066	0.0087	0.0107	0.0207
North Coast	0.2838	0.5917	1.5480	2.6004	4.0569	5.4387	6.7030	7.8929	13.6032
Sacramento	-0.0157	-0.0259	-0.0513	-0.0806	-0.1199	-0.1588	-0.1924	-0.2220	-0.3633
SoCal No PGE	-0.0011	-0.0010	-0.0009	-0.0008	-0.0006	-0.0005	-0.0005	-0.0005	-0.0007
SoCal PGE	-0.0014	-0.0015	-0.0019	-0.0023	-0.0028	-0.0033	-0.0037	-0.0043	-0.0080
South Bay	-0.0013	-0.0011	-0.0005	0.0002	0.0012	0.0020	0.0027	0.0032	0.0057
Sierra Nevada	-0.0085	-0.0116	-0.0212	-0.0316	-0.0452	-0.0585	-0.0706	-0.0829	-0.1410

Source: University of California, Santa Cruz.

For Case B, wildfire caused facility 236 to fail, and it was assumed that the Sacramento Valley region decreased its gas supply by -0.46 percent, a very small change compared with Case A. The results on sectoral supply impacts are further summarized in Table 19. Due to this marginal change in shock, similar results emerged in terms of gas supply increases in regions other than the Sacramento Valley. Crude oil and electricity supplies increased for the North Coast region, and there was a supply reduction in heavily-energy-reliant sectors. However, in this case, the magnitudes of change were all very small (less than +/- 0.2 percent for all sectors and regions). Again, since the North Coast region relies heavily upon gas imports from the Sacramento Valley region, it was the most impacted region in response to this gas shock in the Sacramento Valley. From a price perspective, gas prices in all regions slightly increased. From the consumer point of view, since the initial gas shock was relatively small in scale, private consumption levels in most regions barely changed.

Table 19: Impacts on Sectoral Supply Under Case B (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0000	0.0022	-0.0002	-0.0003	-0.0001	0.0004		-0.0010	-0.0004	0.0033
Central Valley	0.0000	0.0029	-0.0008	-0.0003	-0.0003	0.0048		-0.0009	-0.0002	0.0031
North Bay	-0.0001	0.0059	0.0054	0.0022	-0.0010	0.0067		0.0001	-0.0007	-0.0060
North Coast	-0.0032	0.0193	0.0281	0.0165	-0.0214	0.1570		-0.0318	-0.0125	0.0154
Sacramento	0.0109	-0.0460	-0.0600	-0.0322	0.0092	-0.4600	-0.1359	0.0317	0.0245	-0.1322
SoCal No PGE	-0.0001	0.0015	0.0003	0.0002	-0.0001	0.0011	0.0007	-0.0013	-0.0003	0.0009
SoCal PGE	-0.0001	0.0016	-0.0004	-0.0003	-0.0003	0.0007	-0.0005	-0.0010	-0.0003	0.0007
South Bay	-0.0002	0.0023	0.0007	0.0010	-0.0016	0.0033		-0.0041	-0.0010	0.0040
Sierra Nevada	-0.0012	0.0051	0.0054	0.0027	0.0024	0.0227		-0.0054	-0.0019	0.0076

Source: University of California, Santa Cruz.

In case C2, gas supply in the Sacramento Valley region and gas exports to downstream regions including North Bay, North Coast, Central Valley, and Sierra Nevada, both decreased by 30 percent. In this case, local gas supply for all regions increased to compensate for gas loss within the whole system. In general, the result patterns drawn from this analysis are like those in Case B, but with a much larger magnitude. As shown in Table 20, the Sacramento Valley region is the most impacted region, followed by the North Coast, Sierra Nevada, and North Bay regions.

Table 20: Impacts on Sectoral Supply Under Case C2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0014	0.1416	-0.0138	-0.0219	-0.0070	0.0294		-0.0660	-0.0280	0.2195
Central Valley	-0.0029	0.1895	-0.0543	-0.0224	-0.0192	0.3189		-0.0580	-0.0165	0.2078
North Bay	-0.0054	0.3857	0.3638	0.1462	-0.0672	0.4497		0.0131	-0.0458	-0.3977
North Coast	-0.2364	1.3517	2.0955	1.2221	-1.5814	11.6333		-2.2932	-0.9222	1.2345
Sacramento	0.7064	-2.9868	-3.8681	-2.1086	0.6045	-30.0000	-8.5317	2.1464	1.6358	-8.8403
SoCal No PGE	-0.0057	0.0997	0.0179	0.0140	-0.0102	0.0726	0.0425	-0.0853	-0.0177	0.0579
SoCal PGE	-0.0043	0.1020	-0.0229	-0.0188	-0.0210	0.0465	-0.0362	-0.0642	-0.0206	0.0487
South Bay	-0.0155	0.1463	0.0450	0.0676	-0.1065	0.2223		-0.2662	-0.0635	0.2707
Sierra Nevada	-0.0938	0.3688	0.4159	0.2068	0.1861	1.7385		-0.4032	-0.1426	0.5645

Source: University of California, Santa Cruz.

Table 21 compares GDP for different wildfire cases. First, other than in Case A, most cases saw an increase in total U.S. and California GDP, which means that the economy became more active aftershocks in cases B and C. Particularly, for Case C, one interesting observation is that when the shock increased from -10 percent, -30 percent to -50 percent, the California GDP increased by $12.3101, $22.8753, and $10.2384 million, which did not monotonically increase with the shock. This indicates that when the shock is significantly large, it is much more difficult for the economy to recover.

Table 21: Gross Domestic Product Comparison for Different Wildfire Cases

GDP difference (Million $)	A	B	C1	C2	C3
National	-23.1817	1.0128	19.8918	44.9079	45.8446
California	-16.9848	0.6587	12.3101	22.8753	10.2384
Central Coast	-0.0132	0.0008	0.0148	0.0338	0.0381
Central Valley	-0.3534	-0.0044	-0.1078	-0.4074	-0.8277
North Bay	-3.5918	0.5596	11.2679	27.5279	33.4320
North Coast	-3.3000	-0.0100	-0.2522	-1.0110	-2.2205
Sacramento	-4.4816	-0.2797	-7.0745	-28.2428	-61.1955
SoCal No PGE	-2.9647	0.2420	5.2444	15.6546	26.0418
SoCal PGE	-0.1348	-0.0032	-0.0736	-0.2462	-0.4554
South Bay	-2.1117	0.1539	3.3048	9.6553	15.6737
Sierra Nevada	-0.0336	-0.0003	-0.0137	-0.0889	-0.2481

Source: University of California, Santa Cruz.

CHAPTER 4: Stochastic Analysis of Resilience Options

4.1 Introduction

The concept of resilience is increasingly used to help cope with disasters from climate change by indicating and reducing vulnerabilities (Ainuddin & Routray, 2012; Rose, 2007). Resilience in this report is defined as the ability of a natural gas system to resist, absorb, accommodate, and recover from the impacts of climate change in a timely manner, including mitigation of the impacts and restoration of essential functions (The United Nations Office for Disaster Risk Reduction, 2009). Risk to the natural gas system may result from a combination of climate-change-induced hazards and facility vulnerabilities. To mitigate these risks, utility companies must make investment decisions that improve their systems' resilience while simultaneously facing uncertainties on both the likelihood of future natural disasters and the expected performance of resilience-improving investments. Any decision-maker in such situations must necessarily face the trade-offs between saving money now or facing increased risks of system failure and costly repairs or restoration in the future. Mathematical models and methodologies have been developed to aid decision making when assessing these options. In this chapter, a model will be discussed that builds upon the analyses presented in the previous chapters to study how future uncertainties on sea level rise and wildfire hazards could impact investments in improving system resilience.

4.2 Method

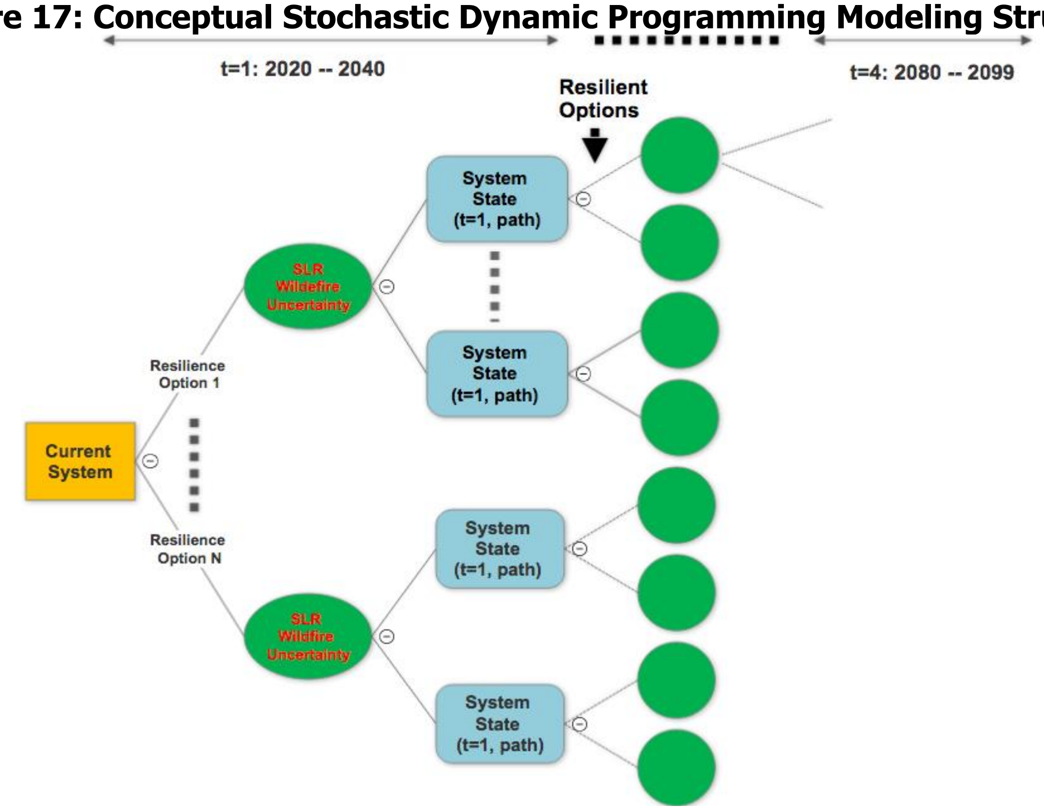
4.2.1 Model Description

In anticipating the potential impacts of climate-change-induced damages to their facilities and other assets, utility companies must face future uncertainties. Various mathematical tools have been developed to aid their decision making. These tools fall into two categories: stochastic programming (SP) (Bertsekas, 2017; Birge & Louveaux., 2011; Powell, 2011; Shapiro, Dentcheva, & Ruszczyński., 2014) and stochastic dynamic programming (SDP) (Bertsekas 2017 and Powell 2011).

The SP approach is referred to as the here-and-now approach since it informs decision-makers as to what actions to take in the short term to maximize an expected total payoff or minimize expected total costs, subject to constraints and uncertainties on input data. The simplest form of this model is the two-stage SP with recourse, where decisions are separated into two groups: those that need to be made before the uncertainty is resolved (for example investment decisions that improve resilience), and those that can be adjusted once the uncertainty is resolved (such as emergency response under various disaster scenarios). The first decisions are made in the first stage of the two-stage model, while the second (also known as recourse decisions), are made in the second stage. The two-stage models can be extended to multiple stages to aid sequential decision-making, usually over a long period of time. In the context of infrastructure investment and updating, SP approaches are best suited to cases where the probability distributions of various uncertainties do not depend on the specific actions taken. In determining what types of electric power generation capacities to build to meet future demand, uncertainties such as demand, wind speed (related to wind power plants), and solar radiation (related to solar facilities) do not depend on what types of power plants are built. In our research the probabilities of how certain infrastructure will fare under SLR or wildfire depend on what specific resilience options are chosen. As a result, the researchers employ the SDP approach in this analysis.

The SDP approach is specifically designed to aid sequential decision-making, so the decisions at the current stage will affect future decisions and corresponding payoffs. A typical situation for the SDP approach, is for a utility to choose from a range of resilience options to harden their physical assets in coastal areas in response to future SLR. The company may choose to do nothing now and instead face increasing risks of facility failure in future cases of SLR and associated service interruptions and repair or restoration costs; alternatively, the company may decide to invest now to harden at-risk facilities, while drastically decreasing the probabilities of damage from SLR in the future, and hence reducing potential service disruptions and costly repairs. The investment decisions, of course, do not have to be made once and for all, and they can be made sequentially over time. A conceptual characterization of the SDP modeling approach used in this analysis is shown in Figure 17. This figure is known as a decision tree; its branches represent the options a decision-maker can choose at each stage, and the green circles represent the underlying uncertainties uncontrolled by human actions. The blue boxes represent possible future states after uncertainties have been realized in that particular period. The multiple blue boxes coming from one green circle emphasize the fact that certain actions, such as building a barrier around an at-risk facility, still involve some uncertainty although the chances of the facility to be flooded may be greatly reduced.

Figure 17: Conceptual Stochastic Dynamic Programming Modeling Structure



Source: University of California, Santa Cruz.

The conceptual formulation of the SDP approach employed in this report follows.

> *Minimize E (the discounted sum of future investment costs^{p} + repair/restoration costs^{p} + costs to Northern California economy^{p})* (4.1)

Note that in Equation 4.1, E represents the expected value while superscript p refers to a policy that can be understood as rules on how to choose a specific feasible action when the system is in a particular state. The SDP approach is to design algorithms to find an optimal policy (if one exists) that minimizes total expected cost.

One feature of the analysis is that the impacts of potential service disruptions on an entire regional economy are explicitly considered. From a utility company's perspective, such costs may be exogenous. Although utility companies want to minimize service interruptions, the actual costs of interruptions are borne by many parties, not just by the utility; consequently, such costs are not factored into the company's decision making. State government policymakers or regulators' perspectives may be interested in learning the best possible options that minimize overall societal costs. With the numerical findings from the modeling analysis in Chapter 3, the results with and without considering societal costs from service interruptions were compared.

4.2.2 Model Assumptions and Input Data

In this section, the details of modeling assumptions and input data used in the SDP model are discussed. One big caveat is that simplifying assumptions is necessary to make modeling and computation work feasible because of the complexity of studying infrastructure decisions over the next 80 years that are subject to highly unpredictable uncertainties. Researchers also relied completely on publicly available data for the modeling, so when certain data were not available, educated estimations were made. Therefore, these assumptions, estimates, and modeling results should not be taken as direct recommendations of specific actions to be taken by utilities. The analyses are meant to shed light on the three questions: (1) how different projections of SLR and wildfire intensity could impact infrastructure investment; (2) how decisions could differ between considering and not considering larger regional economic losses due to utility service interruptions; and (3) how sensitive the modeling results are with respect to input data.

The following discussions are made separately for sea-level rise and wildfire.

4.2.2.1 Sea-Level Rising

It was assumed that sea levels were independent across days. While this assumption is unlikely to be true, this assumption is unrelated to the modeling/computational framework, and its sole purpose was to calculate the probabilities of all possible asset states (such as 20-percent damage due to flooding). This assumption can be replaced by a more sophisticated and realistic stochastic modeling of sea level (and other climate-related natural events). Based on the simulation results in Chapter 2, minimum and maximum sea levels are projected up to 2099 under the modest projection (50 percentile) and the extreme projection (99-percent percentile). The minimum and maximum levels were then used to fit a triangular probability distribution for sea levels on any given day until 2099. With an explicit distribution, the probability for sea level to exceed a certain level at each future date can then be assessed. This directly leads to a specific asset's probability of being flooded, based on the asset's elevation. Note that the crude assumption that the amount of a facility under water equals the difference between the sea level and its elevation level was made. This assumption is unlikely to be true since no facility is located by the sea. When sea water moves inland, it will percolate into the soil, enter surface water like lakes and rivers, and evaporate. Hence, the actual sea level at a certain facility will likely be lower than the originally estimated level. Without access to sophisticated physical models on SLR dynamics, the research included analysis of worst-case scenarios by overestimating the level at which a facility could be submerged.

Damage States. The damage states represent the possibilities of damage of a particular facility under certain natural disasters. Regarding natural gas facilities facing sea-level rising risks, the focus is only on regulating and compressor stations. According to the Federal Emergency Management Agency's (FEMA's) HAZUS model (FEMA 2013) and California's Fourth Climate Change Assessment (Bruzgul et al., 2018) on natural gas system, natural gas pipelines, either exposed or buried, are not subject to flooding. For the damage levels of compressor and regulating stations input data was used from FEMA's HAZUS model (FEMA, 2013), provided in Table 22. Detailed transition probabilities for each facility, from one period to the next, are documented in the technical report.

Table 22: Natural Gas Facility Classifications, Functionality Thresholds, and Damage Functions (FEMA 2013)

Label	Earthquake Classification	Specific Occupancy	Functionality Threshold Depth	Percent Damage by depth of flooding in feet[2]											Comments
				0	1	2	3	4	5	6	7	8	9	10	
NGP1 NGP2	NGP1, NGP2	Exposed Transmission Pipelines River Crossings	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage expected from submergence
NGP1 NGP2	NGP1, NGP2	Buried Transmission Pipelines River Crossings	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage expected from submergence
NGP1 NGP2	NGP1, NGP2	Pipelines (Non-crossing)	N/A	0	0	0	0	0	0	0	0	0	0	0	No damage expected from submergence
NGCV	N/A	Control Valves and Control Stations	1	0	40	40	40	40	40	40	40	40	40	40	Assumes entrance is at grade, and is not sealed.
NGC	NGC1, NGC2	Compressor Stations	4	0	1	2	5	15	30	40	40	40	40	40	Assumes all equipment raised 3 feet above ground level.

[2]*Assumes electrical switch gear is located 3-feet above grade.*

Source: University of California, Santa Cruz.

Damage and Restoration Costs. With the damage states defined, the SDP model requires input data on the repair costs corresponding to each damage state for each at-risk facility. Based on the simulated sea-level rising levels for the next 80 years, seven facilities susceptible to flooding due to rising sea levels were identified, purely based on facility-elevation levels on record. To estimate repair costs, an assumption was made that a facility with 40 percent damage meant that the facility could not be repaired and had to be completely rebuilt (the same assumption as in FEMA's HAZUS model). The rebuilding costs of a compressor or regulating station are based on the numbers reported in the final report of the South Project by Southern California Gas Company (2013). For lesser damage, the repair cost as a portion of the rebuilding cost was estimated. The cost of repairing a facility that suffers 30 percent damage due to flooding will cost 30 percent or 40 percent, or ¾ of the rebuilding cost. For compressor stations, the researchers only considered three damage percentages: 15 percent, 30 percent, and 40 percent, with the implicit assumptions that damage percentages below 15 percent would not incur significant repair costs or service interruptions. All costs are in 2014 real dollars based on most recent year data.

Table 10: Summary of Repair Costs Subject to Sea-Level Rise Under Different Damage States

Location (County)	Asset Type	Asset ID	Elevation Level (ft)	Repair Costs (2014 M$)[i]		
				15% damage	30% damage	40% damage
Humboldt	R/C[ii]	3/827/828/829	6.82	52.50	105.01	174.45[iii]
Marin	R	927	10.70	-[iv]	-	12.65
Contra Costa	R	928	10.96	-	-	12.65
Contra Costa & Solano	R	913/914	8.66	-	-	25.3[v]
San Francisco	C	61	5.77	51.19	102.38	136.5
Alameda	R	946	12.04	-	-	12.65
Santa Clara	M/R	593	10.79	-	-	12.65

i: The costs are estimated based on facility costs reported in "Southern California Gas Company North - South Project, Updated Report." November 2014. The costs are estimated based on facility costs reported in "Southern California Gas Company

North - South Project, Updated Report." November 2014. https://www.socalgas.com/regulatory/documents/a-13-12-013/Attachment%20A_%20Updated%20Buczkowski%20Supplemental%20Testimony%20Final%20Redacted.pdf.

ii: R stands for a regulator station; C stands for a compressor station; M stands for a metering station. R/C means that there is both a regulator and a compressor station in this region.

iii: This cost estimate includes one compressor station and three regulating stations. The compressor station's cost is based on the construction cost of the Adelanto Compressor Station, as reported in (SoCalGas 2014), which includes both labor and non-labor cost, but no right-of-way cost (as the damaged station is assumed to be repaired/rebuilt on the site that the utility company already has right-of-way. For pressure regulating stations, the biggest cost/expenditure would be related to the tied-in pipelines. Since no water damage of pipelines under SLR is assumed, cost estimates of regulating stations were based on the engineering and construction management costs, and the materials costs of valves, as in the same report for the Moreno Valley pressure limiting station. The researchers understand that a pressure regulating station and a pressure limiting station have different functionalities, and hence may have different labor/non-labor costs for repair/rebuilding. However, due to lack of data in the public domain, the assumption is that their cost estimates are the same.

iv: Based on Table , control stations, including regulating, pressure limiting, and metering stations, do not have intermediate damage states.

v: This includes the cost of rebuilding two regulating stations.

Source: University of California, Santa Cruz.

In addition to repair costs, service disruptions from facility damage and its impact on the entire Northern California economy (termed system cost) were also considered. As described in the previous chapter, the CGE model can estimate these impacts on an annual basis. However, most disrupted service is restored in much less time than a year. Therefore, to estimate more accurately the system costs due to service disruptions, annual cost numbers were used from the CGE model which equaled the number of days with service-interruption days. While the service interruption days corresponding to a future event were highly uncertain, the data from Hurricane Katrina were used as an approximation. Based on this report (McCalley & Gil, 2006), utility service was restored by Entergy in 42 days after Hurricane Katrina. While the restoration included electricity and natural gas, researchers used this number as an approximation for gas-service restoration when the damage level to a facility was at 40 percent. For lesser damage, the team also reduced the service-interruption days. Proportionately, 30 percent damage in service would take 42 x 30 percent/40 percent days to be restored. Sensitivity analysis would be conducted on the number of service-interruption days to study its impact on SDP modeling results. In addition, the system costs from CGE models are aggregate costs, not associated with individual facility failures. If the sea level rises above 367 cm, all the seven at-risk facilities would suffer flood damage and the resulting economic cost would be due to the failure of all the facilities. However, in the SDP analysis, without access to a sophisticated natural gas network model, the analysis of infrastructure investment was based on individual facilities. Based on various assumptions, such as medium to long-term scenarios when the economy responds optimally to service interruptions, the indirect costs to the regional economy would be a minor factor in decision-making since repair or relocation costs are relatively small.

Resilient Options and Corresponding Costs. In response to SLR, the focus is on two options for utilities: build flood barriers or relocate. Due to the lack of publicly available data, the cost data for building a 17.2-foot sea wall for the Blue Plains Wastewater Facility in Washington, D.C., was used as a proxy at around $13 million (United States Environmental Protection Agency (US EPA), 2017). For relocation costs, the estimates are based on the construction costs reported for the Southern California Gas Company North-South Project (2013). For relocating a pressure-regulating station, the biggest cost was related to pipeline rerouting and tie-in. The cost estimate here is based on the Adelanto-to-Moreno pipeline construction cost (Southern California Gas Company North-South Project 2013). For relocating a compressor station, the assumption is that the cost would include constructing both the compressor station and the pipeline.

Table 24: Available Resilience Options in Response to Sea-Level Rise

Resilient Options	Overnight Costs (2014 M$)
Build flood barriers	13
Relocate (regulating/metering station)	485
Relocate (compressor station)	622

Source: University of California, Santa Cruz.

4.2.2.2 Wildfire

Event Probabilities: The wildfire probabilities in a certain area, described in Chapter 2, were calculated by burned areas in a cell within a 20-year period for the next 80 years. The burned areas (in percentage) are organized into four bins, corresponding to 0-25 percent (Bin 1), 25 - 50 percent (Bin 2), 50 - 75 percent (Bin 3), and 75 – 100 percent (Bin 4). Bin 2 was added to Bin 4 as a probability for a region to have wildfires that would completely damage natural gas facilities inside that region. The underlying assumptions are that within a 20-year period, at most one wildfire could completely burn down a facility, and that these events are independent across different 20-year periods. The second assumption is that 20 years are enough for vegetation to recover in an area, and hence be subject to another wildfire. The validity of the first assumption, however, heavily depends on the specific regions under consideration. According to the National Aeronautics and Space Administration (NASA), six areas in the western U.S. may experience wildfires every seven years. Note, however, that dividing the future 80-year period into four 20-year decision periods is purely arbitrary (another consideration is that most infrastructure projects can be completed within 20 years). Changing these decision periods to different numbers of years would not change the SDP modeling. However, it would impact the computer solution time to solve the SDP model, where the more decision periods there are, the longer the time frame to consider. The detailed transition probabilities for each facility, from one time to the next (with respect to each resilient action taken in the current time period), are available on Github:

https://github.com/andrew-ll/CEC-Natural-Gas-NorCal-Project-Data-and-Source-Code.

Damage States: Note that, for assets subject to wildfire, and based on the communication with PG&E staff, there are neither historical data nor reasonable modeling approaches to come up with different damage states (that is, percentage of damage) for natural gas facilities from wildfire. As a result, it is only assumed here that there are two states for at-risk facilities: no damage or complete destruction.

Damage and Restoration Costs: Three facilities (one in the North Coast region, and two in the Sacramento Valley region) were identified as subject to wildfire risk. Their repair costs, restoration times, and impacts to Northern California's economy are summarized in Table . Note that the economic costs represented are annual numbers, under the assumption that service interruptions would last for one year and thus likely exaggerates restoration times. However, given recent wildfires, utilities may be subject to liability costs, which are not related to direct repair or restoration costs. It was therefore decided to use the full annual cost as an approximation to any costs (faced either by a utility alone or by the whole economic system) caused by wildfire, but not directly related to repair or restoration costs. Considering vs not considering the non-repair-related costs of future wildfire risks should be established.

Table 11: Summary of Repair and System Costs for Natural Gas Facilities at Wildfire Risk

Location (Subregion)	Asset Type	Asset ID	Repair Cost (2014 M$)	System Costs (2014 M$)
North Coast	M	236	12.65	13.88
Sacramento Valley	R	830	12.65	-0.42
Sacramento Valley	PLS[i]	730	12.65	15.35[ii]

i: Pressure Limiting Station

ii: The worst-case scenario from the CGE modeling results.

Source: University of California, Santa Cruz.

Resilient Options and Corresponding Costs. The available options for utility companies to reduce wildfire risks are mainly based on the *Pacific Gas and Electric Company Amended 2019 Wildfire Safety Plan*, the costs for which provide some basis for estimation. Its sources are provided in Table 26; other costs are purely assumptions.

Table 26: Resilient Options and Corresponding Costs That Reduce Wildfire Risk

No.	Resilient Options	Overnight Costs (2014 M$)[i]
1	Do nothing	0
2	Vegetation Management	2[ii]
3	Vegetation management and install situational awareness technologies[iii]	5
4	Vegetation management and hardening	7
5	Vegetation management, install situational awareness technologies, and hardening	10
6	Relocate (pressure regulating/limiting station)	485[iv]

i: Note that these costs are the costs associated with the programs for the specific cell (or region) where the facility is in, not the costs over the entire service territory of the utility company.

ii: It is assumed that vegetation management must be done each year, and the cost estimate here is the total cost over 20 years for a specific region where a natural gas facility is located.

iii. Situational awareness technologies include, but are not limited to, high-definition cameras, weather stations, and Satellite Fire Detection and Alerting System that incorporates data from Geostationary Operational Environmental Satellite (GOES) and polar orbiting satellites.

iv: The relocation cost includes the cost for both building the pressure limiting station, and for constructing pipelines that are tied to the station. The cost estimate is based on the cost for constructing the Moreno Valley Pressure Limiting Station and the Adelanto to Moreno Pipeline, as reported in (SoCalGas 2014).

Source: University of California, Santa Cruz.

4.3 Results

4.3.1 Sea-Level Rise

Based on the project simulation described in Chapter 2, under the modest projection (50 percentile) of SLR for the next 80 years, facilities in Humboldt County (Units 3/827/828/829) could be affected after 2060, and facilities in Contra Costa and Solano counties (Units 913/914) could be impacted after 2080. Under the more extreme projection (99 percentile), all the identified assets in Table 23 could be affected after 2080. For units 913/914, the probability of flooding over 1-foot above its elevation is 0 even after 2080 under the modest projection. Hence, the focus was first on facilities in Humboldt County.

Unit 3/827/828/829 – Compressor and regulating stations. Under the modest projection, in the last modeling period (2080-2099), the units will face an 80 percent probability of at least one flooding over 1 foot above its elevation. Since the compressor station is assumed to be 3 feet above ground, focus is only on the costs associated with the three regulating stations. With the high probability of flooding in this period, a decision-maker would invest to build barriers. Under the more extreme projection, the units will face probability of 1 to be flooded in 2060-2079 and 2080-2099. Hence, the optimal actions are to build flood barriers in one period earlier than the modest case; that is, to build the barrier in 2060-2079, instead of 2080-2099. The results are robust when the whole economy cost of the NorCal region is considered. This point will be discussed in detail in the analysis for Unit 61.

Unit 61 – Compressor station. This station has the lowest elevation level among the facilities subject to SLR risk. However, based on FEMA's estimate when the water level reaches 4 feet or more above its elevation, a compressor station would face significant flood damage since it is assumed that all equipment is raised 3 feet above ground level. In this scenario, with a modest projection of SLR (50 percentile), the station would not face a flooding risk through 2099. Under the more extreme projection (99 percentile), during the 2060 to 2099 period, the compressor station would face flooding risk. Using the triangular-probability distribution (as described in the technical report), between 2060 and 2079, the probability of 15 percent damage (that is, 4 feet above its elevation) would be 0.05, with zero probability of facing greater damage. Due to the small probability of less severe damage, the optimal choice among the three possible actions (do nothing, build a barrier, or relocate) is to do nothing in the period 2060 – 2079. However, from 2080 to 2099, flooding risk due to SLR increases dramatically to the point where there is a probability of 1 for the facility to suffer 40 percent damage at least once if no action is taken. The researchers assumed that with 40 percent damage, the facility must be either rebuilt or relocated. Due to the high probability of flooding risk and its significant repair or restoration cost, the optimal action is to build barriers, which would be much cheaper than relocating. Note that building barriers would not completely remove the risk of flooding, while relocating would do so. A 20 percent probability of flooding with flood barriers is still assumed, which is likely too high since most flood barriers would be built to withstand a 1-in-a-100-year event. Nevertheless, given the cost difference, building barriers would be the cheaper option even with a 20 percent chance of being flooded. Such results are robust with consideration of the whole Northern California (NorCal region) economy. Under the worst-case of Scenario 5 in the CGE analysis of SLR from Chapter 3, the economy in the NorCal region would suffer a $171 million annual loss due to the disabling of three facilities: Units 61, 913/914, and 927. Converting this loss to a 42-day interruption, which is an assumption based on the restoration time after Hurricane Katrina, the economy cost of the NorCal region would be around $19.3 million. If this cost was added to Unit 61, the optimal solution of choosing to build barriers in the last period (2080-2099) would remain.

For the remaining units (ID 927, 928, 946 and 593) subject to SLR risk, none would face a positive probability of flooding over 1 foot above their elevations before 2080, even under the most extreme projection (99 percentile). During 2080-2099, three units (927, 928, and 593) would all have the probability of 1 to experience flooding over 1 foot of their corresponding elevation levels. Unit 946, which has the highest elevation among all the identified facilities, would have a 0.3 probability of being flooded and suffer 40 percent damage. By running the SDP model, the optimal decisions for all four units are to build flood barriers in the last period (2080-2099). Such results are robust regardless of whether the economy costs of the NorCal region are considered.

4.3.2 Wildfire

Given the three identified facilities subject to wildfire risk, and the relatively low risk of exposure, the expectation would be that neither facility would choose the repair and system cost options when considering repair costs. See Tables 24 and 25. The probabilities of complete burndowns for these facilities follow, under each of the resilience options.

Table 27: Probabilities of Burning Down Under Various Resilience Options Unit ID 236

	Resilience Options					
Time Period	**1**	**2**	**3**	**4**	**5**	**6**
2020 - 2039	0.7%	0.56%	0.42%	0.28%	0.14%	0
2040 - 2059	1.30%	1.04%	0.78%	0.52%	0.26%	0
2060 - 2079	1.50%	1.20%	0.90%	0.60%	0.30%	0
2080 - 2099	2.63%	2.10%	1.58%	1.05%	0.53%	0

Source: University of California, Santa Cruz.

Table 28: Probabilities of Burning Down Under Various Resilience Options Unit ID 730

	Resilience Options					
Time Period	**1**	**2**	**3**	**4**	**5**	**6**
2020 - 2039	0.85%	0.68%	0.51%	0.34%	0.17%	0
2040 - 2059	1.20%	0.96%	0.72%	0.48%	0.24%	0
2060 - 2079	2.30%	1.84%	1.38%	0.92%	0.46%	0
2080 - 2099	3.27%	2.62%	1.96%	1.31%	0.65%	0

Source: University of California, Santa Cruz.

Table 12: Probabilities of Burning Down Under Various Resilience Options Unit ID 830

	Resilience Options					
Time Period	**1**	**2**	**3**	**4**	**5**	**6**
2020 - 2039	0.40%	0.32%	0.24%	0.16%	0.08%	0
2040 - 2059	1.20%	0.96%	0.72%	0.48%	0.24%	0
2060 - 2079	1.45%	1.16%	0.87%	0.58%	0.29%	0
2080 - 2099	2.21%	1.77%	1.33%	0.88%	0.44%	0

Source: University of California, Santa Cruz.

The probabilities for Option 1 (Do Nothing) are based on the project team's analysis, the probabilities under Option 2 to 5 are based on linear interpolation, and the probabilities for Option 6 (relocation) is assumed to be down to 0. While the probabilities of resilience options 2 to 5 are not based on scientific studies, the aim to model the trade-offs between investment costs and their impacts on improving resilience was met. A scenario that is both least expensive and most effective in reducing a facility's wildfire risk, would have no trade-offs.

From the probability tables, the increasing risk of wildfire is evident. However, increasing risk is not sufficient for a company to invest in any of the suggested resilience options if only direct repair or restoration costs are considered. Results changed for units 236 and 730 when the system (or non-repair) costs were considered, as seen in Table 30.

Table 13: Optimal Resilient Options Comparison Between Not Considering and Considering System Costs

Period	Unit 236		Unit 730	
	Repair Cost Only	**Plus System Cost**	**Repair Cost Only**	**Plus System Cost**
2020 - 2039	Do nothing	Do nothing	Do nothing	Do nothing
2040 - 2059	Do nothing	Do nothing	Do nothing	Do nothing
2060 - 2079	Do nothing	Do nothing	Do nothing	Vegetation management
2080 - 2099	Do nothing	Vegetation management and hardening	Do nothing	Vegetation management, Install situational awareness technologies and hardening

Source: University of California, Santa Cruz.

The increasing wildfire risk in the distant future, coupled with higher cost, would likely prompt a decision-maker to invest in certain resilience options. Note that it is optimal to do so in later years because the assumption is that a 5 percent discount rate for the time-value of money (all the calculations are in 2014 money), and the discount rate does not include an inflation rate. Unit 830 does not result in any service disruption costs to the whole economy in NorCal region and is therefore not included in Table 30.

CHAPTER 5: Knowledge Transfer Activities

The research team analyzed the impact of climate-change-induced hazards, specifically sea-level rising and wildfire, on the natural gas infrastructure in Northern California. This analysis is primarily informative to policymakers and decision-makers in the energy sector, though its approach could also be of interest to other researchers. The project benefitted from valuable input from a technological advisory committee that included Dr. Larry Dale (Lawrence Berkeley National Laboratory), Dr. Seith Guikema (University of Michigan), Dr. Nobuhiro Hosoe (National Graduate Institute for Policy Studies), Dr. Sauleh Siddiqui (Johns Hopkins University), Dr. Leah Kaffine (ABB Enterprise Software) as well as PG&E technical staff that included Nathan Bengtsson, Rick Brown, Kit Batten, Valerie Winn, Jane Olivera, and Karen Lee. The research framework and findings have been accepted or presented at several international conferences including the Institute for Operations Research and Management Sciences and the Association of Collegiate Schools of Planning. The overall findings of the project will be submitted to *Climate Change* (https://www.springer.com/journal/10584) to highlight the role of the analytical framework in addressing the impacts of climate-induced hazards on a network infrastructure. The tentative title of the paper is *Analytical Framework to Investigate Climate-Change-Induced Vulnerability of the Northern California Natural Gas Energy System*. The researchers will continue to work with the CEC and other stakeholders to advance continuing research based upon the analysis in this report.

CHAPTER 6: Discussions

Given Northern California's large population, dense forests, and long coastline, the region is in a particularly vulnerable position to the risks associated with climate change. Its energy system and natural gas infrastructure are also likely to be affected by climate-change-induced hazards. In this chapter, the key findings and limitations of the study are summarized, and future research opportunities are discussed.

6.1 Key Study Findings

This project examines the vulnerability of the Northern California natural gas system, with a focus on two types of natural hazards: SLR and wildfire. While the mean ambient temperatures might not change significantly from year to year, the continuously warming climate is likely to increase the frequency and intensity of weather-induced extreme events such as rising sea levels, storm surges, and wildfire. Investments in natural gas sector resilience options without considering the uncertainties of extreme events is unlikely to provide adequate safeguards to protect modern society's energy sources. A lack of accounting for the overall economic impacts of industries outside the natural gas sector could also lead to under investment in resilience options. An evidence- and system-based approach that considers the uncertainty of extreme events and their potential economic losses in other sectors is therefore needed to inform decision-making in resilience options for the natural gas sector.

This project developed a system-level risk-analysis framework that builds upon a regional economic model, coupled with a decision-support tool that addresses the vulnerability of the Northern California natural gas system to climate-change-induced weather events, and identifies resilience options and their implementation. The detailed layout of the Northern California natural gas system was interfaced with downscaled data from the global-climate models provided by the Scripps Institution of Oceanography at the University of California at San Diego (Pierce et al., 2018) and the University of California at Merced (Westerling, 2018) for the years 2020-2100. This helped identify the facilities that are likely vulnerable to climate-change-induced hazards. The location and probability of facility vulnerability were identified and estimated for two hazards: SLR and wildfire. The information was used by the regional economic model to estimate the extent of economic losses that could be incurred by the state of California. Those economic losses, together with the cost of resilience options, were then used in the stochastic decision-support tool to develop the timing for implementing those options.

For SLR, the Northern California natural gas system is generally resilient to the risk of SLR before 2060, even under the most extreme projection (99 percent percentile). After 2060, the most vulnerable facilities are the gas regulating stations in Humboldt County. After 2080, under a modest projection of SLR, no additional facilities would be subject to substantial flooding. However, various gas facilities in seven counties would be subject to significant flooding under the extreme projection of SLR. Between the options of building a flood barrier or relocating the facilities, the optimal choice would be to build a flood barrier in the 2080-2099 period for all the at-risk facilities to avoid economic losses in the region. For wildfire hazard, three clusters of natural gas facilities in the North Coast and Sacramento Valley regions were identified as vulnerable to wildfire risk, especially in the later years of the century when wildfire risk intensifies. The analysis shows that if only repair and recovery costs are considered, the probabilities of wildfires completely burning down facilities do not justify choosing costly measures to mitigate those risks. However, if the costs due to service interruptions caused to the entire Northern California economy are considered, as calculated in the CGE models, mitigation measures should be chosen in the 2080-2099 period despite their high investment costs.

6.2 Limitations of the Study

The vulnerability of the natural gas system could vary under different urban scenarios, technological advances, and adaptation or other measures taken by utilities toward the end of the century. Technological adaptations could help reduce the vulnerability of the natural gas system while unplanned urban growth or expansion could increase vulnerability.

In this project, the climate-change-induced risk analysis was conducted by mapping layers of geographical information. Natural gas facilities exposed to SLR or wildfire were identified by spatially overlaying calculated-risk maps with the natural gas system. The research team could not determine more accurately the extent of facility exposure to hazards due to a lack of access to relevant engineering information, such as existing resilience measures taken.

The economic model is a static model that does not take into consideration the possibility of endogenous economic expansion, which could lead to future changes in industry structures. Modeling economic growth in the distant future at a macro level was challenging because it requires knowledge of future population growth, land-use changes, and technological progress, which are uncertain and intertwined with the global economy. See, for example, Chen et al. (2015) which uses outputs from the National Energy Modeling System (NEMS) to generate power plant investment decisions. The economic propensity as the baseline year is repetitively subject to upsets induced by climate change over future years. The future layout of the natural gas system could also be very different from what it is today. However, predicting future economic activities and natural gas systems in an arbitrary way is unlikely to produce informative results. Furthermore, a population-based estimate of gas service disruptions when facilities are affected by either SLR or wildfire is a necessary compromise due to the lack of publicly available data to develop a bottom-up gas model.

Regarding the stochastic modeling of resilience investment decisions, researchers lacked information at each facility site about responses to potential flooding or fire. As a result, only hypothetical options based on public reports for other facilities (such as building flood barriers for water-treatment plants, and vegetation and monitoring programs for electric distribution systems), and some simple yet costly solutions such as facility relocation, were proposed. The costs of such resilience options are hence suggestive, and only reflect relative relationships among all possible options. The repair costs of each gas facility under different damage states are also estimated based on the project costs of corresponding facility types reported by SoCalGas's North – South Project. The repair costs for facilities in Northern California are expected to be very different than those in the South. Finally, natural gas service interruptions are estimated based on the complete utility service restoration times after Hurricane Katrina, which can vary from expected restoration times for Northern California natural gas systems.

In addition to shortcomings in the various cost estimations, the SDP modeling framework has notable limitations. First, for the investment decisions regarding SLR, we run the SDP model twice, each time with a different projection of sea level through 2099. Note that this is not intended to be a full-fledged decision-support tool. More sophisticated SDP modeling frameworks could lead to promising future research opportunities discussed in the next subsection. Second, although only one path of future projection was used to represent wildfire risk, the uncertainties in future outcomes would not likely follow the projections made. Given SDP modeling and the algorithm framework, the corresponding optimal policies may change with a different projection of future uncertainties. An important future research area would be to study if there are modeling and algorithmic methods that can identify one set of optimal investment decisions for distribution of underlying uncertainties. Such methods are generally referred to as robust optimizations, which have experienced tremendous growth in recent years and are discussed in the next subsection. The third limitation is that the analysis considers isolated events when a single natural gas facility may be damaged by flooding or wildfire. This is not a limitation of the SDP model itself but rather the lack of access to detailed natural gas network and supply/demand data to build a networked model that considers the effect if several facilities are damaged at the same time, such as when SLR floods occur. With a fully detailed network model, the simple SDP algorithm of this study, based on backward induction, may be too inefficient to identify an optimal policy and more sophisticated algorithms are required.

6.3 Future Research Opportunities

In addition to investigating SLR further, inland flooding inland flooding would be important to study within the context of climate-change-induced hazards to the natural gas system. The potential damages caused by inland flooding have not been fully investigated due to the unavailability of appropriate data. Most projects and studies on inland flooding use Federal Emergency Management Agency (FEMA) floodplain data. Existing FEMA floodplain maps account for fluvial flooding hazards along rivers or streams, based on historical flood events. Such floodplain maps do not account for climate. A possible way to integrate climate-change data (such as temperature, precipitation) is the flooding simulation model, HAZUS, developed by FEMA to simulate floods for the late twenty-first century. Another flood, a pluvial flood, should be considered as well in the inland flooding risk analysis. Pluvial floods generally occur in urban areas when urban runoff is beyond the capacity of the sewer system. Such a flood could impact the terminal ends of a natural gas system. The risk analysis of pluvial floods is a complicated process that requires a variety of data including weather, land use, and other physical features.

In addition, a primary natural disaster could cause a secondary disaster. For instance, a building fire often occurs after a catastrophic earthquake. Two or more independent disasters, or convoluted disasters, occurring over a short time could also exacerbate damages. Climate is a complex system, with numerous possible natural hazards triggered at once.

Another future research opportunity is for the Energy Commission to work with the state's large investor-owned gas utilities — Pacific Gas & Electric, Southern California Gas, and San Diego Gas & Electric (SDG&E) —to jointly develop a simplified version of a regional natural gas model similar to the Western Electricity Coordinating Council's (WECC) electricity/power model

(Price & Goodin, 2011). It could then be used by researchers within their own models. This would require regular updating to reflect changes in the system.

Regarding the stochastic dynamic optimization model, an important future research direction is to ensure that the model can provide a coherent set of optimal investment timing and decisions (as opposed to what-if-type analyses) where investment decisions may change significantly under different future-scenario forecasts. In addition, optimal decisions from the stochastic model need to be robust against simulation or forecasting errors. Even when the simulation or forecasting results do not reflect the actual future, modeling results should not be too far off from optimal decisions. There have been two recent research streams towards this goal. The first stream includes a risk measure in the decision-making model, which ensures that the model seeks a balance between minimizing expected costs and losses under a worst-possible scenario. Representative works include Chow and Ghavamzadeh (2014) and Borkar and Jain (2014). This approach still assumes known distributions for underlying uncertainties. The second stream aims to identify robust optimal decisions without assumptions on distributions. Representative works include Hanasusanto and Kuhn (2013) and Duque and Morton (2019). While both research streams attempt to address the robustness issue, their solutions may be overly conservative, such as over-investing in hardening options. The scalability of algorithms is another subject for further investigation.

Another future research direction is to study how the interdependencies of multiple critical infrastructure systems, especially electricity and natural gas systems, may increase system risk and intensify losses that may cause cascading failures in other systems. Understanding such interdependencies would help avoid catastrophic system failures and further improve the overall resilience of the energy systems.

CHAPTER 7: Benefits to Ratepayers

This study is important to ratepayers since it provides a general understanding of how resilient Northern California's natural gas system is against future sea-level rising and wildfire. Since the study found that the system is fairly resilient to those risks through the end of the century, impacts on utility rates specifically related to hardening natural gas systems may be insignificant in the near future. In addition, the developed CGE model can help state government and policymakers understand system-wide economic impacts from natural gas service interruptions while the developed stochastic modeling can help decision-makers balance tradeoffs between the costs and benefits of hardening natural gas systems under various uncertainties. Finally, this study lays out a scalable framework of how to consider system-wide costs and decision-making under uncertain conditions, with more detailed modeling of interdependent sectors including natural gas, electricity, and water conveyance.

LIST OF ACRONYMS

Term	Definition
AGR	Agriculture sector
BEA	Bureau of Economic Analysis
CES	Constant elasticity of substitution
CET	Constant elasticity of transformation
CFS	Commodity flow survey
CGE	Computational General Equilibrium Model
COL	Coal-related sector
EIS	Energy-intensive sector
ELE	Electricity sector
FEMA	Federal Emergency Management Agency
GCM	Global Circulation Model
GDP	Gross Domestic Product
IO	Input-output
LULC	Land use and land cover
NPMS	National Pipeline Mapping System
PG&E	Pacific Gas and Electric
PLS	Pressure limit station
RCP	Representative Concentration Pathway
ROIL	Refined-oil sector
SAM	Social accounting matrix
SDP	Stochastic Dynamic Programming
SLR	Sea-level rise
SP	Stochastic programming
SRN	Service sector
TRN	Transportation sector
WH	Wildfire hazard

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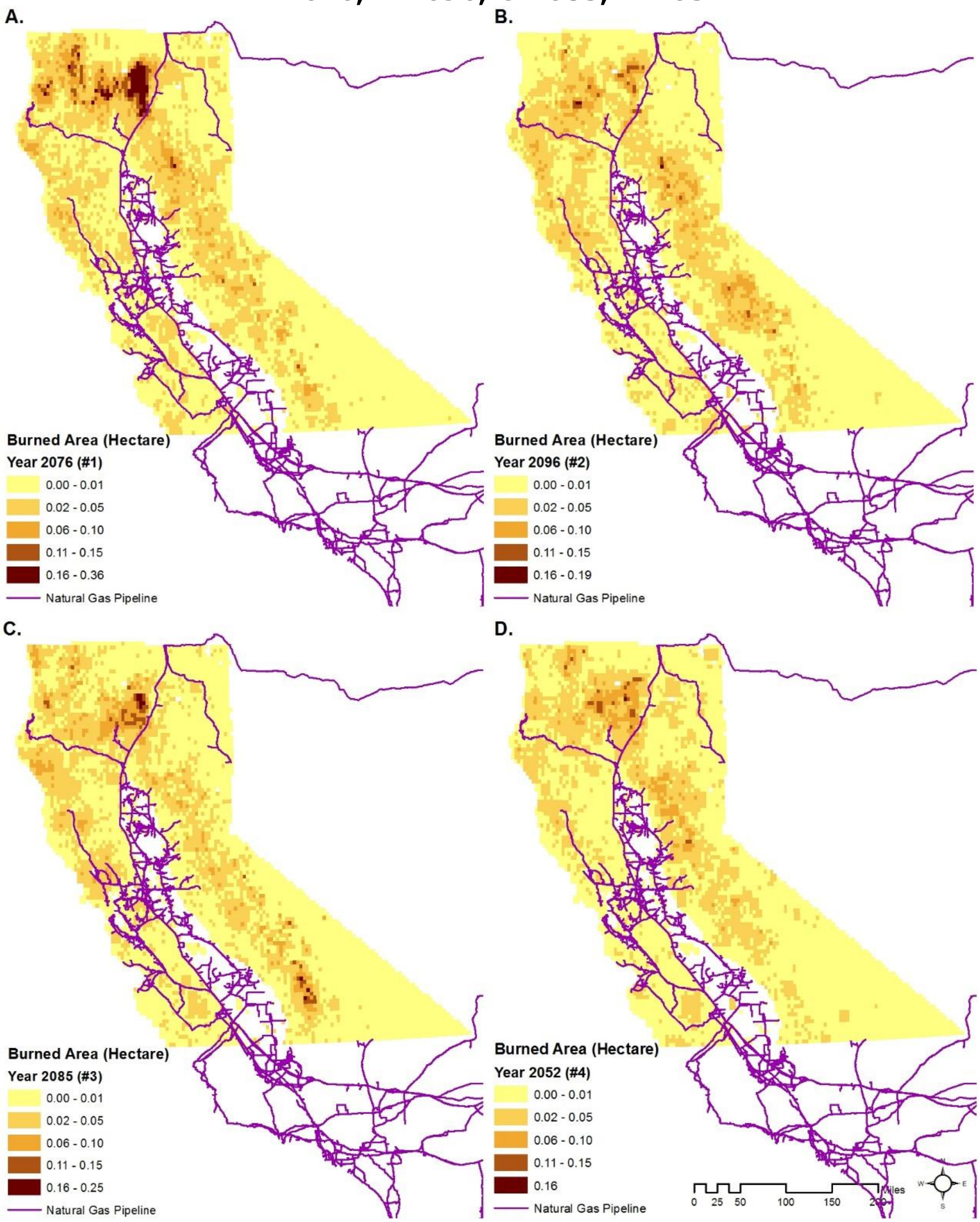
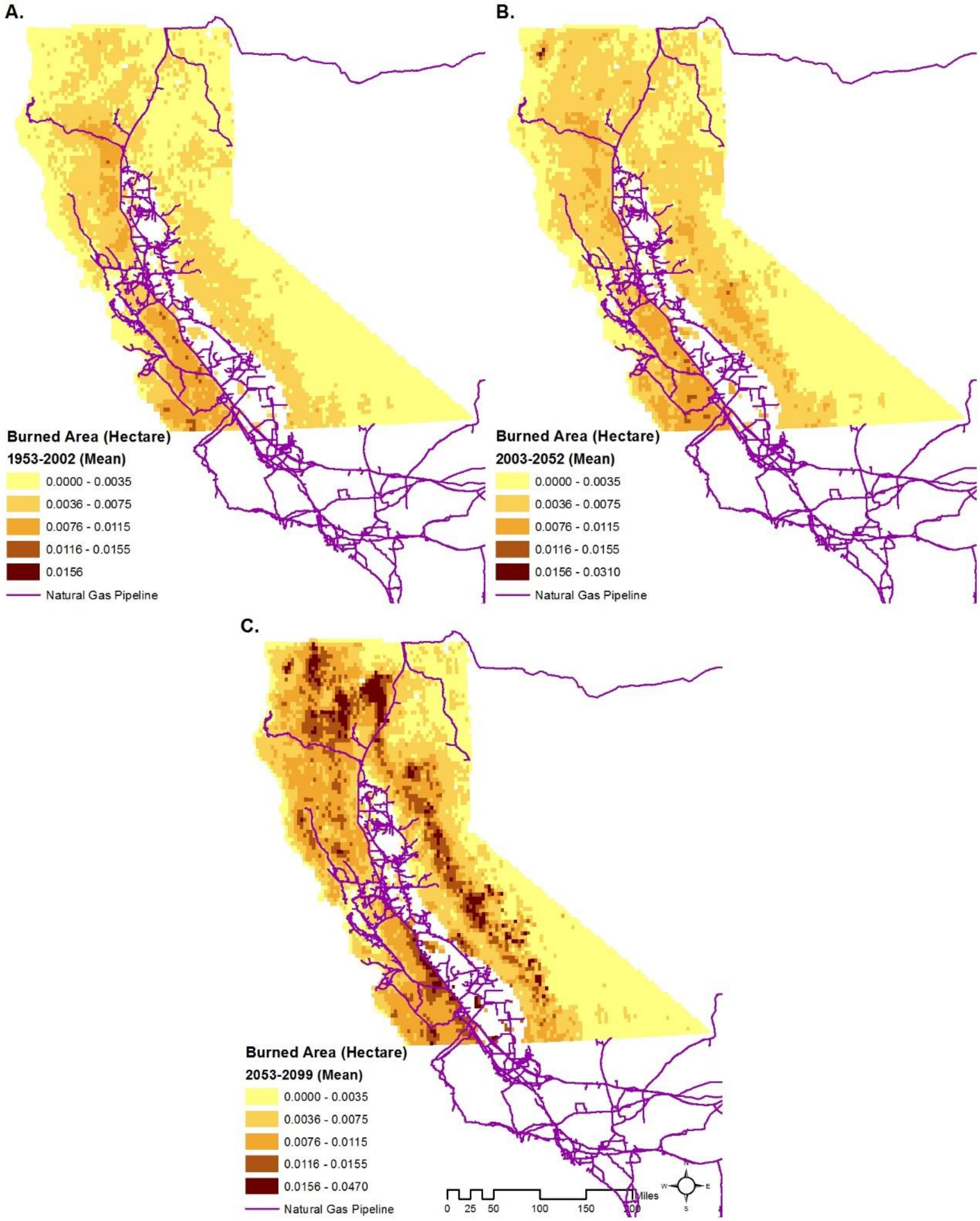
APPENDIX A:
Yearly Burn Probabilities

Figure A-1: Top four worst cases of yearly burn probabilities over 147 years A-2076; B-2096; C-2085; D-2052



Source: University of California, Santa Cruz

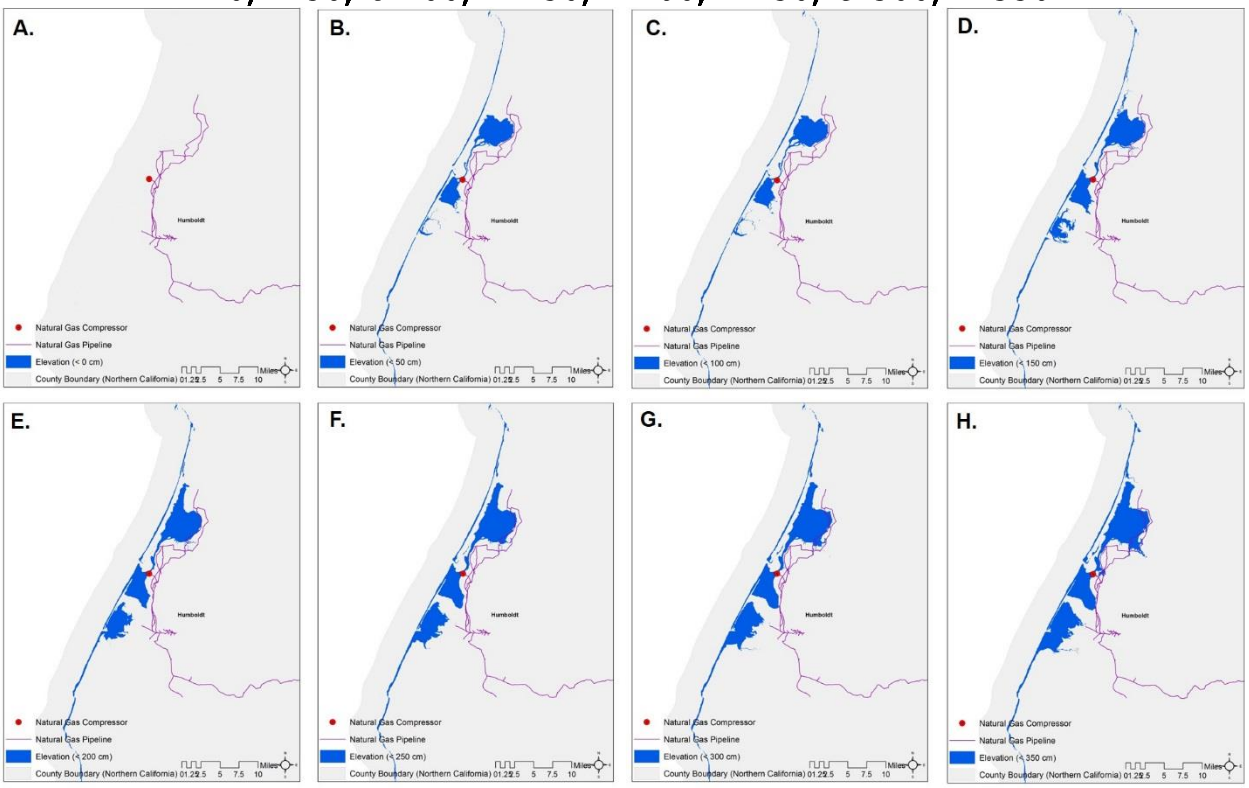
Figure A-2: Yearly burn probabilities in various time periods A: 1953-2002; B: 2003-2052; C: 2053-2099



Source: University of California, Santa Cruz

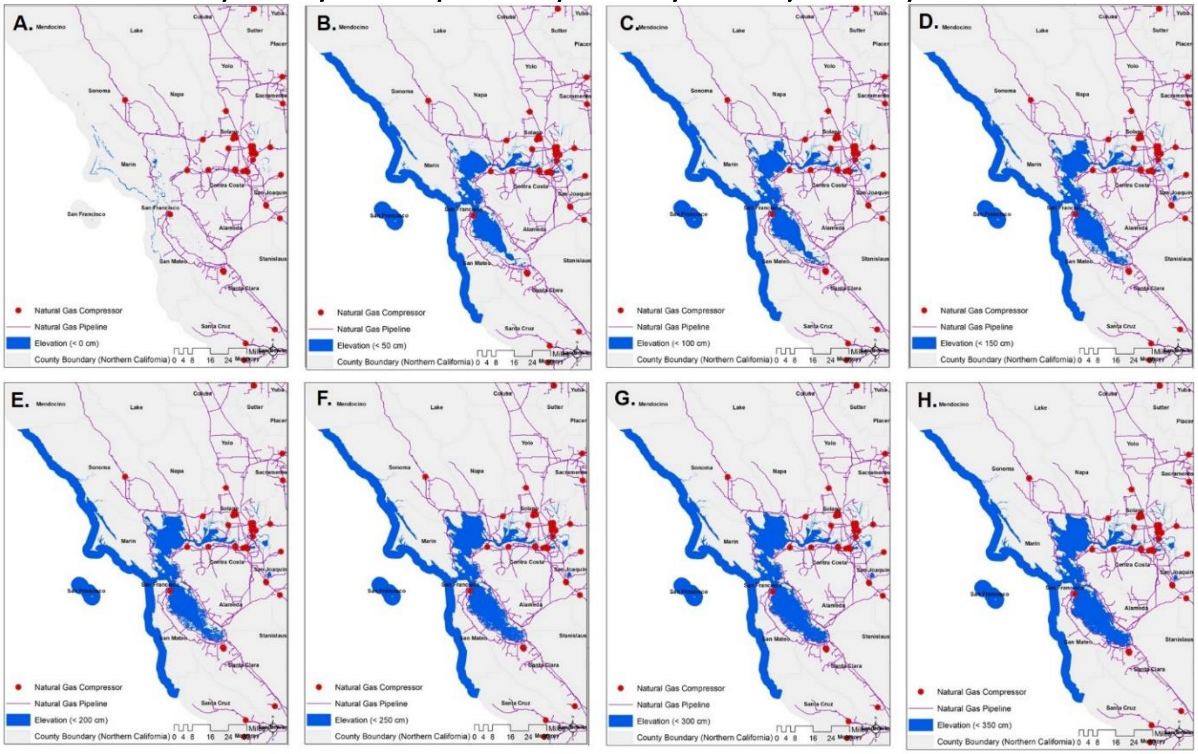
APPENDIX B:
Maps of Elevation and Pipeline

Figure B-1: North region: pipelines, compressors & various elevations (cm)
A-0; B-50; C-100; D-150; E-200; F-250; G-300; H-350



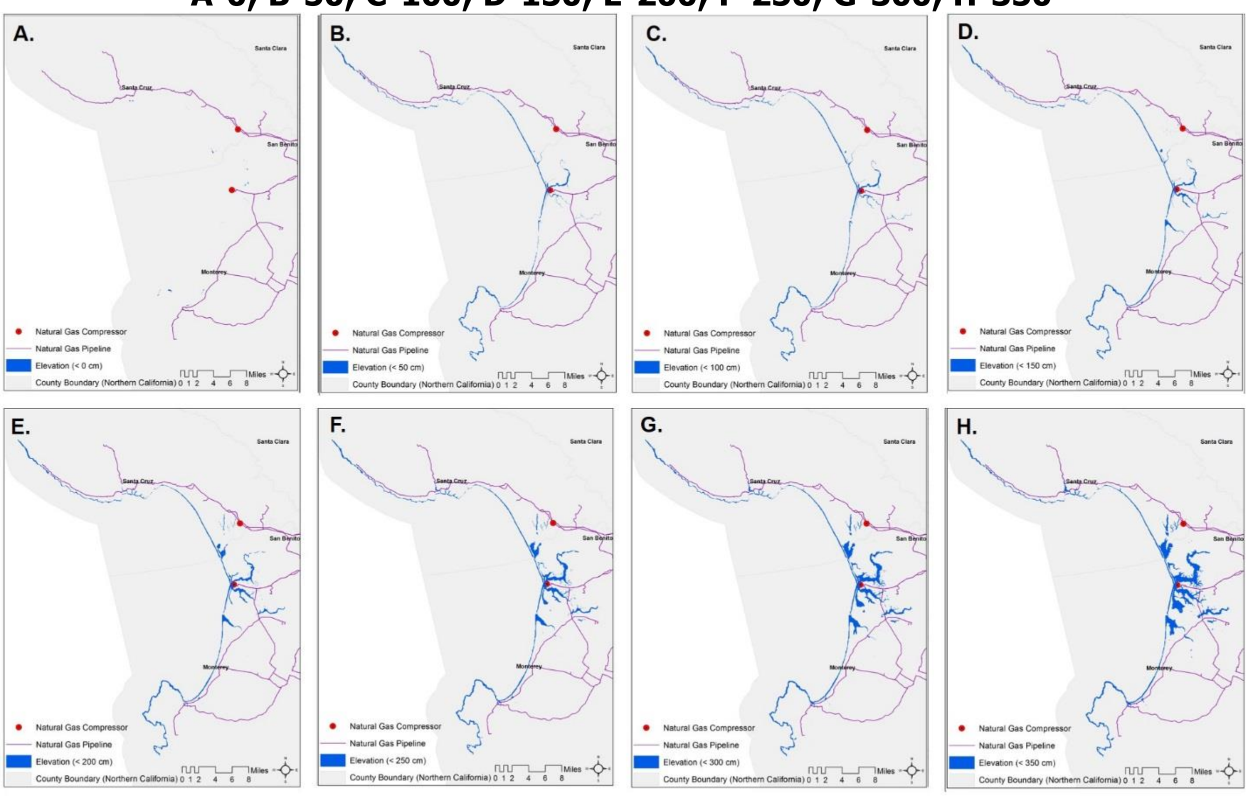
Source: University of California, Santa Cruz

Figure B-2: Bay region: pipelines, compressors & various elevations (cm) A-0; B-50; C-100; D-150; E-200; F-250; G-300; H-350



Source: University of California, Santa Cruz

Figure B-3 MT: pipelines, compressors & various elevations (cm) A-0; B-50; C-100; D-150; E-200; F-250; G-300; H-350



Source: University of California, Santa Cruz

APPENDIX C: Probabilities (%) for natural gas facilities to be inundated within a water depth

Table C-1a: Probabilities (%) for natural gas facilities to be inundated within a water depth (2021-2040) (RCP 8.5)

		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 8.5 (99.9%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	92.77	7.11*	0.12	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 8.5 (50%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	96.22	3.75	0.03	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

Table C-1b: Probabilities (%) for natural gas facilities to be inundated within a water depth (2021-2040) (RCP 4.5)

		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 4.5 (99.9%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	91.85	8.00*	0.15	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 4.5 (50%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	96.24	3.73	0.03	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

Table C-2a: Probabilities (%) for natural gas facilities to be inundated within a water depth (2041-2060) (RCP 8.5)

		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 8.5 (99.9%)					
CC	3 (208)	99.87	0.13	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.95	0.05	0.00	0.00
SF	61 (176)	99.98	0.02	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	99.98	0.02	0.00	0.00
SF	386 (213)	99.99	0.01	0.00	0.00
SF	387 (96)	73.83	22.18*	3.90	0.09
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 8.5 (50%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	91.20	8.57*	0.23	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

Table C-2b: Probabilities (%) for natural gas facilities to be inundated within a water depth (2041-2060) (RCP 4.5)

		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 4.5 (99.9%)					
CC	3 (208)	99.96	0.04	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.98	0.02	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	79.30	18.71*	1.98	0.02
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 4.5 (50%)					
CC	3 (208)	100	0.00	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	92.49	7.39*	0.12	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

Table C-3a: Probabilities (%) for natural gas facilities to be inundated within a water depth (2061-2080) (RCP 8.5)

		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 8.5 (99.9%)					
CC	3 (208)	94.06	5.39*	0.51	0.03
CC	827 (256)	99.39	0.57	0.04	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	96.33	3.38	0.28	0.01
SF	61 (176)	91.95	7.47*	0.58	0.01
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	91.95	7.47*	0.58	0.01
SF	386 (213)	93.41	6.20*	0.39	0.00
SF	387 (96)	30.29	29.68*	27.55*	12.47*
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	99.63	0.37	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 8.5 (50%)					
CC	3 (208)	99.91	0.09	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.96	0.04	0.00	0.00
SF	61 (176)	99.98	0.02	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	99.98	0.02	0.00	0.00
SF	386 (213)	99.99	0.01	0.00	0.00
SF	387 (96)	73.29	22.90*	3.72	0.09
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

Table C-3b: Probabilities (%) for natural gas facilities to be inundated within a water depth (2061-2080) (RCP 4.5)

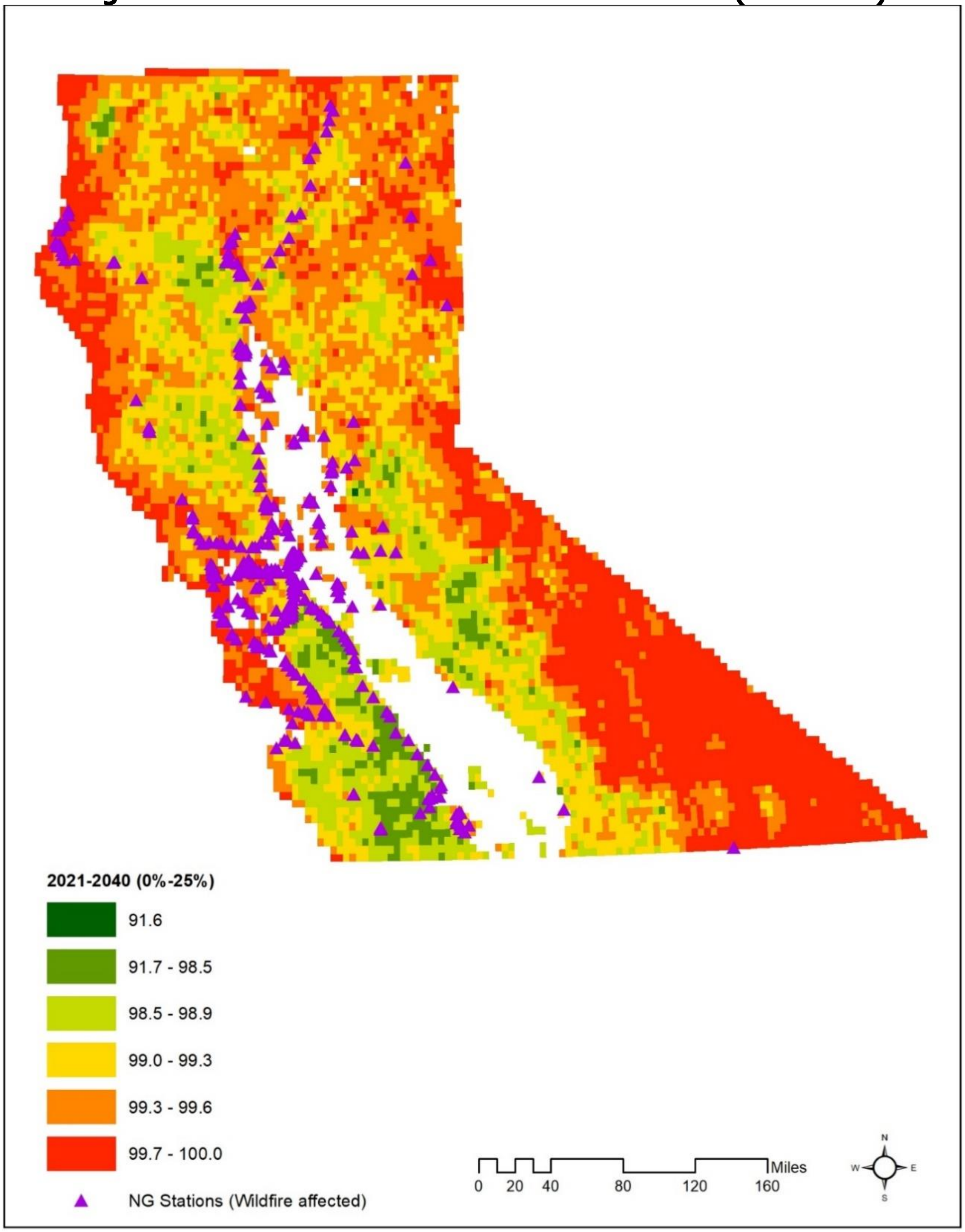
		Water depth (cm)			
Scenario	**NG Station ID (CM)**	**<=0**	**0-50**	**50-100**	**>100**
RCP 4.5 (99.9%)					
CC	3 (208)	99.32	0.67	0.01	0.00
CC	827 (256)	99.99	0.01	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	99.69	0.30	0.00	0.00
SF	61 (176)	99.48	0.52	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	99.48	0.52	0.00	0.00
SF	386 (213)	99.68	0.32	0.00	0.00
SF	387 (96)	50.04	32.60*	15.90*	1.46
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00
RCP 4.5 (50%)					
CC	3 (208)	99.99	0.01	0.00	0.00
CC	827 (256)	100	0.00	0.00	0.00
CC	828 (344)	100	0.00	0.00	0.00
CC	829 (220)	100	0.00	0.00	0.00
SF	61 (176)	100	0.00	0.00	0.00
SF	357 (334)	100	0.00	0.00	0.00
SF	376 (176)	100	0.00	0.00	0.00
SF	386 (213)	100	0.00	0.00	0.00
SF	387 (96)	84.18	15.03*	0.80	0.00
SF	593 (329)	100	0.00	0.00	0.00
SF	913 (264)	100	0.00	0.00	0.00
SF	914 (342)	100	0.00	0.00	0.00
SF	927 (326)	100	0.00	0.00	0.00
SF	928 (334)	100	0.00	0.00	0.00

***: Indicates that the percentage larger than 5% for inundation**

Source: University of California, Santa Cruz

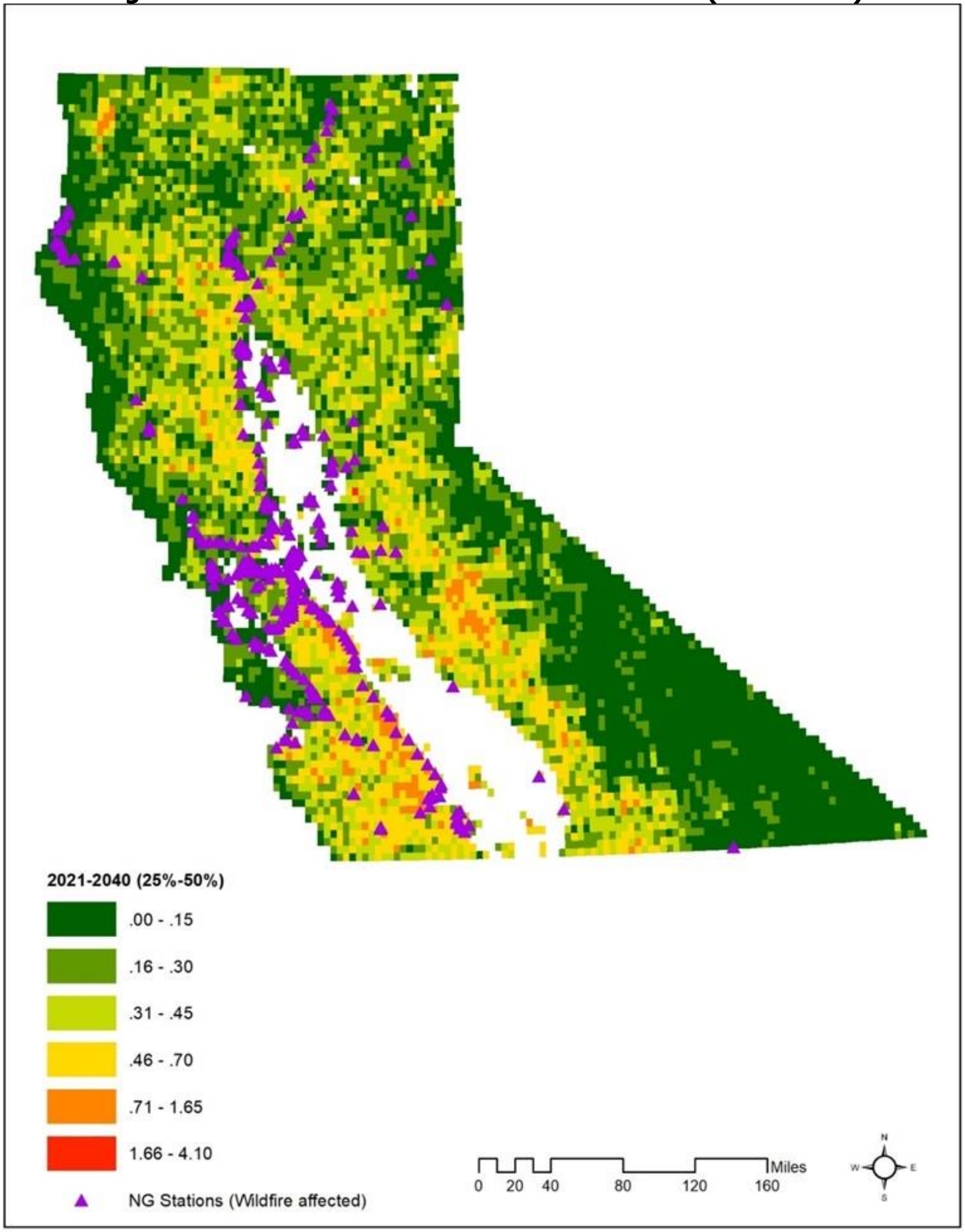
APPENDIX D:
Calculated Wildfire Risks

Figure D-1: 2021-2040 calculated wildfire risks (0%-25%)



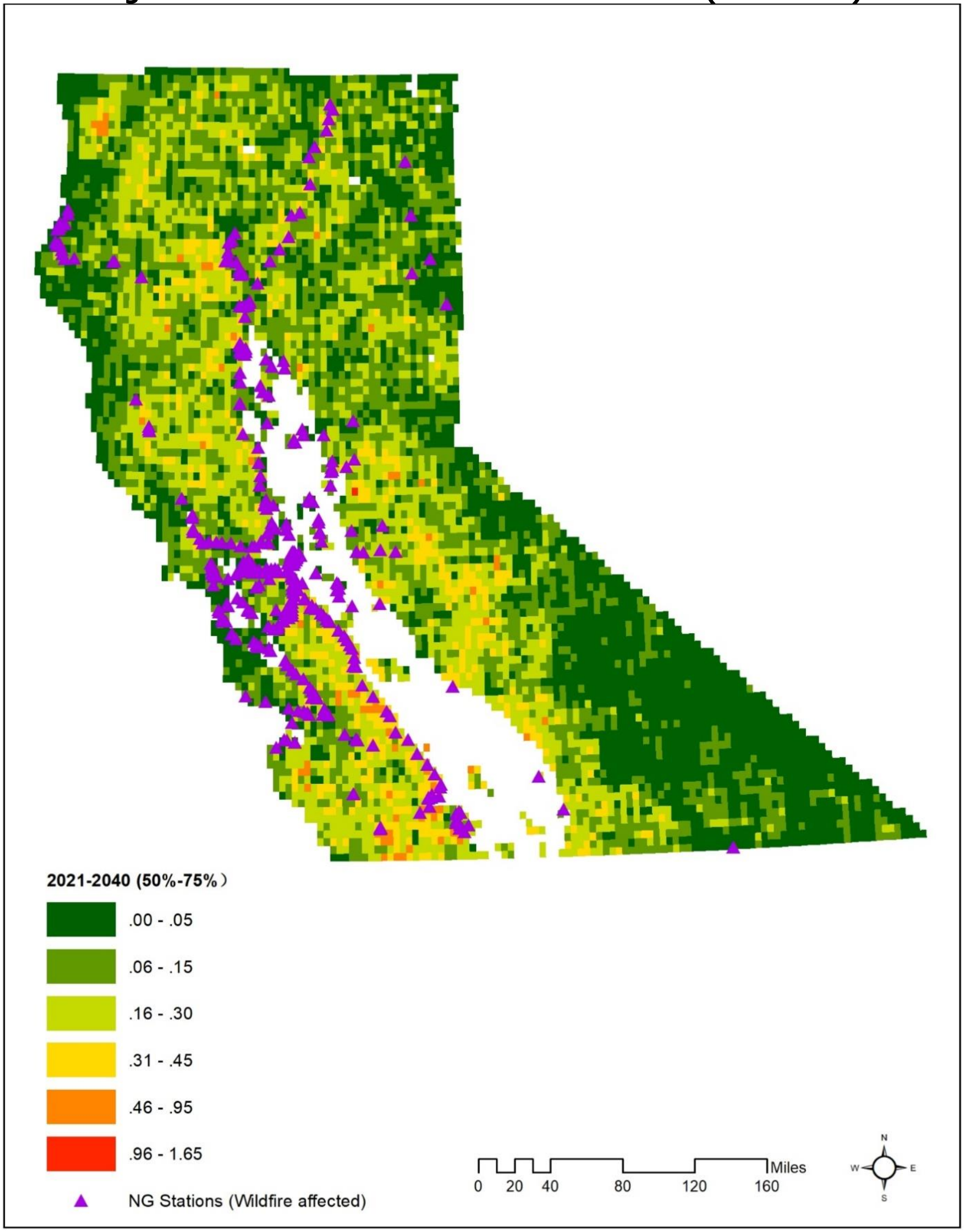
Source: University of California, Santa Cruz

Figure D-2: 2021-2040 calculated wildfire risks (25%-50%)



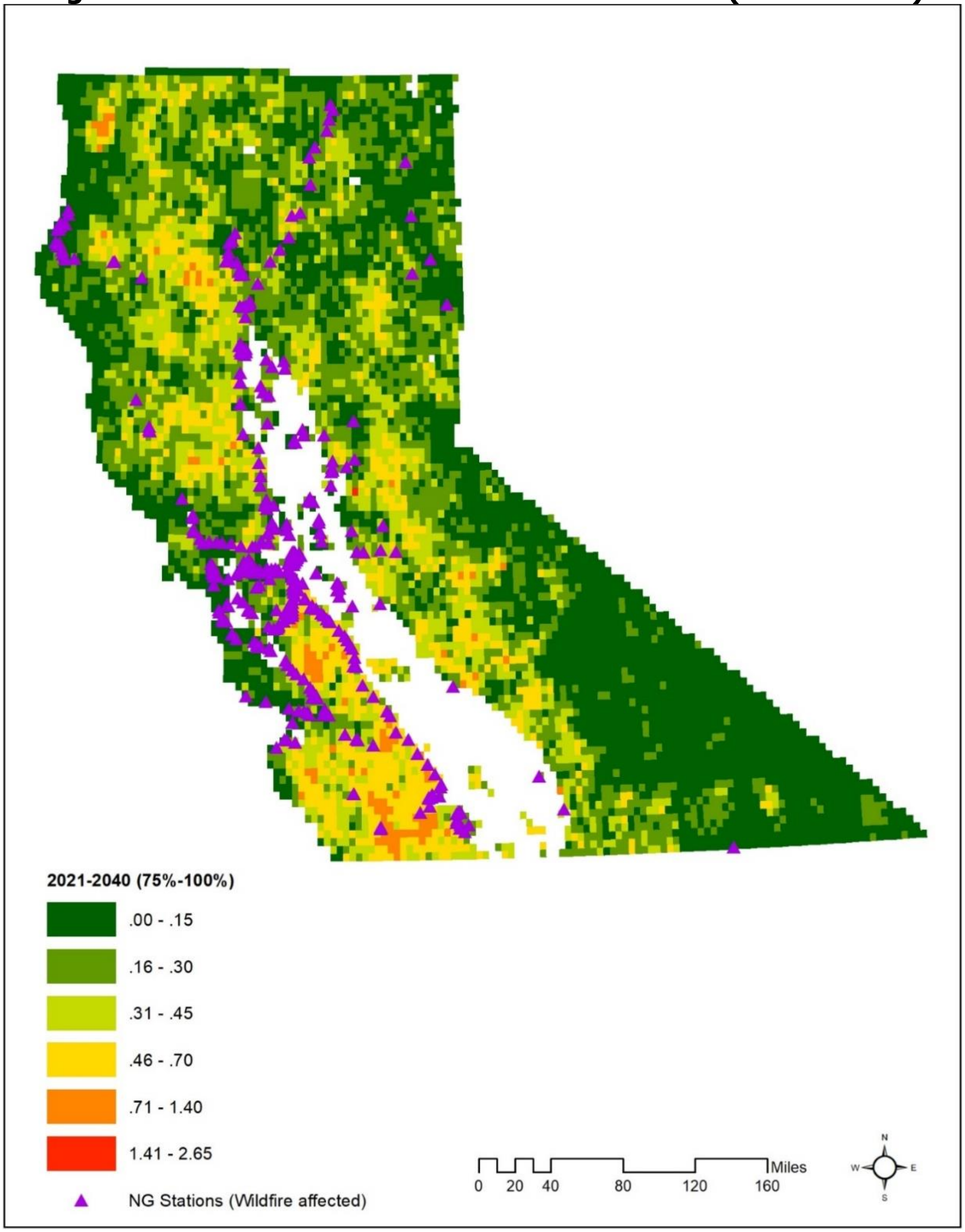
Source: University of California, Santa Cruz

Figure D-3: 2021-2040 calculated wildfire risks (50%-75%)



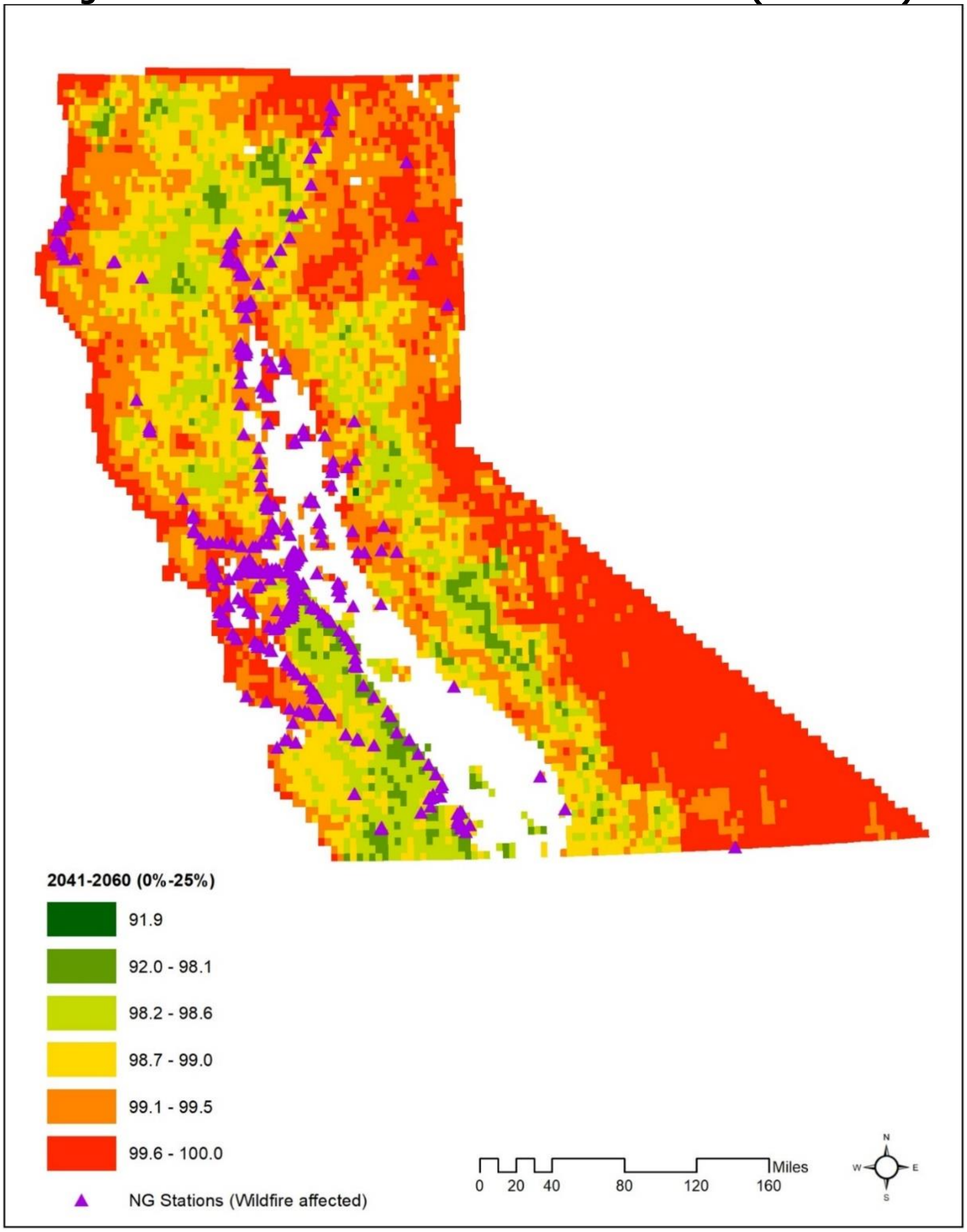
Source: University of California, Santa Cruz

Figure D-4: 2021-2040 calculated wildfire risks (75%-100%)



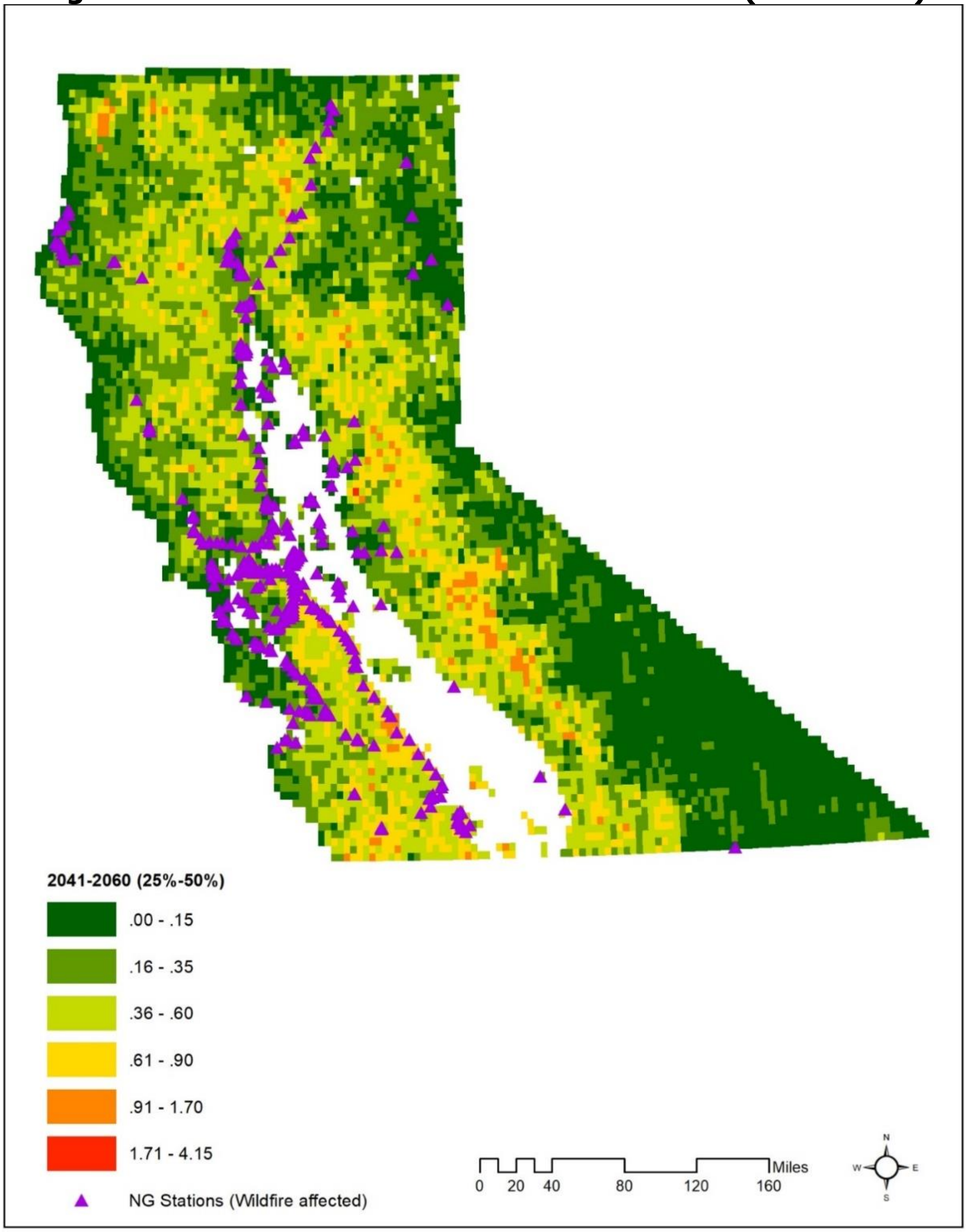
Source: University of California, Santa Cruz

Figure D-5: 2041-2060 calculated wildfire risks (0%-25%)



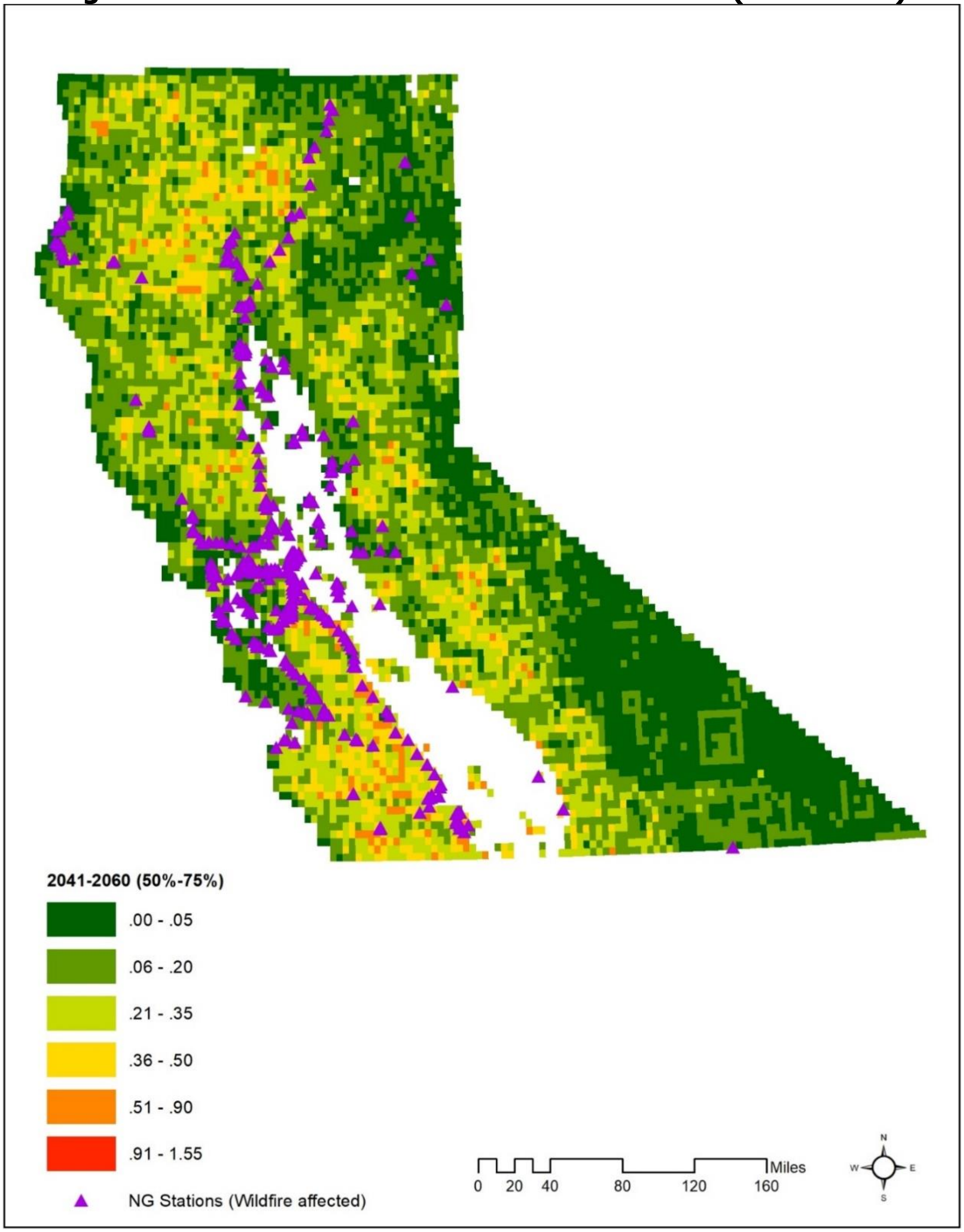
Source: University of California, Santa Cruz

Figure D-6: 2041-2060 calculated wildfire risks (25%-50%)



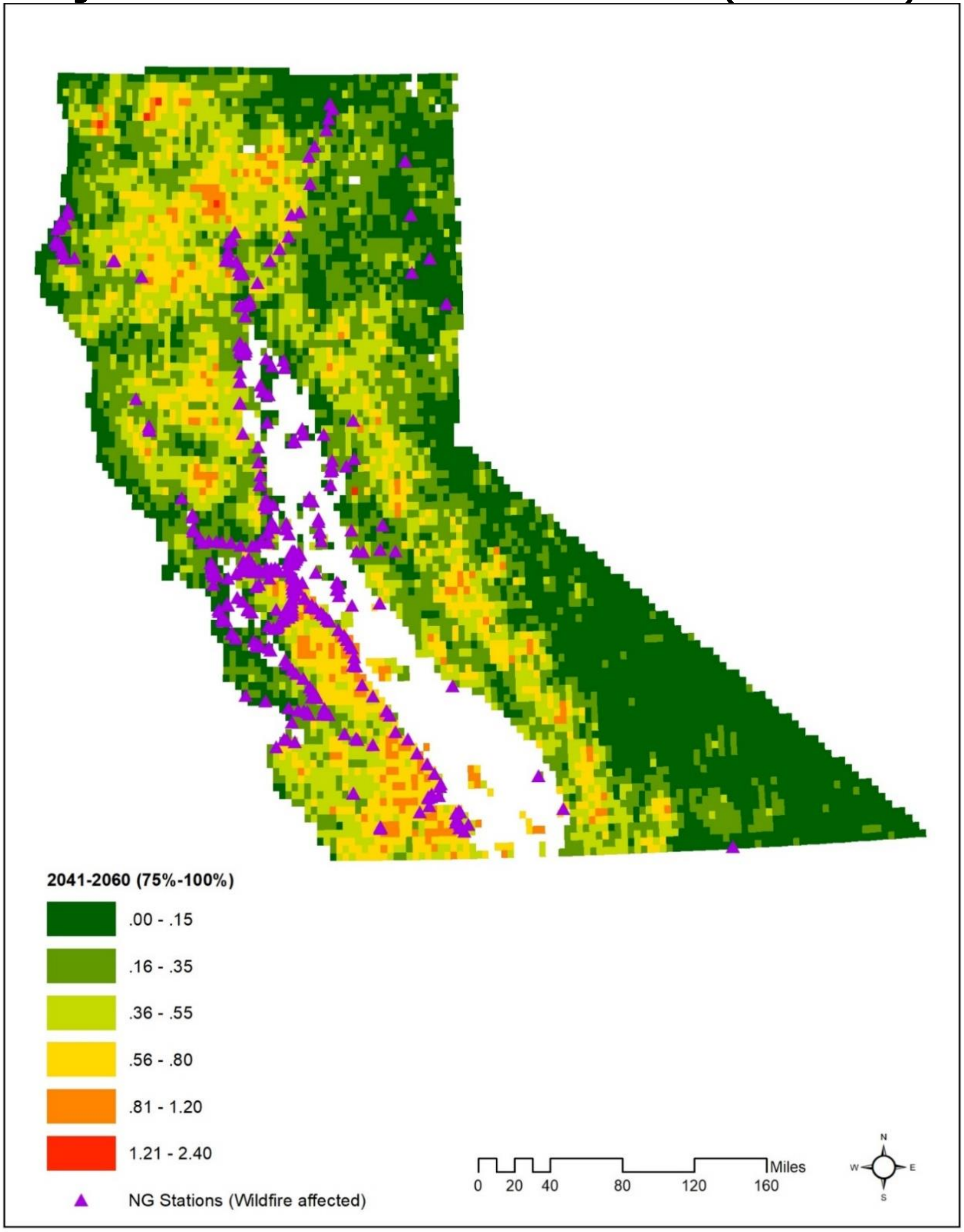
Source: University of California, Santa Cruz

Figure D-7: 2041-2060 calculated wildfire risks (50%-75%)



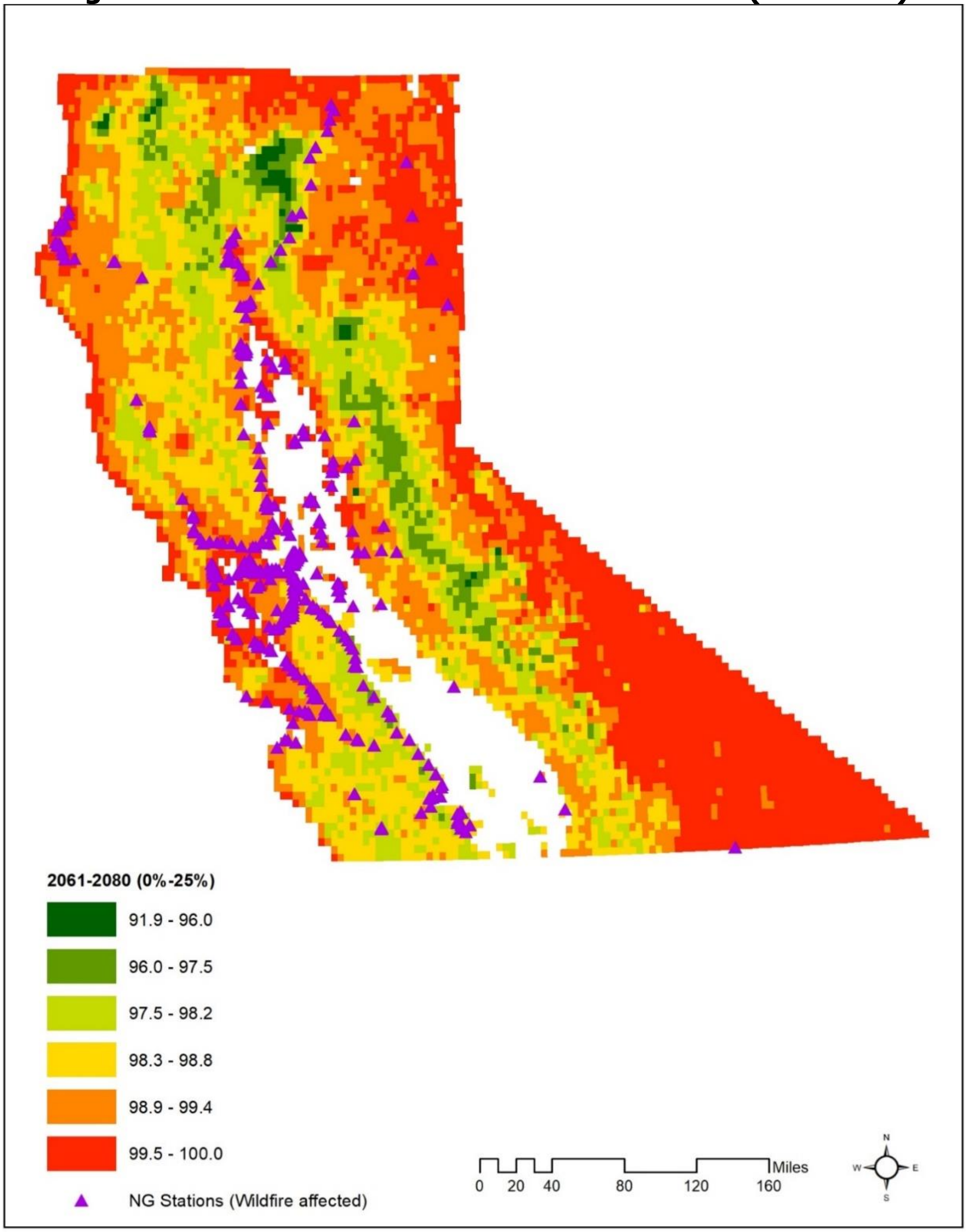
Source: University of California, Santa Cruz

Figure D-8: 2041-2060 calculated wildfire risks (75%-100%)



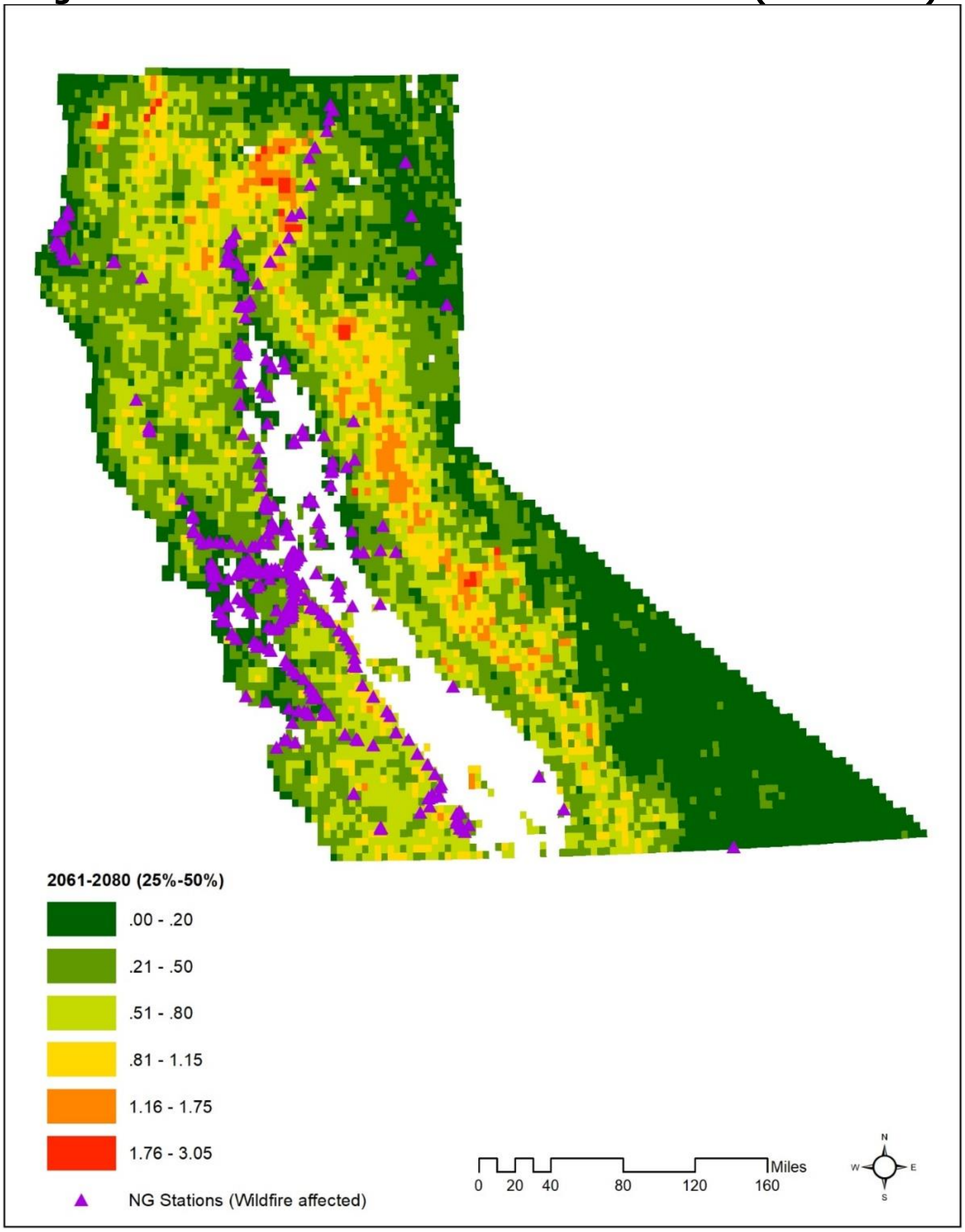
Source: University of California, Santa Cruz

Figure D-9: 2061-2080 calculated wildfire risks (0%-25%)



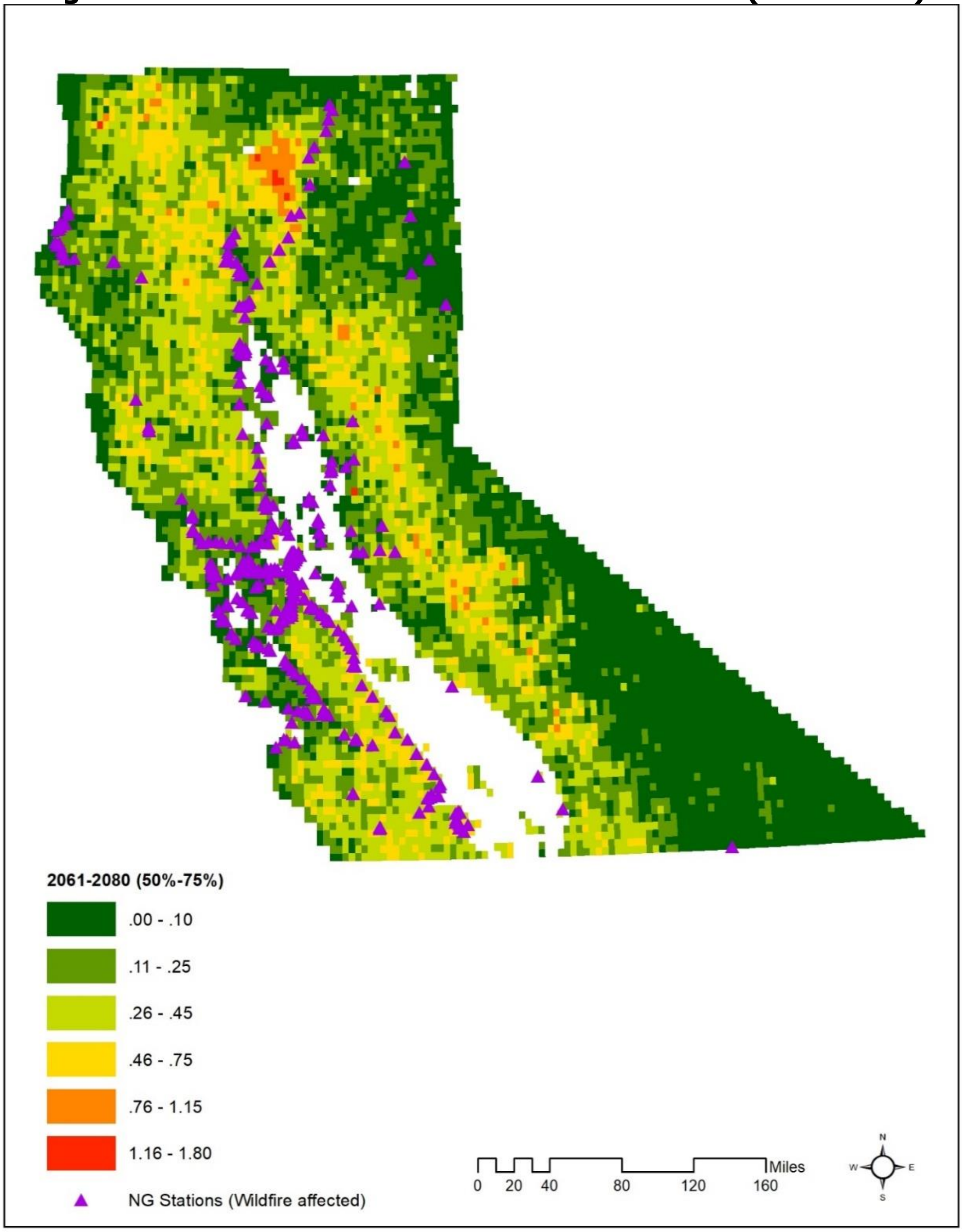
Source: University of California, Santa Cruz

Figure D-10: 2061-2080 calculated wildfire risks (25%-50%)



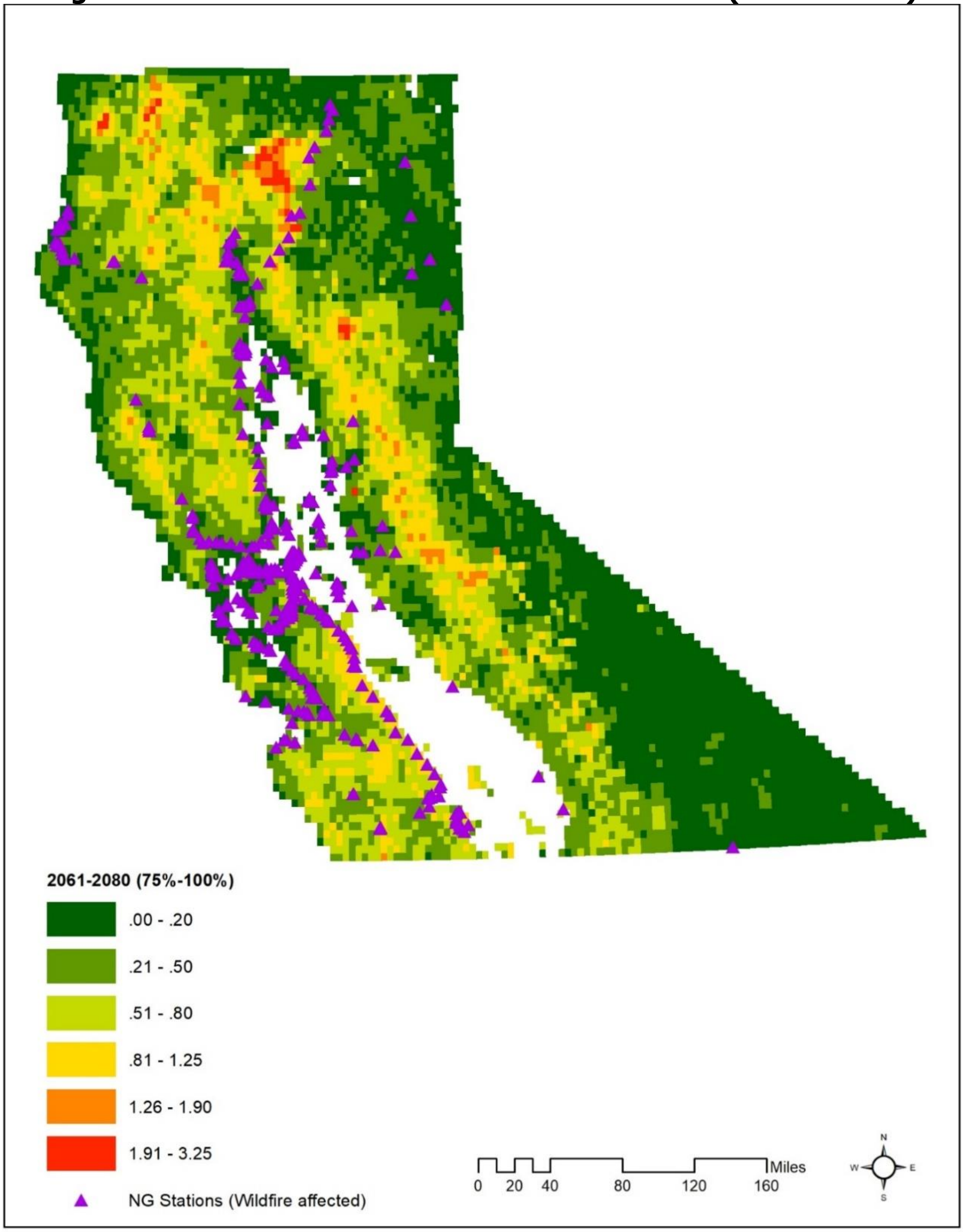
Source: University of California, Santa Cruz

Figure D-11: 2061-2080 calculated wildfire risks (50%-75%)



Source: University of California, Santa Cruz

Figure D-12: 2061-2080 calculated wildfire risks (75%-100%)



Source: University of California, Santa Cruz

APPENDIX E:
Economic Modeling Results of Sea-level Rise

Table E-1: 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

Source: University of California, Santa Cruz

Table E-2: 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

Source: University of California, Santa Cruz

Table E-3: 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

Source: University of California, Santa Cruz

Table E-4: 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

Source: University of California, Santa Cruz

Table E-5: 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

Source: University of California, Santa Cruz

Table E-6: 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

Source: University of California, Santa Cruz

Table E-7: 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

Source: University of California, Santa Cruz

Table E-8: 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

Source: University of California, Santa Cruz

Table E-9: 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

Source: University of California, Santa Cruz

Table E-10: 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

Source: University of California, Santa Cruz

Table E-11: Impacts on sectoral supply under scenario 3 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-12: Impacts on Armington aggregate under scenario 3 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-13: Impacts on supply price under scenario 3 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-14: 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

Source: University of California, Santa Cruz

Table E-15: 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

Source: University of California, Santa Cruz

Table E-16: 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

Source: University of California, Santa Cruz

Table E-17: 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

Source: University of California, Santa Cruz

Table E-18: 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

Source: University of California, Santa Cruz

Table E-19: 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

Source: University of California, Santa Cruz

Table E-20: 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

Source: University of California, Santa Cruz

Table E-21: Impacts on sectoral supply under scenario 6 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-22: Impacts on Armington aggregate under scenario 6 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-23: Impacts on supply price under scenario 6 (%)

Regions \ Sectors	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

Source: University of California, Santa Cruz

Table E-24: 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

Source: University of California, Santa Cruz

Table E-25: 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

Source: University of California, Santa Cruz

Table E-26: 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

Source: University of California, Santa Cruz

Table E-27: 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

Source: University of California, Santa Cruz

Table E-28: 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

Source: University of California, Santa Cruz

Table E-29: 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

Source: University of California, Santa Cruz

Table E-30: 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

Source: University of California, Santa Cruz

APPENDIX F: Economic Modeling Results of Wildfire

Table F-1: Impacts on sectoral supply under case A (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0016	-0.0059	0.0053	0.0069	-0.0097	-0.0082		-0.0078	-0.0052	-0.0122
Central Valley	0.0013	-0.0065	0.0060	0.0075	-0.0070	0.0025		-0.0044	-0.0034	0.0099
North Bay	0.0010	-0.0262	-0.0391	-0.0168	-0.0158	0.0055		-0.0127	0.0060	0.0361
North Coast	1.2497	-4.8809	-10.6647	-6.6170	9.4359	-66.6200		11.5700	6.0452	-28.7037
Sacramento	-0.0561	0.2408	0.2969	0.1677	-0.0537	2.7547	0.7256	-0.2287	-0.1821	-4.3749
SoCal No PGE	0.0003	-0.0054	-0.0017	0.0002	-0.0147	0.0081	-0.0079	-0.0051	-0.0014	0.0029
SoCal PGE	0.0001	-0.0015	0.0048	0.0034	-0.0101	0.0048	-0.0165	-0.0002	-0.0048	0.0075
South Bay	0.0017	-0.0178	-0.0077	-0.0036	-0.0225	0.0048		-0.0119	-0.0013	0.0109
Sierra Nevada	-0.0314	0.0723	0.1534	0.0787	0.0601	0.5860		-0.1316	-0.0474	0.1624

Source: University of California, Santa Cruz

Table F-2: Impacts on Armington aggregate under case A (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0020	-0.0018	-0.0007	-0.0005	-0.0049	-0.0034	-0.0044	-0.0011	-0.0004	-0.0028
Central Valley	-0.0021	-0.0017	-0.0006	0.0002	-0.0042	0.0011	-0.0026	0.0002	-0.0007	-0.0030
North Bay	0.0043	0.0067	-0.0013	-0.0005	0.0012	0.0317	-0.0035	-0.0018	0.0069	0.0057
North Coast	2.7874	0.8768	0.6584	0.0006	5.0788	-22.2427	2.7248	-9.6291	3.2398	1.0631
Sacramento	-0.0799	0.0273	0.0032	0.0013	-0.0923	-0.4363	-0.0896	0.2924	-0.0993	0.0656
SoCal No PGE	-0.0006	-0.0008	-0.0006	-0.0005	-0.0025	0.0023	-0.0014	0.0010	0.0000	-0.0011
SoCal PGE	-0.0022	-0.0013	-0.0006	-0.0003	-0.0060	0.0061	-0.0005	0.0018	-0.0017	-0.0012
South Bay	0.0009	-0.0006	-0.0036	-0.0015	-0.0002	0.0045	-0.0022	-0.0010	0.0014	-0.0051
Sierra Nevada	-0.0399	-0.0066	0.0108	0.0047	0.0042	0.1521	-0.0086	0.0672	-0.0379	-0.0080

Source: University of California, Santa Cruz

Table F-3: Impacts on supply price under case A (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0008	0.0008	0.0001	-0.0001	-0.0011	0.0046		0.0019	0.0083	0.0044
Central Valley	0.0008	-0.0004	0.0001	-0.0002	-0.0013	0.0023		0.0016	0.0060	0.0004
North Bay	0.0051	0.0045	0.0058	0.0062	0.0000	0.0029		0.0036	-0.0049	0.0015
North Coast	0.7981	1.7230	1.8893	2.0044	-1.3808	29.6683		-4.5809	-10.2461	7.3384
Sacramento	-0.0104	-0.0505	-0.0401	-0.0414	0.0056	0.2763	-0.1444	0.0784	0.3442	0.7558
SoCal No PGE	0.0017	0.0015	0.0011	0.0011	0.0006	0.0026	0.0006	0.0018	0.0012	0.0016
SoCal PGE	0.0011	0.0002	0.0001	0.0002	-0.0003	0.0021	0.0023	0.0010	0.0063	0.0013
South Bay	0.0030	0.0026	0.0022	0.0025	0.0007	0.0033		0.0030	-0.0012	0.0019
Sierra Nevada	0.0000	-0.0206	-0.0196	-0.0219	-0.0137	0.0437		0.0429	0.0773	-0.0273

Source: University of California, Santa Cruz

Table F-4: Impacts on private consumption under case A (%)

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	-0.0011	-0.0012	-0.0016	-0.0020	-0.0025	-0.0030	-0.0035	-0.0041	-0.0074
Central Valley	-0.0011	-0.0012	-0.0017	-0.0022	-0.0028	-0.0035	-0.0041	-0.0047	-0.0087
North Bay	-0.0015	-0.0010	0.0005	0.0022	0.0045	0.0066	0.0087	0.0107	0.0207
North Coast	0.2838	0.5917	1.5480	2.6004	4.0569	5.4387	6.7030	7.8929	13.6032
Sacramento	-0.0157	-0.0259	-0.0513	-0.0806	-0.1199	-0.1588	-0.1924	-0.2220	-0.3633
SoCal No PGE	-0.0011	-0.0010	-0.0009	-0.0008	-0.0006	-0.0005	-0.0005	-0.0005	-0.0007
SoCal PGE	-0.0014	-0.0015	-0.0019	-0.0023	-0.0028	-0.0033	-0.0037	-0.0043	-0.0080
South Bay	-0.0013	-0.0011	-0.0005	0.0002	0.0012	0.0020	0.0027	0.0032	0.0057
Sierra Nevada	-0.0085	-0.0116	-0.0212	-0.0316	-0.0452	-0.0585	-0.0706	-0.0829	-0.1410

Source: University of California, Santa Cruz

Table F-5: Impacts on GDP under case A

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19846.40	-0.0001	-23.18
California	2545.73	-0.0007	-16.98
Central Coast	37.41	0.0000	-0.01
Central Valley	114.13	-0.0003	-0.35
North Bay	150.52	-0.0024	-3.59
North Coast	6.79	-0.0486	-3.30
Sacramento	137.45	-0.0033	-4.48
SoCal No PGE	1376.19	-0.0002	-2.96
SoCal PGE	128.38	-0.0001	-0.13
South Bay	536.30	-0.0004	-2.11
Sierra Nevada	58.56	-0.0001	-0.03

Source: University of California, Santa Cruz

Table F-6: Impacts on sectoral supply under case B (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0000	0.0022	-0.0002	-0.0003	-0.0001	0.0004		-0.0010	-0.0004	0.0033
Central Valley	0.0000	0.0029	-0.0008	-0.0003	-0.0003	0.0048		-0.0009	-0.0002	0.0031
North Bay	-0.0001	0.0059	0.0054	0.0022	-0.0010	0.0067		0.0001	-0.0007	-0.0060
North Coast	-0.0032	0.0193	0.0281	0.0165	-0.0214	0.1570		-0.0318	-0.0125	0.0154
Sacramento	0.0109	-0.0460	-0.0600	-0.0322	0.0092	-0.4600	-0.1359	0.0317	0.0245	-0.1322
SoCal No PGE	-0.0001	0.0015	0.0003	0.0002	-0.0001	0.0011	0.0007	-0.0013	-0.0003	0.0009
SoCal PGE	-0.0001	0.0016	-0.0004	-0.0003	-0.0003	0.0007	-0.0005	-0.0010	-0.0003	0.0007
South Bay	-0.0002	0.0023	0.0007	0.0010	-0.0016	0.0033		-0.0041	-0.0010	0.0040
Sierra Nevada	-0.0012	0.0051	0.0054	0.0027	0.0024	0.0227		-0.0054	-0.0019	0.0076

Source: University of California, Santa Cruz

Table F-7: Impacts on Armington aggregate under case B (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0000	-0.0001	0.0000	-0.0001	0.0000	0.0000	-0.0003	0.0002	0.0002	0.0001
Central Valley	0.0000	0.0001	-0.0001	-0.0001	-0.0001	0.0009	-0.0002	0.0005	0.0002	0.0004
North Bay	-0.0009	-0.0014	-0.0002	-0.0002	-0.0012	-0.0053	0.0011	0.0014	-0.0003	-0.0008
North Coast	-0.0068	-0.0024	-0.0014	0.0000	-0.0116	0.0238	-0.0033	0.0224	-0.0057	-0.0014
Sacramento	0.0147	-0.0058	-0.0013	-0.0007	0.0182	-0.0726	0.0192	-0.0484	0.0201	0.0016
SoCal No PGE	-0.0001	0.0000	0.0000	0.0000	-0.0001	0.0007	-0.0001	0.0002	0.0000	0.0002
SoCal PGE	0.0000	0.0001	-0.0001	-0.0001	-0.0002	0.0006	-0.0002	0.0001	0.0000	0.0002
South Bay	-0.0004	-0.0003	0.0003	0.0001	-0.0008	0.0021	-0.0001	0.0004	-0.0001	0.0003
Sierra Nevada	-0.0015	-0.0003	0.0004	0.0001	0.0002	0.0061	-0.0003	0.0026	-0.0013	-0.0001

Source: University of California, Santa Cruz

Table F-8: Impacts on supply price under case B (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0001	0.0003	0.0001	0.0002	0.0002	0.0001		0.0001	0.0000	0.0001
Central Valley	0.0002	0.0003	0.0002	0.0002	0.0002	0.0002		0.0002	0.0000	0.0000
North Bay	-0.0003	-0.0002	-0.0006	-0.0004	0.0003	0.0004		0.0000	0.0017	0.0014
North Coast	-0.0017	-0.0030	-0.0044	-0.0044	0.0040	0.0078		0.0117	0.0258	-0.0027
Sacramento	0.0029	0.0117	0.0087	0.0092	-0.0007	0.1178	0.0273	-0.0139	-0.0395	0.0227
SoCal No PGE	0.0001	0.0002	0.0000	0.0000	0.0002	0.0002	-0.0001	0.0001	0.0001	0.0001
SoCal PGE	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002
South Bay	0.0001	0.0007	0.0000	-0.0001	0.0005	0.0011		0.0007	0.0005	0.0000
Sierra Nevada	0.0001	-0.0005	-0.0006	-0.0007	-0.0003	0.0017		0.0016	0.0028	-0.0007

Source: University of California, Santa Cruz

Table F-9: Impacts on private consumption under case B (%)

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	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001
Central Valley	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0001	0.0001	0.0001	0.0002
North Bay	-0.0001	-0.0001	-0.0003	-0.0006	-0.0009	-0.0012	-0.0015	-0.0018	-0.0036
North Coast	-0.0009	-0.0016	-0.0041	-0.0067	-0.0103	-0.0138	-0.0170	-0.0200	-0.0350
Sacramento	0.0019	0.0037	0.0085	0.0141	0.0214	0.0289	0.0351	0.0404	0.0641
SoCal No PGE	-0.0001	-0.0001	-0.0001	-0.0001	-0.0002	-0.0002	-0.0002	-0.0002	-0.0004
SoCal PGE	-0.0001	-0.0001	-0.0001	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0001
South Bay	-0.0001	-0.0002	-0.0003	-0.0004	-0.0005	-0.0006	-0.0007	-0.0008	-0.0014
Sierra Nevada	-0.0004	-0.0005	-0.0008	-0.0012	-0.0017	-0.0021	-0.0026	-0.0030	-0.0051

Source: University of California, Santa Cruz

Table F-10: Impacts on GDP under case B

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19846.42	0.0000	1.01
California	2545.75	0.0000	0.66
Central Coast	37.41	0.0000	0.00
Central Valley	114.13	0.0000	0.00
North Bay	150.53	0.0004	0.56
North Coast	6.79	-0.0001	-0.01
Sacramento	137.46	-0.0002	-0.28
SoCal No PGE	1376.20	0.0000	0.24
SoCal PGE	128.38	0.0000	0.00
South Bay	536.30	0.0000	0.15
Sierra Nevada	58.56	0.0000	0.00

Source: University of California, Santa Cruz

Table F-11: Impacts on sectoral supply under case C1 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0005	0.0472	-0.0046	-0.0073	-0.0023	0.0096		-0.0222	-0.0092	0.0721
Central Valley	-0.0010	0.0631	-0.0182	-0.0075	-0.0064	0.1045		-0.0196	-0.0054	0.0679
North Bay	-0.0018	0.1280	0.1190	0.0480	-0.0218	0.1472		0.0035	-0.0148	-0.1306
North Coast	-0.0721	0.4283	0.6362	0.3733	-0.4835	3.5522		-0.7131	-0.2827	0.3579
Sacramento	0.2362	-0.9983	-1.2996	-0.7017	0.2006	-10.0000	-2.9183	0.6967	0.5364	-2.8978
SoCal No PGE	-0.0019	0.0332	0.0058	0.0046	-0.0032	0.0236	0.0143	-0.0288	-0.0058	0.0191
SoCal PGE	-0.0014	0.0339	-0.0077	-0.0063	-0.0070	0.0151	-0.0112	-0.0218	-0.0067	0.0160
South Bay	-0.0051	0.0491	0.0147	0.0223	-0.0349	0.0722		-0.0884	-0.0209	0.0885
Sierra Nevada	-0.0279	0.1148	0.1232	0.0612	0.0548	0.5181		-0.1222	-0.0428	0.1715

Source: University of California, Santa Cruz

Table F-12: Impacts on Armington aggregate under case C1 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0002	-0.0013	-0.0007	-0.0013	-0.0009	0.0005	-0.0073	0.0043	0.0050	0.0027
Central Valley	0.0004	0.0015	-0.0017	-0.0021	-0.0032	0.0193	-0.0046	0.0101	0.0044	0.0095
North Bay	-0.0198	-0.0312	-0.0034	-0.0044	-0.0271	-0.1161	0.0238	0.0297	-0.0076	-0.0179
North Coast	-0.1537	-0.0550	-0.0325	-0.0009	-0.2615	0.5448	-0.0754	0.5068	-0.1301	-0.0325
Sacramento	0.3200	-0.1253	-0.0280	-0.0150	0.3954	-1.5791	0.4215	-1.0519	0.4387	0.0351
SoCal No PGE	-0.0026	-0.0006	0.0006	0.0004	-0.0033	0.0146	-0.0018	0.0037	-0.0005	0.0033
SoCal PGE	-0.0005	0.0020	-0.0013	-0.0018	-0.0035	0.0130	-0.0051	0.0027	0.0001	0.0047
South Bay	-0.0080	-0.0065	0.0057	0.0021	-0.0164	0.0455	-0.0033	0.0095	-0.0021	0.0068
Sierra Nevada	-0.0334	-0.0067	0.0083	0.0033	0.0054	0.1400	-0.0060	0.0602	-0.0306	-0.0028

Source: University of California, Santa Cruz

Table F-13: Impacts on supply price under case C1 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0032	0.0069	0.0027	0.0036	0.0035	0.0027		0.0027	0.0005	0.0023
Central Valley	0.0044	0.0071	0.0035	0.0043	0.0044	0.0036		0.0035	0.0008	0.0006
North Bay	-0.0062	-0.0035	-0.0127	-0.0096	0.0076	0.0081		-0.0002	0.0370	0.0307
North Coast	-0.0383	-0.0676	-0.1003	-0.0992	0.0891	0.1751		0.2644	0.5821	-0.0638
Sacramento	0.0624	0.2550	0.1905	0.2012	-0.0157	2.7130	0.5966	-0.3038	-0.8614	0.5063
SoCal No PGE	0.0021	0.0033	0.0006	0.0008	0.0033	0.0051	-0.0020	0.0028	0.0018	0.0022
SoCal PGE	0.0029	0.0039	0.0023	0.0028	0.0032	0.0032	0.0031	0.0028	0.0016	0.0034
South Bay	0.0029	0.0152	0.0000	-0.0012	0.0111	0.0238		0.0147	0.0106	-0.0002
Sierra Nevada	0.0021	-0.0123	-0.0142	-0.0153	-0.0079	0.0386		0.0365	0.0646	-0.0172

Source: University of California, Santa Cruz

Table F-14: Impacts on private consumption under case C1 (%)

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	-0.0028	-0.0024	-0.0021	-0.0015	-0.0008	-0.0001	0.0004	0.0008	0.0030
Central Valley	-0.0029	-0.0024	-0.0017	-0.0008	0.0004	0.0015	0.0023	0.0030	0.0048
North Bay	-0.0013	-0.0024	-0.0076	-0.0128	-0.0197	-0.0262	-0.0330	-0.0405	-0.0787
North Coast	-0.0207	-0.0372	-0.0921	-0.1517	-0.2338	-0.3117	-0.3837	-0.4520	-0.7908
Sacramento	0.0419	0.0808	0.1863	0.3073	0.4677	0.6300	0.7662	0.8808	1.3989
SoCal No PGE	-0.0022	-0.0022	-0.0026	-0.0030	-0.0035	-0.0040	-0.0047	-0.0053	-0.0091
SoCal PGE	-0.0023	-0.0021	-0.0017	-0.0012	-0.0005	0.0001	0.0006	0.0010	0.0018
South Bay	-0.0032	-0.0036	-0.0056	-0.0077	-0.0104	-0.0135	-0.0161	-0.0185	-0.0297
Sierra Nevada	-0.0092	-0.0115	-0.0192	-0.0275	-0.0384	-0.0490	-0.0586	-0.0684	-0.1163

Source: University of California, Santa Cruz

Table F-15: Impacts on GDP under case C1

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19846.44	0.0001	19.89
California	2545.76	0.0005	12.31
Central Coast	37.41	0.0000	0.01
Central Valley	114.13	-0.0001	-0.11
North Bay	150.54	0.0075	11.27
North Coast	6.79	-0.0037	-0.25
Sacramento	137.45	-0.0051	-7.07
SoCal No PGE	1376.20	0.0004	5.24
SoCal PGE	128.38	-0.0001	-0.07
South Bay	536.30	0.0006	3.30
Sierra Nevada	58.56	0.0000	-0.01

Source: University of California, Santa Cruz

Table F-16: Impacts on sectoral supply under case C2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0014	0.1416	-0.0138	-0.0219	-0.0070	0.0294		-0.0660	-0.0280	0.2195
Central Valley	-0.0029	0.1895	-0.0543	-0.0224	-0.0192	0.3189		-0.0580	-0.0165	0.2078
North Bay	-0.0054	0.3857	0.3638	0.1462	-0.0672	0.4497		0.0131	-0.0458	-0.3977
North Coast	-0.2364	1.3517	2.0955	1.2221	-1.5814	11.6333		-2.2932	-0.9222	1.2345
Sacramento	0.7064	-2.9868	-3.8681	-2.1086	0.6045	-30.0000	-8.5317	2.1464	1.6358	-8.8403
SoCal No PGE	-0.0057	0.0997	0.0179	0.0140	-0.0102	0.0726	0.0425	-0.0853	-0.0177	0.0579
SoCal PGE	-0.0043	0.1020	-0.0229	-0.0188	-0.0210	0.0465	-0.0362	-0.0642	-0.0206	0.0487
South Bay	-0.0155	0.1463	0.0450	0.0676	-0.1065	0.2223		-0.2662	-0.0635	0.2707
Sierra Nevada	-0.0938	0.3688	0.4159	0.2068	0.1861	1.7385		-0.4032	-0.1426	0.5645

Source: University of California, Santa Cruz

Table F-17: Impacts on Armington aggregate under case C2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0007	-0.0040	-0.0021	-0.0039	-0.0028	0.0016	-0.0221	0.0132	0.0151	0.0079
Central Valley	0.0010	0.0044	-0.0050	-0.0063	-0.0096	0.0592	-0.0140	0.0308	0.0131	0.0285
North Bay	-0.0605	-0.0949	-0.0103	-0.0134	-0.0830	-0.3535	0.0723	0.0906	-0.0236	-0.0547
North Coast	-0.5020	-0.1777	-0.1043	-0.0022	-0.8537	1.8188	-0.2494	1.6620	-0.4340	-0.1104
Sacramento	0.9614	-0.3734	-0.0784	-0.0434	1.1889	-4.7477	1.2891	-3.1486	1.3268	0.1124
SoCal No PGE	-0.0079	-0.0019	0.0017	0.0011	-0.0101	0.0443	-0.0053	0.0116	-0.0016	0.0098
SoCal PGE	-0.0017	0.0061	-0.0039	-0.0054	-0.0107	0.0396	-0.0154	0.0086	0.0000	0.0142
South Bay	-0.0244	-0.0198	0.0174	0.0064	-0.0500	0.1393	-0.0099	0.0288	-0.0065	0.0199
Sierra Nevada	-0.1119	-0.0215	0.0283	0.0116	0.0193	0.4677	-0.0200	0.2020	-0.1033	-0.0101

Source: University of California, Santa Cruz

Table F-18: Impacts on supply price under case C2 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0095	0.0207	0.0077	0.0106	0.0104	0.0081		0.0078	0.0016	0.0067
Central Valley	0.0130	0.0212	0.0104	0.0126	0.0130	0.0107		0.0105	0.0026	0.0014
North Bay	-0.0192	-0.0111	-0.0392	-0.0297	0.0228	0.0245		-0.0010	0.1125	0.0932
North Coast	-0.1262	-0.2253	-0.3289	-0.3263	0.2893	0.5679		0.8619	1.9016	-0.2253
Sacramento	0.1890	0.7719	0.5766	0.6087	-0.0475	9.3615	1.8070	-0.9204	-2.5960	1.6058
SoCal No PGE	0.0060	0.0098	0.0016	0.0022	0.0098	0.0153	-0.0064	0.0081	0.0055	0.0066
SoCal PGE	0.0084	0.0115	0.0066	0.0081	0.0093	0.0097	0.0092	0.0081	0.0054	0.0100
South Bay	0.0084	0.0456	-0.0004	-0.0041	0.0333	0.0720		0.0443	0.0325	-0.0012
Sierra Nevada	0.0057	-0.0433	-0.0491	-0.0529	-0.0280	0.1284		0.1219	0.2165	-0.0601

Source: University of California, Santa Cruz

Table F-19: Impacts on private consumption under case C2 (%)

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	-0.0081	-0.0072	-0.0061	-0.0045	-0.0023	-0.0004	0.0010	0.0022	0.0086
Central Valley	-0.0086	-0.0072	-0.0052	-0.0025	0.0012	0.0044	0.0066	0.0087	0.0142
North Bay	-0.0037	-0.0072	-0.0229	-0.0388	-0.0598	-0.0799	-0.1008	-0.1235	-0.2399
North Coast	-0.0672	-0.1213	-0.3008	-0.4954	-0.7638	-1.0185	-1.2539	-1.4769	-2.5806
Sacramento	0.1269	0.2446	0.5639	0.9299	1.4152	1.9062	2.3180	2.6649	4.2328
SoCal No PGE	-0.0065	-0.0066	-0.0078	-0.0091	-0.0106	-0.0123	-0.0144	-0.0165	-0.0282
SoCal PGE	-0.0069	-0.0063	-0.0051	-0.0037	-0.0018	0.0000	0.0015	0.0025	0.0046
South Bay	-0.0096	-0.0107	-0.0169	-0.0234	-0.0317	-0.0411	-0.0491	-0.0562	-0.0905
Sierra Nevada	-0.0296	-0.0376	-0.0635	-0.0917	-0.1283	-0.1643	-0.1967	-0.2299	-0.3905

Source: University of California, Santa Cruz

Table F-20: Impacts on GDP under case C2

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19846.47	0.0002	44.91
California	2545.77	0.0009	22.88
Central Coast	37.41	0.0001	0.03
Central Valley	114.13	-0.0004	-0.41
North Bay	150.56	0.0183	27.53
North Coast	6.79	-0.0149	-1.01
Sacramento	137.43	-0.0205	-28.24
SoCal No PGE	1376.21	0.0011	15.65
SoCal PGE	128.38	-0.0002	-0.25
South Bay	536.31	0.0018	9.66
Sierra Nevada	58.56	-0.0002	-0.09

Source: University of California, Santa Cruz

Table F-21: Impacts on sectoral supply under case C3 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0024	0.2360	-0.0223	-0.0367	-0.0118	0.0505		-0.1084	-0.0474	0.3731
Central Valley	-0.0049	0.3162	-0.0894	-0.0375	-0.0322	0.5425		-0.0946	-0.0281	0.3549
North Bay	-0.0090	0.6462	0.6207	0.2482	-0.1154	0.7662		0.0278	-0.0790	-0.6751
North Coast	-0.4343	2.3851	3.8719	2.2414	-2.8936	21.3336		-4.1235	-1.6820	2.3610
Sacramento	1.1731	-4.9632	-6.3943	-3.5194	1.0155	-50.0000	-13.8582	3.6845	2.7718	-14.9844
SoCal No PGE	-0.0096	0.1662	0.0309	0.0240	-0.0181	0.1252	0.0701	-0.1400	-0.0300	0.0980
SoCal PGE	-0.0075	0.1707	-0.0377	-0.0311	-0.0351	0.0798	-0.0655	-0.1044	-0.0351	0.0826
South Bay	-0.0262	0.2418	0.0767	0.1139	-0.1809	0.3831		-0.4451	-0.1072	0.4621
Sierra Nevada	-0.1771	0.6652	0.7895	0.3926	0.3552	3.2795		-0.7475	-0.2667	1.0436

Source: University of California, Santa Cruz

Table F-22: Impacts on Armington aggregate under case C3 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	-0.0013	-0.0069	-0.0035	-0.0064	-0.0048	0.0030	-0.0372	0.0224	0.0250	0.0129
Central Valley	0.0016	0.0073	-0.0082	-0.0105	-0.0161	0.1011	-0.0237	0.0523	0.0217	0.0473
North Bay	-0.1029	-0.1610	-0.0174	-0.0227	-0.1414	-0.6001	0.1227	0.1540	-0.0413	-0.0933
North Coast	-0.9183	-0.3214	-0.1869	-0.0026	-1.5593	3.3896	-0.4598	3.0526	-0.8104	-0.2092
Sacramento	1.6031	-0.6184	-0.1217	-0.0699	1.9854	-7.9350	2.1913	-5.2347	2.2276	0.1998
SoCal No PGE	-0.0135	-0.0033	0.0030	0.0020	-0.0174	0.0750	-0.0089	0.0200	-0.0031	0.0162
SoCal PGE	-0.0031	0.0102	-0.0065	-0.0089	-0.0182	0.0673	-0.0258	0.0155	-0.0005	0.0238
South Bay	-0.0413	-0.0336	0.0297	0.0108	-0.0849	0.2384	-0.0165	0.0487	-0.0114	0.0319
Sierra Nevada	-0.2108	-0.0388	0.0543	0.0227	0.0387	0.8783	-0.0376	0.3809	-0.1956	-0.0203

Source: University of California, Santa Cruz

Table F-23: Impacts on supply price under case C3 (%)

Regions \ Sectors	Service	Trans-portation	Manuf-acturing	Energy-intensive	Agri-culture	Natural gas	Coal	Crude oil	Electricity	Refined oil
Central Coast	0.0153	0.0343	0.0123	0.0171	0.0167	0.0133		0.0125	0.0026	0.0109
Central Valley	0.0212	0.0349	0.0167	0.0204	0.0210	0.0175		0.0171	0.0044	0.0014
North Bay	-0.0334	-0.0201	-0.0676	-0.0513	0.0379	0.0408		-0.0025	0.1908	0.1579
North Coast	-0.2332	-0.4199	-0.6037	-0.6007	0.5262	1.0315		1.5730	3.4785	-0.4383
Sacramento	0.3171	1.2976	0.9691	1.0230	-0.0808	18.6381	3.0403	-1.5508	-4.3465	2.8405
SoCal No PGE	0.0094	0.0160	0.0019	0.0031	0.0159	0.0254	-0.0117	0.0131	0.0095	0.0108
SoCal PGE	0.0136	0.0187	0.0103	0.0128	0.0150	0.0159	0.0152	0.0131	0.0097	0.0166
South Bay	0.0135	0.0763	-0.0016	-0.0077	0.0556	0.1207		0.0742	0.0555	-0.0031
Sierra Nevada	0.0085	-0.0859	-0.0949	-0.1028	-0.0555	0.2400		0.2287	0.4082	-0.1176

Source: University of California, Santa Cruz

Table F-24: Impacts on private consumption under case C3 (%)

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	-0.0132	-0.0116	-0.0099	-0.0074	-0.0039	-0.0009	0.0013	0.0033	0.0135
Central Valley	-0.0140	-0.0117	-0.0085	-0.0042	0.0018	0.0069	0.0106	0.0139	0.0230
North Bay	-0.0057	-0.0116	-0.0385	-0.0656	-0.1016	-0.1358	-0.1714	-0.2100	-0.4081
North Coast	-0.1223	-0.2217	-0.5500	-0.9061	-1.3977	-1.8638	-2.2947	-2.7029	-4.7160
Sacramento	0.2145	0.4121	0.9488	1.5640	2.3795	3.2048	3.8970	4.4802	7.1167
SoCal No PGE	-0.0105	-0.0107	-0.0130	-0.0153	-0.0181	-0.0213	-0.0249	-0.0286	-0.0487
SoCal PGE	-0.0112	-0.0103	-0.0084	-0.0063	-0.0034	-0.0007	0.0016	0.0031	0.0062
South Bay	-0.0156	-0.0176	-0.0282	-0.0393	-0.0536	-0.0697	-0.0833	-0.0953	-0.1536
Sierra Nevada	-0.0535	-0.0690	-0.1180	-0.1717	-0.2413	-0.3095	-0.3712	-0.4342	-0.7369

Source: University of California, Santa Cruz

Table F-25: Impacts on GDP under case C3

Regions	GDP (billion $)	GDP change (%)	GDP difference (Million $)
National	19846.47	0.0002	45.84
California	2545.76	0.0004	10.24
Central Coast	37.41	0.0001	0.04
Central Valley	114.13	-0.0007	-0.83
North Bay	150.56	0.0222	33.43
North Coast	6.79	-0.0327	-2.22
Sacramento	137.40	-0.0445	-61.20
SoCal No PGE	1376.22	0.0019	26.04
SoCal PGE	128.38	-0.0004	-0.46
South Bay	536.32	0.0029	15.67
Sierra Nevada	58.56	-0.0004	-0.25

Source: University of California, Santa Cruz

APPENDIX G:
Economic Model Formulation

G.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. The marginal cost of the inputs of an activity is equal to the marginal price of output for each market participant at equilibrium. 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

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

where

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

- Armington aggregation

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

where

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

- Investment

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

- Public consumption

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

- Private consumption

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

G.2 Market Clearance Conditions

At equilibrium, all markets are cleared, meaning excess supply is non-negative for all goods and factors, thereby giving a positive price for each sector. 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 cannot 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

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

- Market of Armington aggregate

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

- Market for intra-national trade

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

- Market of investment

$$\overline{vinv}_r INV_r = \sum \overline{vinvh}_{h,r}$$

- Market of public consumption

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

- Market of primary factors

$$\sum_h evo_{h,fa,r} = \sum_s \overline{vfm}_{fa,s,r}Y_{s,r}\frac{cf_{s,r}}{pf_{fa,r}}$$

- Market of foreign exchange

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

where

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

- Market of private consumption

$$\overline{vpm}_{h,r}C_{h,r}pc_{h,r} = rh_{h,r}$$

- Market of business taxes

$$\sum_s \overline{vfm}_{btax,s,r} = \sum_s \overline{vfm}_{btax,s,r} Y_{s,r}$$

G.3 Income Balance 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 cannot exceed its income level.

- Private income

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

- Public income

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

- Income of tax revenue agent

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