

POTENTIAL CLIMATE CHANGE IMPACTS AND ADAPTATION ACTIONS FOR GAS ASSETS IN THE SAN DIEGO GAS AND ELECTRIC COMPANY SERVICE AREA

A Report for:

California's Fourth Climate Change Assessment

Prepared By:

**Judsen Bruzgul¹, Robert Kay¹, Beth Rodehorst¹, Andy
Petrow¹, Tommy Hendrickson¹, Maya Bruguera¹, Kevin
Petak¹, Dan Moreno¹, Julio Manik¹, David Revell²**

¹ICF

²Revell Coastal

DISCLAIMER

This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.



Edmund G. Brown, Jr., *Governor*

August 2018
CCCA4-CEC-2018-009

ACKNOWLEDGEMENTS

The research team would like to thank the California Energy Commission for funding this study under Agreement Number PIR-15-004. The research team would also like to thank Karineh Gregorian and her colleagues at Southern California Gas Company (SoCalGas), and Brian D'Agostino and Katie Giannecchini at San Diego Gas & Electric (SDG&E), for their substantial contributions throughout the study.

Finally, we'd like to thank the following for participating on the study's Technical Advisory Committee: Kathleen Ave (Sacramento Municipal Utility District); Laura Engeman (San Diego Regional Climate Collaborative); Mikhail Chester (Arizona State University); Jim Blatchford (California Independent System Operator); Nicola Hedge (San Diego Foundation); Kristin Ralff-Douglas (California Public Utilities Commission (CPUC)); Joe Casola (University of Washington); Adam Smith (Southern California Edison); Jessie Knapstein (Pacific Gas & Electric).

PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report contributes to energy sector resilience by assessing natural gas sector vulnerabilities and resilience options specific to San Diego Gas & Electric Company's service territory.

ABSTRACT

Climate change poses a threat to California’s infrastructure, including its energy infrastructure. To better understand this threat, this study analyzed the exposure of gas assets in the San Diego Gas and Electric (SDG&E) Company Service Area to climate change-driven hazards, including coastal hazards, inland flooding, wildfire, extreme heat, and landslides. The study found that the gas system may experience some impacts to the climate change hazards assessed, mostly in the form of increased repair/maintenance needs or localized disruptions. Widespread disruptions, based on climate impacts explored in this paper, are not expected due to limited projected exposure to climate hazards and existing physical protections that limit potential impacts. However, there are assets which are more likely to experience impacts from projected changes in climate, such as pipelines at water crossings and aboveground regulators. The study also found that while the system is likely to experience impacts to gas supply and market prices, such as a potential natural gas market price spike of \$10 per MMBtu under a climate extreme “shock” scenario in 2050, the SoCalGas system – the predominate supplier of gas into the SDG&E service area – has sufficient pipeline capacity to avoid shortfalls in regional supply. Based on average monthly projected demands modelled through the study, overall pipeline capacity appears to be sufficient to avoid shortfalls in regional supply. However, this conclusion can only be confirmed with modelling potential changes to daily peak demands that were beyond the scope of this study. For example, a one-day spike in demand may lead to curtailment. Looking at monthly averages can understate the impacts of short-term spikes in demand.

The research team identified potential adaptation measures to help build resilience to potential impacts. The application of flexible adaptation pathways emerged through the study as the best approach to guide implementation of these measures in the face of future uncertainty. Rather than selecting a set of adaptation measures based only on what is known today, flexible adaptation pathways help establish information that should be tracked, termed signposts, to navigate uncertainty, set thresholds that trigger adaptation actions, and determine if an adaptation plan is meeting its objectives. Using these pathways, the research team recommended four initial adaptation actions: 1) integrate climate change hazard maps into planning and operations; 2) identify signposts and thresholds that identify when the need for an adaptation decision is approaching; 3) consult regional stakeholders to identify opportunities to improve community-wide resilience; and 4) develop a cost-benefit analysis methodology to evaluate adaptation measures.

Keywords: Climate change exposure; direct and indirect impacts; coastal hazards; inland flooding; wildfire; landslides; flexible adaptation pathways; natural gas infrastructure and services

Please use the following citation for this paper:

Bruzgul, Judsen, Robert Kay, Andy Petrow, Beth Rodehorst, David Revell, Maya Bruguera, Tommy Hendrickson, Kevin Petak, Dan Moreno, Julio Manik. (ICF and Revell Coastal). 2018. *Potential Climate Change Impacts and Adaptation Actions for Gas Assets in the San Diego Gas and Electric Company Service Area*. California’s Fourth Climate Change Assessment, California Energy Commission. Publication number: CCA4-CEC-2018-009.

HIGHLIGHTS

- The research team analyzed the exposure of gas assets within the SDG&E Company Service Area to climate change-driven coastal hazards (wave flooding, tidal inundation, and coastal erosion) and inland hazards (inland flooding, wildfire, extreme heat, and landslides). This analysis found that many gas assets will potentially experience increased exposure to these hazards. By mid-century:
 - over 6,500 point assets (which are located at a particular point, such as substations; rather than spread over a distance, such as transmission lines) and 120 mi. (193 km) of line length are projected to be exposed to 100-year coastal wave flooding, over 5,600 point assets and 75 mi. (120 km) of line assets could be exposed to annual tidal flooding, and nearly 4,000 point assets and 60 mi. (96 km) could be exposed to 100-year event low-lying erosion; these exposed assets represent <1% of the total assets in the study area,
 - the great majority of assets (88%) will experience an increase of extreme heat days of as many as 14 days per year,
 - between 171,100 and 230,400 point assets and between 2,800 and 3,900 mi. (4,500 - 6,200 km) of line length are projected to be within areas that may experience an increase in wildfire area burned (representing 17 - 23% of point assets and 18 - 25% of line asset length),
 - over 13,000 point assets and nearly 270 mi. (435 km) of line asset length lie within 100-year floodplains (representing <2% of point assets and line asset length), and
 - over 43,000 point assets and over 340 mi. (547 km) of line asset length lie within landslide and slide-prone formations (representing <5% of point assets and line asset length).
- Overall, natural gas assets and services are likely to experience limited impacts from the climate hazards investigated in this study. Impacts may occur in the form of increased repair/maintenance needs or localized disruptions. Widespread disruptions are not expected due to limited projected exposure to climate hazards and existing physical protections that limit potential impacts.
- Based on the ICF Gas Market Model (GMM®) analysis of potential impacts to demand, supply availability, and market prices, the SoCalGas system has capacity to adjust to projected changes. Based on average monthly projected demands modelled through the study, overall pipeline capacity appears to be sufficient to avoid shortfalls in regional supply. However, this conclusion can only be confirmed with modelling potential changes to daily peak demands that were beyond the scope of this study. For example, a one-day spike in demand may lead to curtailment. Looking at monthly averages can understate the impacts of short-term spikes in demand. There could be an increase in market price of natural gas under this scenario, with gas prices potentially spiking above \$10 per MMBtu, before likely returning near to the long-term average.
- The research team identified potential “flexible adaptation pathways,” which refers to the implementation of adaptation actions over time to allow for adjustment of actions based

on new information or circumstances. Rather than predetermining a set of adaptation investments based only on what is known today, flexible adaptation pathways would allow SoCalGas to make and adjust adaptation decisions as technologies, climate change information, and other factors change over time. For example, under one pathway, the utility might first integrate climate change hazard maps into its geographic information system (GIS) that support planning and operations, providing the utility with the detailed information needed to identify the most cost-effective infrastructure hardening or operational adaptation actions.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
PREFACE	iii
ABSTRACT	iv
HIGHLIGHTS	v
TABLE OF CONTENTS.....	vii
1: Introduction	1
1.1 Purpose of the Study.....	1
1.2 Scope of the Study.....	2
1.3 Policy and Planning Context	6
1.4 Key Terms Used in this Report	7
1.5 Overview of Report Structure	8
2: Methodology	9
2.1 Overview	9
2.2 Foundational Literature Review	10
2.3 Exposure Analysis.....	11
2.3.1 Coastal Hazards	12
2.3.2 Inland Flooding.....	16
2.3.3 Wildfire.....	17
2.3.4 Extreme Heat	18
2.3.5 Landslides	20
2.4 Evaluation of Direct and Indirect Impacts.....	21
2.4.1 Stakeholder-Driven Approach to Understanding Direct Impacts	22
2.4.2 Quantitative Analysis of Potential Gas Market Impacts from Climate Change.....	22
2.5 Identification of Adaptation Measures and Pathways.....	23
2.5.1 Overview of Approach.....	23
2.5.2 What are Flexible Adaptation Pathways and Why Use Flexible Adaptation Pathways for this Study?	24
2.5.3 Methodology for Adaptation Workshops	24
3: Findings	26

3.1 Exposure and Direct Impacts	26
3.1.1 Overview	26
3.1.2 Coastal Hazards	28
3.1.3 Wildfire.....	35
3.1.4 Extreme Heat	42
3.1.5 Inland Flooding.....	45
3.1.6 Landslides	48
3.2 Indirect Impacts.....	50
3.3 Flexible Adaptation Pathways.....	54
3.3.1 Key Findings from Workshops	54
4: Conclusion and Future Directions.....	61
4.1 Key Study Findings.....	61
4.2 Limitations of This Study	62
4.3 Future Research Opportunities	64
5: References.....	67
APPENDIX A: Detailed Coastal Hazard Exposure Methodology	A-1
APPENDIX B. Detailed Exposure Results.....	B-1
B.1 Coastal Hazards.....	B-3
B.1.1 Coastal Wave Flooding.....	B-3
B.1.2 Coastal Erosion	B-4
B.1.3 Tidal Inundation	B-7
B.2 Wildfire	B-8
B.3 Extreme Heat.....	B-17
B.4 Inland Flooding.....	B-18
B.5 Landslides.....	B-21
APPENDIX C: Detailed Methodology for Modeling Natural Gas Indirect Impacts.....	C-1
C.1 Reference Case	C-1
C.2 Climate Hazard Case	C-2
APPENDIX D: Potential Adaptation Measures	D-1
APPENDIX E. Example Existing Adaptation Efforts Relevant to SDG&E and SoCalGas.....	E-1

E.1 Existing Adaptation Efforts Within SDG&E and SoCalGas E-1

E.2 National, State, and Local-Level Energy Adaptation Efforts Relevant to SDG&E/SoCalGas
..... E-2

APPENDIX F. References Reviewed During Literature Review -F1

1: Introduction

1.1 Purpose of the Study

This study aimed to further the state of knowledge on how climate change-driven hazards could affect gas infrastructure and services. The main influence of climate change-driven coastal hazards is sea level rise (SLR), while climate change affects inland areas through river and floodplain inundation, extreme heat, wildfire, and landslides. These climate change hazards present a critical threat to California's energy infrastructure. The reliability and resilience of California's gas service could be threatened by permanent inundation from SLR; temporary coastal flooding events due to SLR combined with infrequent storms; accelerated coastal erosion driven by higher sea levels; changes in the frequency and intensity of precipitation events and associated inland flooding; an increase in areas burned by wildfire; more frequent and intense extreme heat events; and changes in landslides.

Despite these risks, investor-owned utilities (IOUs) in California lack key climate hazard information, as well as clear guidance or best practices for methodology, necessary to inform proactive adaptation and resiliency investments in infrastructure. Southern California Gas Company (SoCalGas) recognized the risks posed by climate hazards and actively participated in this study to assess the potential impacts of climate hazards on its infrastructure in order to identify adaptation measures. SoCalGas also saw an opportunity to deliver outcomes from this study in a way that would be beneficial not only to its own customers, but to other gas IOUs and regulators in California and beyond.

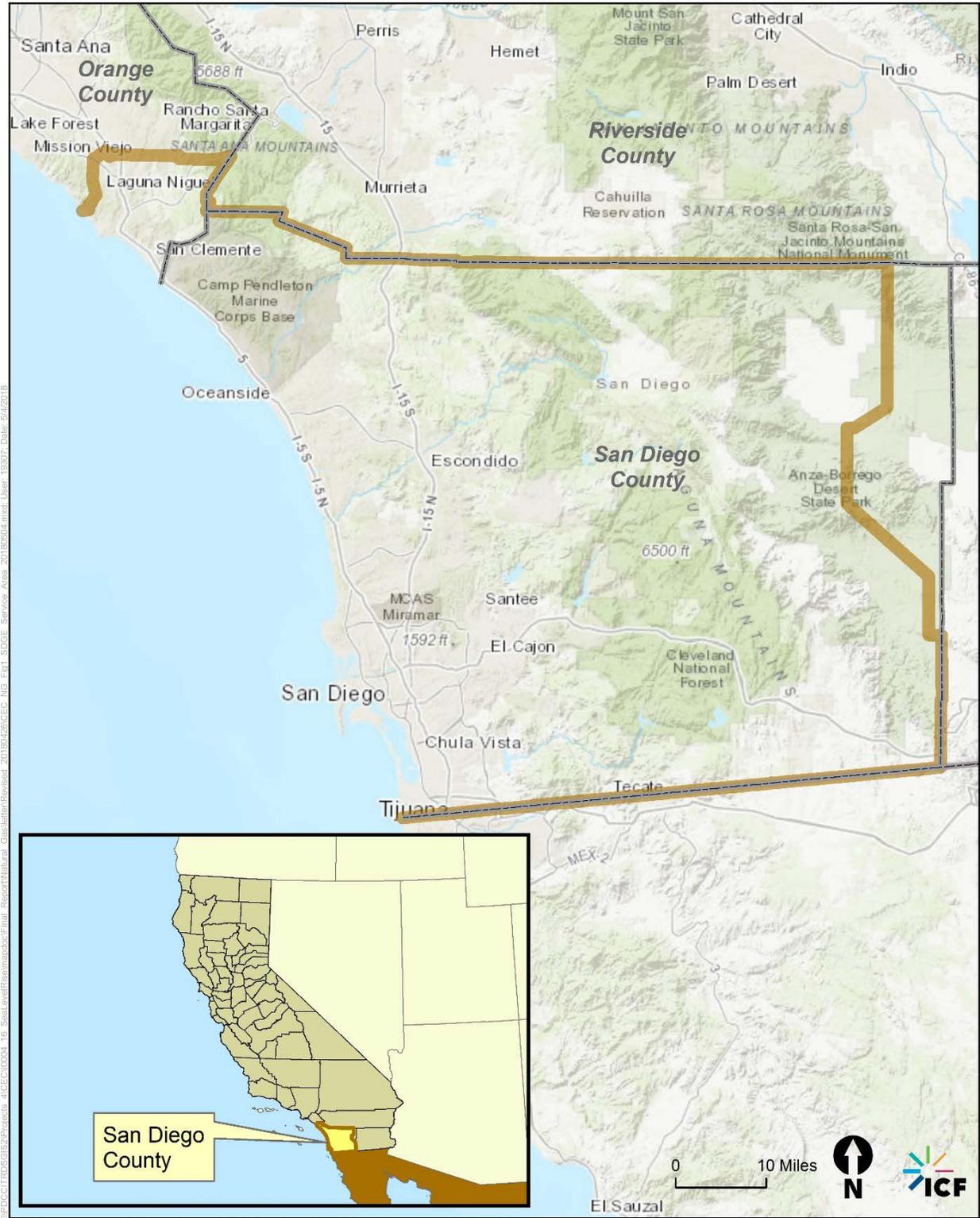
The first objective of the study was to develop an in-depth understanding of the potential exposure of the gas system within the SDG&E Service Area to specific climate change hazards and its associated effects. The selection of climate hazards was pre-determined by the overall scope of the awarded research grant. The second objective was to investigate how gas infrastructure could be affected by climate change (including both direct impacts, such as physical damage to infrastructure, and indirect impacts, such as impacts on gas demand, supply, and market prices). The third objective was to identify potential near- and long-term adaptation measures and identify potential implementation of those measures over time (i.e., "flexible pathways" to adaptation over time). Altogether, the study aimed to provide insights into potential impacts and adaptation measures that can benefit other gas-sector IOUs in California and the United States while informing policy and planning decisions at the state and local levels.

1.2 Scope of the Study

The research team conducted a system-wide climate change exposure and impact assessment to determine potential impacts to gas assets within most of the SDG&E Service Area (Figure 1).^{1, 2} The results of the exposure assessment were used to analyze potential direct impacts on infrastructure and assets and potential indirect impacts to gas supply and market prices. The identification of potential impacts from climate change hazards enabled a practical and decision-focused review of various adaptation measures. A flexible adaptation pathways approach enabled the identification of a sequence of potential adaptation measures tailored to SoCalGas' risk management and operational processes.

¹ The natural gas system within the SDG&E area includes assets operated and maintained by SoCal Gas, limited to coastal areas, and those operated and maintained by SDG&E. SDG&E and SoCalGas are both owned by Sempra Energy. Therefore, this report refers to SoCalGas as the operating utility, recognizing the shared operating and maintenance responsibility between SoCalGas and SDG&E.

² The SDG&E Service Area covers part of Orange County; however, the coastal hazard data used in this study (with the exception of coastal cliff erosion data) was available for San Diego County and not Orange County. Therefore, the results for those coastal hazards reflect San Diego County only.



I:\PDC\11050102\Projects_4\CEC\0004_12_SanDiego\SanDiego\Final_Report\Natural_Consultation\Revised_20150225\EC_MG_Fig1_SDGE_Service_Area_20100504.mxd Deser_150317 Date: 5/4/2016

Figure 1: SDG&E Service Area. Sources: SDG&E, ESRI

SoCalGas and SDG&E are public utility companies owned by Sempra Energy. SoCalGas purchases natural gas from southwestern United States suppliers and stores the natural gas for its own and SDG&E’s customers. SDG&E then transports, distributes, and sells the natural gas to 3.3 million consumers within San Diego County and southern Orange County. The gas is delivered to residential consumers (96% of gas meters), commercial consumers (3% of gas meters), and electric generation and transportation facilities (<1% of gas meters). Electricity generation and building heating are the two major sources of natural gas demand. Demand is seasonal, and is generally highest during winter heating months. However, demand can peak during extremely hot summer days when air conditioning use spikes, causing electricity demand and natural gas demand for electricity generation to also spike (Sempra Energy 2018).

SoCalGas provided the study with data under a nondisclosure agreement on the type and location of key assets within its Service Area, including available metadata for each asset. These data, totaling over 1.68 million “point assets” and 26,000 mi. (42,000 km) of “line assets” (Table 1), were vetted and categorized to gain a better understanding of the key assets and possible dependencies and interdependencies between the assets for the study.

Table 1. Key Gas Assets in the SDG&E Service Area

Asset Type	Brief Description	Potential Direct Impacts	# of Features	Length
Line				
Gas Pipe Casing	Pipe that protects actual natural gas pipe from damage underground.	Pipelines at water crossings may experience scouring, damage from debris, and/or damage from contact with bridges. Depending on pipeline material, potential corrosion damage from increased exposure to saltwater immersion from sea level rise. Damage or potential rupture due to landslides.	48,106	337 mi. (542 km)
High Pressure Pipe	Gas pipe mains operated >60 psi. bringing gas to Service Area.		13,738	582 mi. (937 km)
High Pressure Service Pipe	Gas pipe to customers requiring high pressure (e.g. power plants or industrial).		304	2 mi. (3 km)
Medium Pressure Pipe	Gas pipe distribution mains for the majority of distribution system operating at <60psi.		222,306	7,769 mi. (12,503 km)
Medium Pressure Service Pipe	Gas pipe from distribution main to customer meter operating at <60psi.		928,975	6,831 mi. (10,993 km)
Miscellaneous Gas Line	Small diameter pipeline rarely used.		531	4 mi. (6 km)
Point				

Asset Type	Brief Description	Potential Direct Impacts	# of Features	Length
Regulator	Regulates pressure from one level to another (e.g., from transmission to distribution pressures).	Above-ground regulators could experience physical damage from wildfire and inland flooding.	607	
Controllable Gas Valve	Any valve that is accessible where flow could be controlled by opening and closing it.	Limited impacts identified. If damaged, however, could be problematic in areas with large increases in wildfire, as it would limit ability to restrict gas flow.	24,224	
Non-Controllable Gas Valve	A check valve that allows for flow of gas in one direction, for example.		5	
Excess Flow Valve	Valve designed to automatically close upon detection of flow rates beyond specified limit.		10,441	
In-Line Meter	Measures volume of gas going through segment of pipeline.	Limited impacts identified.	4	
Non-Controllable Fitting	Pipeline component that does not provide any control functions (e.g., elbow fitting).	Limited impacts identified.	137,175	
Service Connection	Location of customer connection.	Service connections in coastal exposure areas may lead to increased cost for the utility, due to damage or abandoning. Service connections in areas exposed to an increase in wildfire could incur increased costs from restoring service after wildfire events.	816,977	
TOTAL			2,203,393	15,526 mi. (24,987 km)

1.3 Policy and Planning Context

In California, climate change adaptation policy is rapidly evolving as the State adjusts to emerging climate impacts, develops plans, and enacts legislation to reduce its climate change vulnerabilities. Since 2009, California has coordinated its approach to adaptation policy through the Safeguarding California Plan. The most recent version, which was released in 2018, (CNRA 2018) includes a chapter dedicated to the Energy Sector that, in turn, builds off of a detailed Energy Sector Plan Implementation Action Plan, released in 2016 (CNRA 2016).

In addition, there is a growing body of legislation in California that requires consideration of climate change impacts. For example, California Senate Bill 379 (Jackson) requires that the Safety Elements of General Plans and Local Hazard Mitigation Plans (LHMP) be reviewed and updated to include climate adaptation and resiliency strategies (CA-SB 379 2015). Assembly Bill 2800 (Quirk) has established a Climate- Safe Infrastructure Working Group that is actively examining how to integrate scientific data on projected climate change impacts into state infrastructure engineering and investments (CA-AB 2800 2016).

Also of note is the guidance *Planning and Investing for a Resilient California* issued by the Office of Planning and Research (OPR, 2017) (pursuant to B-30-15). Targeted specifically at State agencies, the document directs agencies to cal-adapt.org as a source for peer-reviewed, state-sanctioned data depicting projected climate risks and for map overlays to facilitate planning and investment. These policies and guidance, and other sectoral adaptation policies, guides, and tools that support adaptation are coordinated through the Integrated Climate Adaptation and Resiliency Program (ICARP) established by Senate Bill 246 (Wieckowski) (CA-SB 246 2015).

The California Public Utilities Commission (CPUC) Rulemaking 13-11-006 was created in 2013 to incorporate a risk-based decision-making framework into utility General Rate Cases (GRCs) (Haine 2016). This rulemaking requires that IOUs submit a Risk Assessment and Mitigation Phase (RAMP) filing with their GRCs, which are filed every three years (CPUC 2018, Haine 2016). The RAMP filings present a prioritization of risks that utilities are facing and aim to provide insight into how the utilities identify and quantify risks and risk mitigation, particularly safety-related risks. SoCalGas submitted their first RAMP report in November 2016 (Sempra Energy 2016). This report covers risks posed by climate change to the gas system in the entire SoCalGas Service Area, and identifies near-term mitigation actions. In addition, the SDG&E RAMP filing provided additional information on the electricity and gas system specifically within the SDG&E Service Area. In this report, SLR is identified as one of the climate change hazards that pose a risk to the utility. SoCalGas notes that some of the potential risks of climate change are addressed through ongoing safety and risk management initiatives unrelated to climate change, such as ongoing geohazards assessments that seek to mitigate risks from land movements, including subsidence. SoCalGas outlines immediate-term actions intended to improve their understanding of the risk and risk mitigation needs associated with climate change. This goal to better understand climate change risks and mitigation needs is a key driver for this project.

The State's coastal zone management system is required to consider potential sea level rise impacts, a process which is coordinated by the California Coastal Commission (CCC). Specifically, the California Ocean Protection Council (OPC) Sea Level Rise Guidance, released in 2013, was translated by the CCC into the document Sea Level Rise Policy Guidance in 2015 to

guide the Commission's planning and regulatory actions; an update is currently being developed. The OPC Sea Level Rise Guidance was approved in March 2018 (OPC 2018).

Importantly, SoCalGas and SDG&E are actively engaged in adaptation planning policy dialogues at regional, state, and national levels. These range from the San Diego Regional Climate Change Collaborative through to participation in the U.S. Department of Energy Partnership for Energy Sector Resilience (see Appendix E for additional examples). The utility's involvement in these dialogues ensures that it is up to date with the latest adaptation policy and developments.

In addition to climate change-specific policies and plans, there are several plans that aim to mitigate the impacts of non-climate change risks. Most notable are the LHMPs and catastrophic incident plans (i.e., sudden events resulting tens of thousands of casualties and evacuees (CA OES 2018). LHMPs have been prepared by San Diego County and many of the incorporated cities within San Diego County (SDC OES 2018). Also of significance is the catastrophic plan for the San Diego area prepared by Federal Emergency Management Agency (FEMA) and the California Governor's Office of Emergency Services in response to a San Andreas Fault earthquake event. This Southern California Catastrophic Earthquake Response Plan (2010) summarizes the consequences of potential earthquake disasters and outlines federal and state response coordination efforts (CalEMA and FEMA 2010).

1.4 Key Terms Used in this Report

Key terms and concepts used in this report include (in approximate order of their use in the report):

- **Asset** refers to physical infrastructure elements of the gas system within the SDG&E Service Area as categorized by the SoCalGas asset management database.
- **Exposure** in this report refers to whether natural gas assets are in geographic areas that are projected to experience climate change-driven hazards. That is, if a regulator is in a location projected to experience coastal wave flooding, that regulator is considered to potentially be exposed under future conditions. It is important to note that just because something is exposed does not necessarily mean that it would experience an impact.
- **Coastal Wave Flooding** refers to a temporary episodic flooding impact that is caused by large wave events. This wave flooding typically has velocity and depth which can cause substantive damages and affect access and maintenance needs.
- **Tidal inundation** refers to periodic tidal fluctuations causing predictable flooding.
- **Coastal erosion** refers to the loss of land caused by both coastal wave processes and terrestrial mass wasting, or the movement of mass downslope.
 - **Coastal erosion of low-lying land** includes beach and dune systems that can recover over time.
 - **Coastal cliff erosion**, also known as coastal bluff erosion, is the permanent loss of higher elevation cliff-backed shorelands.

- **Direct Impacts** refer primarily to direct physical damage to infrastructure that would either result in costs to the utility or potentially disrupt service to customers.
- **Indirect Impacts** refer to impacts on characteristics of the natural gas system that are not directly controlled physical assets of SDG&E or SoCalGas, including gas supply, demand, and market prices due to climate change-driven local supply constraints or supply disruptions outside of the SDG&E Service Area.
- **Sensitivity** is the degree to which a system is affected by climate variability or change (based on IPCC 2014). For example, *if* an asset or system is exposed to a certain stressor (such as wildfire), how, and to what extent, is it affected?
- **Climate Change Adaptation** is the adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects (USGCRP 2016).
- **Flexible Adaptation Pathways** are an approach to adaptation that allows for decision makers to react and adjust to new information and circumstances over time. This approach allows the decision maker to manage uncertainty of the future, rather than getting locked upfront into a set of adaptation measures in anticipation of potential impacts that may not occur for decades, if at all. The pathways illustrate immediate adaptation measures that could be taken today to begin the adaptation process, and, as new information becomes available and certain thresholds are met, other adaptation measures could be undertaken. This approach helps prevent under- and over-adaptation that could result by making a full set of adaptation decisions based only on today's assumptions and understanding of the future (Wise et al. 2014; Haasnoot et al. 2013; Wilby and Dessai 2010).
- **Adaptation Measures** are the activities that could potentially be undertaken to address a perceived climate change impact.
- **Adaptation Actions** (or just Actions) are the activities that are actually undertaken to begin dealing with climate change risks. In this report, Actions are the specific activities identified as part of the flexible adaptation pathways.
- **Signposts** specify the types of information that should be tracked to help determine if the utility's adaptation efforts are meeting their objectives or conditions for success (adapted from Haasnoot 2013).
- **Thresholds** and **triggers** are used interchangeably, and are used to define the critical values of signpost variables beyond which additional actions should be implemented are specified (adapted from Haasnoot 2013).

1.5 Overview of Report Structure

This report is structured as follows. Section 2 describes the research team's methodology. Section 3 summarizes findings of the exposure and impact analysis and adaptation measures assessment. Section 4 discusses conclusions and future research needs. Section 5 lists the references cited in the study. Finally, several appendices provide more extensive detail on the methodology and results.

2: Methodology

2.1 Overview

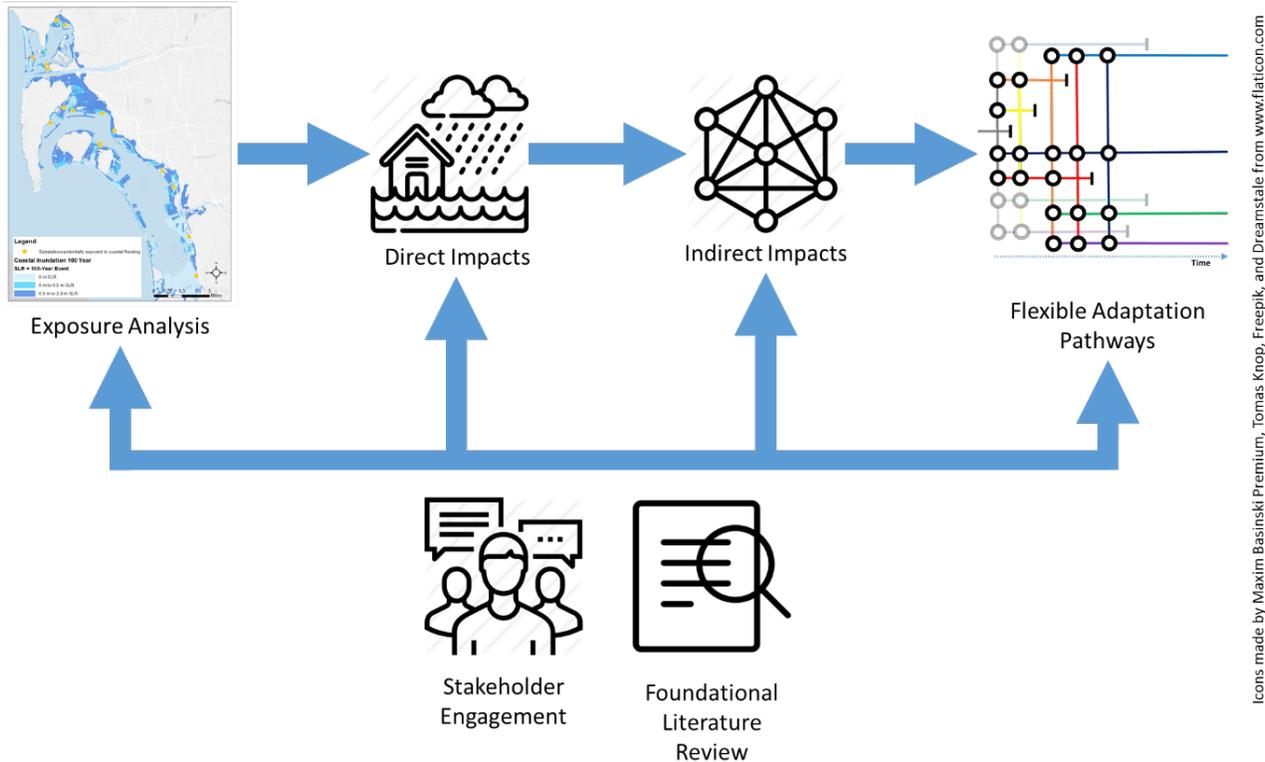


Figure 2: Visual Representation of Study Methodology

As shown in Figure 2, this study was conducted using the following approach:

- A **foundational literature review** to understand the current state of knowledge on coastal and inland hazards in the region, natural gas sector impacts and adaptation with respect to climate change, and concurrent efforts related to adaptation planning in the region and beyond.
- **Stakeholder engagement** that consisted of meetings of the Technical Advisory Committee and ongoing engagement throughout the study with internal utility stakeholders across SoCalGas departments. Throughout the study, the research team coordinated closely with SoCalGas experts who provided input through regular phone calls, workshops, and phone-based interviews, and also provided data and other information otherwise not easily accessible. Their contribution provided important insights and data that allowed this study to be customized to a California IOU. SoCalGas also provided direction on assumptions for the modeling work and advised on the use and application of the most appropriate datasets.

- An **exposure analysis**, which utilized the latest SLR information to understand where coastal and inland hazards might intersect with gas infrastructure.
- An **assessment of potential direct impacts** from the exposure analysis, with an emphasis on how types of infrastructure could be damaged from the projected exposure and geographic locations where impacts could be particularly concentrated.
- **Quantitative modeling and qualitative assessment of indirect impacts** that could arise, specifically potential impacts to gas demand, supply availability, and market prices.
- **Development of potential “flexible adaptation pathways” and priority adaptation measures for SoCalGas**, with an emphasis on implementing measures that would facilitate access to key information, signposts, and thresholds to help SoCalGas evaluate and select additional appropriate adaptation measures as time goes on.

These steps are explained more in the subsections that follow, as well as in the appendices.

2.2 Foundational Literature Review

The purpose of the foundational literature review was to ensure that the study was building on, not replicating, the latest research on climate change, its impacts on energy systems, and known adaptation measures and processes. It also enabled the research team to identify recent and ongoing adaptation efforts that might be complementary to this study, such as the U.S. Department of Energy (DOE) *Partnership for Energy Sector Climate Resilience* program and local adaptation efforts underway in the San Diego area.

The research involved a systematic review of publicly available literature, expert inputs from the study Technical Advisory Committee (TAC) and the study team’s previous experience, and interviews with select industry experts. Specifically, the research team conducted a literature search using the Elton B Stephens Company (EBSCO) Host Research Databases, the California Natural Resources Agency *Planning for Sea Level Rise* database (AB 2516, Gordon), and general internet searches using Google and other search engines. This effort was supplemented by coordinating with the TAC made up of climate change experts and stakeholders from other California utilities and regional/local government representatives.

Members of the research team also provided relevant material, drawing from: 1) current and past efforts, 2) other meetings and conferences, and 3) general experience in the subject areas. An example of this is the leveraging of recently produced climate-related studies by utility companies. As part of the requirement under the U.S. *DOE Partnership for Energy Sector Climate Resilience* (DOE 2017), partnering utility companies were requested to submit vulnerability assessments. The research team reached out to a variety of utility companies to obtain copies of their DOE-requested vulnerability assessments and also inquired about other material that might be of use for the study (i.e., regulatory filings, design standards). The research team augmented the literature research with interviews of climate change experts and representatives from energy utilities. The interviews were used for three purposes: 1) to validate findings, 2) to fill knowledge gaps, and 3) to understand concurrent efforts contributing to California’s Fourth Climate Change Assessment (Fourth Assessment).

For a list of references reviewed and interviews conducted during the literature review, please see Appendix G.

2.3 Exposure Analysis

The study analyzed potential natural gas asset exposure to the following hazards:

- **Coastal hazards** - Coastal wave flooding, coastal erosion, and tidal inundation;
- **Inland Flooding** - Floodplains;
- **Wildfire** - Change in area burned per year;
- **Extreme Heat** - Change in extreme heat days per year;
- **Landslides** - Landslide-prone geologic formations.

The exposure analysis provided detailed spatial information about potential hazard extents, and where these hazard areas intersect with natural gas infrastructure. The research team and its partner, SoCalGas, implemented a three-phased approach to complete the exposure analysis:

- Phase 1 involved comprehensive research, data collection, and evaluation of the data quality relevant to the individual hazards and the locations of key natural gas assets.
- Phase 2 included recommendations to augment (e.g., fill data gaps in spatial coverage) and/or adjust (e.g., localize to SDG&E Service Area) the hazard information to better determine natural gas asset exposure.
- Phase 3 applied Geographic Information Systems (GIS) software to overlay natural gas assets against each hazard to determine potential exposure.

The research team sought to find and use the best available scientific information and leverage existing, validated hazard and asset information to the greatest extent possible. A broader suite of geohazards were discussed with the utility on project initiation in relation to the scope of the project and the current level of sensitivity of these hazards in the SDG&E service area. As a result, this study excludes precipitation induced landslides that may occur outside of geologically slide-prone formations (discussed in 2.3.5) and land subsidence as geohazards.

SoCalGas included potential drought impacts from land subsidence (groundwater overdraft) and cathodic protection (dry soils) in their most recent RAMP (Sempra Energy 2016). For this study, the utility reported that land subsidence is currently not a relevant hazard in SDG&E's Service Area. This is because any local groundwater overdraft has not lowered water tables to the point that significant land subsidence is occurring. Also, if the land subsidence is vertical in nature, which SoCalGas stakeholders reported is a widespread issue in the San Joaquin Valley, the natural gas pipeline will generally move with the ground and will not experience significant stress damage. On the other hand, SoCalGas stakeholders reported horizontal subsidence can create compression forces on pipelines that could cause buckling type damage in localized areas. To prevent future overdraft and associated subsidence, three separate groundwater basins in the local San Diego area (San Diego River Valley, San Luis Rey Valley, San Pasqual Valley) are developing groundwater sustainability plans (GSPs) to monitor and maintain sustainable groundwater levels during droughts to comply with the state-issued Sustainable Groundwater Management Act (San Diego County 2018).

In addition, the California Energy Commission (CEC) is currently performing analyses to model the structural risks from land subsidence to natural gas infrastructure (CEC 2016). Dry soil

impacts that degrade cathodic protection performance could increase with future climate-induced droughts, but specific impacts are outside the scope of this current study.

The sections below provide an overview of Phase 1 and 2 of the exposure methodology. The results from the Phase 3 GIS overlay are provided as part of the results. Additional detail on the coastal hazards methodology is provided in Appendix A.

2.3.1 Coastal Hazards

The following sections describe an exposure analysis for several coastal hazards, being:

- **Coastal wave flooding** – A temporary episodic flooding impact that is caused by large wave events. This flooding typically has velocity and depth which can cause substantive damages and affect access and maintenance needs.
- **Coastal erosion** – The loss of land caused by both coastal wave processes and terrestrial mass wasting, or the downslope movement of mass. In some dune systems the beaches and dunes can recover over time, but in cliff-backed shorelines, the loss of land is permanent.
- **Tidal inundation** – Periodic tidal fluctuations causing predictable flooding.

2.3.1.1 Phase 1—Research, Collection, and Analysis

As with other Fourth Assessment research projects, this research made use of quasi-probabilistic sea level rise projections developed by Cayan et al. (2016) based on an approach that interprets the range of potential SLR values based on numerical experiments and expert elicitation. The Cayan et al. (2016) study identifies probabilities (50th, 95th, and 99.9th percentile) associated with different future SLR by decade for multiple emissions scenarios, or representative concentration pathways (RCPs).

Emissions scenarios and RCPs are global projections for how socioeconomic change, technological change, energy and land use, greenhouse gas (GHG) emissions, air pollutant emissions, and other variables may evolve over time. These projections provide researchers with scenarios to generate climate models and impacts, mitigation strategies, and other climate change related research (Van Vuuren et al. 2011). Four RCPs are commonly used in research; Cayan et al. (2016) uses two specific RCPs (RCP 8.5 and RCP 4.5). RCP 8.5 assumes the largest global GHG emission concentration of the four scenarios (~1370 parts per million CO₂e by 2100), and RCP 4.5 the third highest concentration (~650 parts per million CO₂e stabilization after 2100) (Van Vuuren et al. 2011). RCP 8.5 then represents the high-end of climate impacts, with RCP 4.5 representing more of an average.

The CEC Climate Action Team Research Working Group released the latest guidance for selecting SLR scenarios for the Fourth Assessment (Franco et al. 2016). This guidance (which was based on the same modeling efforts from Cayan et al. 2016) recommended using the RCP 8.5 50th, 95th, and 99.9th percentile projections for planning horizons before 2060, and RCP 4.5 and 8.5 (50th, 95th, and 99.9th percentile) beyond 2060.

2.3.1.2 Phase 2—Hazard Scenario Changes/Adjustments

A key challenge with directly implementing the SLR recommendations for Fourth Assessment research was interpreting how available coastal hazard model data aligned with the particular increments of SLR. The research team worked with SoCalGas to evaluate several coastal hazard

models and identify specific scenarios and recurrence intervals of wave and water levels to match the recommended SLR scenarios as closely as possible. In addition, Fourth Assessment research teams were provided specific guidance on harmonizing sea level rise increments with the USGS CoSMoS model (CEC 2017b).

The research team consulted with SoCalGas on how best to develop “project scenarios” that would be based on the best available science – as per CEC guidance – while also being practical for the study, including during engagement with SoCalGas stakeholders. The outcome of these deliberations was to use several SLR scenarios, combined with an annual event (i.e., 1-year return interval) and a 1% annual chance (i.e., 100-year return interval) event. These scenarios include:

- 0 m (0.0 ft.) SLR (annual and 100-year events) – *baseline*
- 0.5 m (1.6 ft.) SLR (annual and 100-year events) – *selected to represent a mid-century timeframe*
- 2.0 m (6.6 ft.) SLR (annual and 100-year events) – *selected to represent an end-of-century timeframe*

These scenarios span from the current baseline to a high scenario of 2.0 m (6.6 ft.) SLR plus a 100-year storm event, which supports the ability to investigate potential impacts and adaptation measures over a range of potential future conditions. While several scenarios were modeled, the exposure analysis results and direct and indirect impact analyses focus on the mid-century exposure because (1) infrastructure planning horizons generally do not go beyond mid-century and (2) the energy systems – including supply, demand, and infrastructure (for example, the extent of future distributed energy generation) – are likely to change significantly by end-of-century. However, end-of-century exposure information (using 2.0 m or 6.6 ft. SLR) is also described to help illustrate the potential extent of exposure that SoCalGas could face within this century. It is important to note that the use of 2.0 m (6.6 ft.) SLR for the late 21st century exposure assessment does not encompass the highest possible SLR projections of 2.4 m and 2.9 m (7.9 ft. and 9.5 ft.)

Based on the needs of the study, the above model assessment, and the suggested combination of SLR and flood event recurrence periods, the team primarily utilized the USGS CoSMoS 3.0 (2017) model, augmented by other coastal hazard models including FEMA and SPAWAR. Notably, because USGS CoSMoS 3.0 coastal wave flooding, tidal inundation, and dune and low-lying erosion layers were available for San Diego County but not Orange County when the analysis was conducted, this component of the hazard analysis only includes the portion of the SDG&E Service Area that is within San Diego County and does not include the portion that is within Orange County. Below is a summary of models used for each coastal hazard; please see Section 2.3.1.2.1 and Appendix A for detailed information about these models and why they were selected:

- Coastal Wave Flooding (episodic storm impacts)
 - USGS CoSMoS 3.0
- Tidal Inundation (periodic flood impacts)
 - USGS CoSMoS 3.0 (used maximum annual tidal conditions with minor wave runup)

- Coastal Erosion (potential loss of land and assets)
 - Erosion of dune and low-lying inlets from USGS CoSMoS 3.0 COAST module (plus geomorphic interpretation³) and SPAWAR (see Section 2.3.1.2.1, below)
 - Cliff erosion of higher-elevation coasts from USGS CoSMoS 3.0⁴

The selection of the SLR and recurrence intervals and the coastal hazard spatial models resulted in several hazard scenarios, as described in Table 2 below.

Table 2. Coastal hazard exposure scenarios analyzed.

Hazard	Hazard Sub-Type	Conditions	Armoring	SLR Scenario [m (ft.)]
Flooding/ Inundation	Tidal Inundation	Annual event	N/A	0.0 (0.0)
				0.5 (1.6)
				2.0 (6.6)
	Wave Flooding	100-year event	N/A	0.0 (0.0)
				0.5 (1.6)
				2.0 (6.6)
Erosion	Low-lying and Dune Erosion	Annual event	Do Not Hold (no armoring)	0.5 (1.6)
				2.0 (6.6)
		100-year event		0.5 (1.6)
				2.0 (6.6)
	Cliff Erosion	Average conditions	Do Not Hold (no armoring)	0.5 (1.6)
				2.0 (6.6)

2.3.1.2.1 Data Gap Filling

The CoSMoS 3.0 model at the time of the research modeled erosion of the coastal cliffs (Limber et al. 2016) and long-term shoreline evolution of low-lying coasts as defined by the Mean High Water (MHW) (CoSMoS COAST, Vitousek et al. 2016). The CoSMoS MHW shoreline evolution model maps the projected location of an MHW shoreline for four coastal management scenarios, namely:

1. **Hold the Line + Continuing Nourishment:** Shoreline erosion is not permitted to continue beyond existing urban infrastructure, plus inclusion of historical rates of sand nourishment in future projections.

³ CoSMoS cliff erosion data does not include a ‘baseline’ for existing erosion hazard conditions

⁴ The CoSMoS data available at the time of analysis did not explicitly map dune erosion hazard extents or maximum wave run-up extents.

2. **Hold the Line + No nourishment:** Shoreline erosion is not permitted to continue beyond existing urban infrastructure, plus no inclusion of sand nourishment.
3. **No Hold the Line + Continuing nourishment:** Shoreline erosion is unrestrained by urban infrastructure, plus inclusion of historical rates of sand nourishment.
4. **No Hold the Line + No Nourishment:** Shoreline erosion is unrestrained by urban infrastructure plus, no inclusion of sand nourishment.⁵

To model greatest potential exposure, this project used the “No Hold the Line + No Nourishment” scenario. In addition, for purposes of comparison with a coastal management scenario that assumes ongoing coastal armoring, the “Hold the Line + No Nourishment” scenario was adopted.

CoSMoS modeling results also show bands of uncertainties for MHW projections for each coastal management scenario, including MHW positional uncertainty and MHW with storm erosion uncertainty.

The location of MHW does not account for wave runup process and the potential extent of coastal erosion hazards. Wave runup can produce water levels upwards of 10 to 15 ft. (3.0 to 4.6m) higher in elevation than MHW, leaving a data gap related to the extent of potential erosion at upper portions of the beach profile (e.g. dunes). The research team deemed it necessary to fill this data gap to complete the coastal hazard analysis by expanding the existing CoSMoS COAST MWH shoreline model. These hazard zones were tied directly to the CoSMoS COAST model outputs for Hold the Line and No Hold the Line (no nourishment) coastal management scenarios using the available CoSMoS COAST transects.

To fill the gap and be consistent with CoSMoS COAST, a geomorphic approach was applied to the MHW projections to an inland distance based on a “natural shoreline” condition. The methodology essentially buffered the CoSMoS COAST results based on the distance from MHW to the top of the dune under a natural condition (see Appendix B – Coastal Hazards for further details).

The most natural shoreline condition in the historical data sets given the extensive changes to the coastal system in San Diego was assumed to be the 1870s historic T-sheet (caltsheets.org). The analysis was undertaken by first calculating the distance of the “natural” 1870s dune and beach system along each of the CoSMoS COAST transects. Then, the MHW 1870s shoreline was adjusted to the present MHW shoreline to account for historic mapping biases and engineering changes along the shoreline which affect the present day “natural MHW” shoreline location. The calculated “Natural Offset” distance conceptually extends MHW to the inland extent of dune and beaches along each CoSMoS COAST transect. For each of the CoSMoS COAST shoreline projections (0.5m , 1.0m, and 2.0m), the Natural Offset distance was intersected for each projection along the CoSMoS COAST transects. Given the desire to evaluate a 1-year and 100-year event, the research team assumed that the final CoSMoS COAST projections were

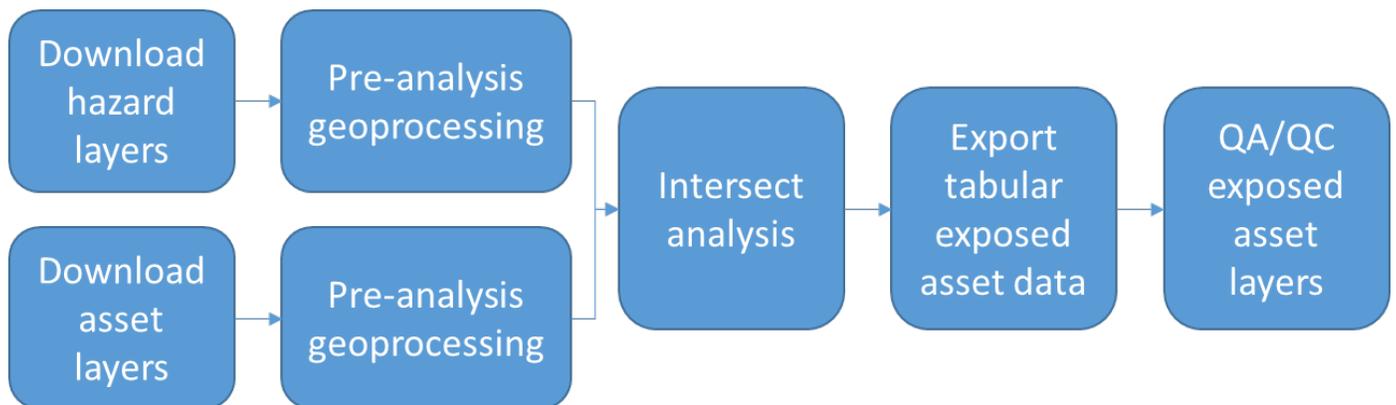
⁵ The CoSMoS 3.0 FAQs provides further information coastal management scenarios https://dornsife.usc.edu/assets/sites/291/docs/CoSMoS3.0_FAQ.pdf

equivalent to a 1-year recurrence while the inland extent of the CoSMoS COAST uncertainty band with storm erosion represented the 100-year erosion event.

2.3.1.3 Phase 3—GIS Exposure Analysis

The team analyzed exposure using geographic information system (GIS) analysis. First, the team downloaded the coastal hazard and asset GIS data and conducted pre-analysis geoprocessing to prepare the data for analysis, including projecting the layers to project standard coordinate system, deleting asset fields that were not needed, and conducting unions to combine data from separate layers into one composite layer (e.g., for USGS CoSMoS). The research team then performed ArcMap’s intersect function between the asset layers and the exposure layers, and then tabulated the acres of land, the linear feet of line assets, and the count of point assets that fall within exposure layers. The research team conducted quality control by cross-checking map results against the tabular data for a selection of features. These processes are depicted in Figure 3, below.

Figure 3. GIS Exposure Analysis Process



2.3.2 Inland Flooding

2.3.2.1 Phase 1—Research, Collection, and Analysis

While there are several studies detailing potential inland flooding impacts, they are limited in scope and focused on small land areas; the research team is not aware of comprehensive studies. The work conducted by the FEMA, through its National Flood Insurance Program (NFIP), is the most comprehensive flood work done within San Diego County. The FEMA NFIP Flood Insurance Rate Maps (FIRM) are well vetted and utilized by many to analyze inland flooding potential. The only limitation of the FEMA NFIP FIRM information is that it does not incorporate recent information on climate change, such as changes in precipitation.

In conversations with FEMA, staff indicated that there are some discussions on how to best incorporate climate change information, but no actions have been taken or initiated to adjust the FEMA NFIP FIRMs for future climate change in the San Diego area to date. However, FEMA did indicate that some initial discussions led them to believe that methods being considered to incorporate climate change information may not alter the NFIP FIRM footprints, but rather may change the frequency of events.

The State of California Department of Water Resources, in partnership with the California Ocean Science Trust, has prepared a Technical Methods Manual titled *Relating Future Coastal Conditions to Existing FEMA Flood Hazard Maps* (2016); however, the manual is focused on adjustments to coastal flooding, not inland flooding.

The research team coordinated with other Fourth Assessment project managers, including the University of California at Irvine (UCI) and the University of California at Berkeley (UCB). UCI is researching climate change vulnerability to the Southern California natural gas system under a CEC grant. UCB has a grant to research extreme weather impacts to California's transportation fuel sector. While similar in nature, these projects are sufficiently different that the approaches cannot be leveraged at this time.

2.3.2.2 Phase 2—Hazard scenario changes/adjustments

The research team utilized the FEMA NFIP FIRM 100-year and 500-year flood data and maps. As previously mentioned, FEMA indicated that there are some initial discussions about incorporating climate change data, but these discussions indicate that the frequency will change but the hazard footprint will not. Based on this information, and the lack of available data regarding these potential changes to frequency of events, the research team did not change or adjust the hazard layer. Instead, current hazard extents (derived from the FEMA NFIP FIRM) were used to determine exposure, and the possibility of an increase in frequency of events will be incorporated as part of qualitative discussions with SoCalGas and SoCalGas experts during a workshop on potential impacts.

2.3.2.3 Phase 3—GIS Exposure Analysis

The research team used these hazard layers as inputs to analyze exposure with geographic information system (GIS) analysis. The research team downloaded the flood hazard GIS data, geoprocesed the data to prepare it for analysis, performed a GIS intersect function between the gas asset layers and the hazard layers, and then tabulated the exposed assets. The research team conducted quality control by cross-checking map results against the tabular data for a selection of features.

2.3.3 Wildfire

2.3.3.1 Phase 1—Research, Collection, and Analysis

None of the available wildfire data sources incorporate climate change in the manner needed for this project. Therefore, the research team relied on two (2) different sets of data: 1) fire fuels and 2) future wildfires. The current wildfire hazard data comes from SDG&E and the future wildfire data come from a parallel effort under the Fourth Assessment.

SDG&E provided fire fuels data that is current, covers the entire Service Area, leverages other efforts, and was generated in coordination with a team of internal experts at SDG&E and external consultants. The SDG&E team included all known vegetation resources to identify vegetation fuel type zones. The current SDG&E wildfire fuel map provides a baseline for the wildfire hazards. In the SDG&E Service Area, two distinct fire-types are possible. The first is a grass-fuel driven fire, which is characterized by fast moving and lower temperature fires, compared to the second type, the shrub-fuel driven fire.

To assist with the consideration of climate change, the research team utilized future wildfire information developed by Dr. LeRoy Westerling (available on the cal-adapt.org website). The wildfire scenario projections use a statistical model based on historical data of climate,

vegetation, population density, and fire history, coupled with regionally downscaled localized constructed analogs (LOCA) climate projections. The research team used the four recommended global climate models (MIROC5, HadGEM2-ES, CNRM-CM5, CanESM2) as well as the ensemble average of these models for RCP 8.5 and the central population growth scenario, using the wildfire simulation average (see map below). The focus of this effort is on the directional change for future wildfires based on available modeling of future wildfire area burned. By later this century, these wildfire projections indicate a 40% increase in wild fire area burned statewide. Detailed exposure statistics and maps are provided in Appendix B.

The research team identified the natural gas assets exposed to the current fire fuels map to understand the current and future exposure footprint. The research team also identified the natural gas assets that could be exposed to increases in future area burned to get a general sense of the percentage of assets that might have greater risk in the future.

2.3.3.2 Phase 2—Hazard scenario changes/adjustments

No adjustments were made to the available data sets provided by SDG&E. The team used GIS to overlay the assets with the SDG&E fire fuel map. Potential increases in wildfire due to climate change were informed by the data available from Dr. Westerling, which were used to determine potential areas for future area burned, rather than any explicit change in the fire fuel locations.

2.3.3.3 Phase 3—GIS Exposure Analysis

The research team used these hazard layers as inputs to analyze exposure with geographic information system (GIS) analysis. The research team downloaded the fire fuel and wildfire area burned hazard data, geoprocessed the data to prepare it for analysis, performed a GIS intersect function between the gas asset layers and the hazard layers, and then tabulated the exposed assets. The research team conducted quality control by cross-checking map results against the tabular data for a selection of features.

Notably, approximately 9% of assets were excluded from the analysis as they fall outside of the spatial extent of the future wildfire hazard data. These excluded assets lie within an area of approximately 35 square miles which stretches along the coast from southern Carlsbad to northern Point Loma, southwest of the point -33.18, -117.25⁶. Currently, the majority of this area is not designated as a severe fire hazard zone, though some areas within Encinitas and Solana beach are designated as very high fire hazard severity (Ready San Diego 2018). Information on projected change in wildfire risk for these areas is not available, and may increase, decrease, or stay the same.

2.3.4 Extreme Heat

2.3.4.1 Phase 1—Research, Collection, and Analysis

As a first step, the research team considered which specific heat metric would be most useful for evaluating potential impacts to the natural gas sector. To do so, the research team consulted with the utility partners to understand which metrics they tend to use in planning, design, operations, and other key decisions. The discussions indicated that there is no one, single metric that would be universally relevant to all aspects of the natural gas system. For example, the

⁶ Starting at grid cell 33.15625, -117.28125 on cal-adapt.org.

maximum temperature experienced is relevant when designing and engineering certain infrastructure, while the number of days above certain temperature thresholds might be relevant for worker safety. When considering cooling needs of compressor stations and other buildings, a combination of factors may be relevant such as maximum temperature, number of days in a row above a certain threshold, and also the *minimum* temperature reached at night during a heat wave, since if nighttime temperatures do not fall sufficiently to cool down buildings, the cooling needs are higher the next day. A range of metrics also influence the demand of natural gas, as electricity demand may peak, causing more gas to be used as part of generation.

Since this study is taking a *system-wide* look at potential impacts (rather than an asset-specific one), it was important to understand changes in extreme heat in a general way. For example, how dramatically will the change in extreme heat events be, and how will the changes look different across the Service Area? Thus, it was more important to understand these general trends and magnitude of changes than it was to focus overly on finding a metric that is universally relevant to all aspects of the system (which, as noted above, is not possible). For purposes of designing a specific facility, on the other hand, more tailored metrics would be needed. In those cases, the appropriate metric would vary based on the specific needs of the decisions at hand.

Also, the research team determined that looking at a single metric, rather than a large number of metrics, would be ideal for the strategic-level, system-wide look. Considering too many metrics can be confusing and overwhelming, and ultimately not provide additional insight regarding the big picture of trends across the Service Area.

The research team decided to look at how the number of extreme heat days would increase in the future. This metric was selected for the following reasons:

- It is a good indicator of how extreme heat will change in the future because it shows how the frequency of extreme heat events will change in different geographic areas.
- The temperature threshold that constitutes an “extreme heat day” is relative by location, as explained below. The research team found the relative nature of this metric to be beneficial since locations tend to be already somewhat adapted to their current climate. In the San Diego region, inland areas tend to experience hotter conditions than coastal areas. So, when looking at absolute temperatures, a temperature might be considered extremely hot in a coastal area but more of a normal temperature in an inland area. The extreme heat metric therefore is useful for showing how temperatures may increase beyond what a specific location is already used to.
- This indicator is already processed in cal-adapt.org, meaning other users can access the metric easily without additional processing. While not the primary driver for selection of this metric, this ease-of-availability allows this study to serve as an easily-replicable model for other institutions that may wish to pull heat information from cal-adapt.org.

An extreme heat day is one that exceeds the location’s extreme heat threshold, which is calculated as the 98th percentile of historical maximum temperatures, based on observed daily temperature data from 1961-1990; this range of years for the baseline was selected based on guidance from CEC. Per CEC guidance, the research team collected extreme heat hazard data from the cal-adapt.org. The research team used LOCA climate projection data and the extreme

heat tool (<http://cal-adapt.org/tools/extreme-heat/>) to determine: 1) extreme heat threshold, 2) number of days exceeding the extreme threshold during the historical period (1961-1990), and 3) number of days exceeding the extreme heat threshold by mid-century (2036- 2065) under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 for each cal-adapt.org grid cell within the SDG&E Service Area.

RCPs were selected based on CEC guidance for the Fourth Assessment Report research projects. RCP 8.5 is appropriate for long-lived infrastructure such as natural gas assets; data for RCP 4.5 shows similar geographic pattern of increase, but with smaller change in number of extreme heat days. For each RCP, the four climate models recommended by the CEC were used, including HadGEM2-ES (warm/dry), CNRM-CM5 (cool/wet), CanESM2 (average), and MIROC5 (complement/covers range of outputs). The change in the number of days above the extreme heat threshold was estimated by subtracting the average number of extreme heat days in the 30-year historical period 1961 - 1990 from the model ensemble average of the projected number of extreme heat days in the 30-year period centered on 2050 (2036 - 2065).

2.3.4.2 Phase 2—Hazard scenario changes/adjustments

No adjustments were made to the hazard footprint.

2.3.4.3 Phase 3—GIS Exposure Analysis

The research team used these hazard layers as inputs to analyze exposure with geographic information system (GIS) analysis. The research team entered the extreme heat data from Cal-Adapt and associated grid cell centroid latitude and longitude into an Excel spreadsheet, imported the spreadsheet into GIS, used a GIS function to convert the points to grid cells, performed a GIS intersect function between the gas asset layers and the hazard layers, and then tabulated the exposed assets. The research team conducted quality control by cross-checking map results against the tabular data for a selection of features.

2.3.5 Landslides

2.3.5.1 Phase 1—Research, Collection, and Analysis

California Geological Survey has led several efforts to study and document landslides, including in San Diego. Much of this work analyzes “*potential*” landslide areas and areas “*susceptible*” to landslides. The “*potential*” analysis is based on historical data or areas with evidence of historical landslides. The “*susceptible*” analysis is based on existing current geological conditions: areas with weak rock or soils and steep slopes. Although it is difficult to project areas where future landslides may occur, the research team was able to use the San Diego Geographic Information System (SANGIS⁷) geohazards data to understand where landslides may take place based on geological susceptibility and potential.

While numerous triggers exist for landslides in California, including earthquakes and other slope destabilizations from human action, recent research by the California Geological Survey has investigated the potential for heavy precipitation events to cause landslide events. The analysis provided potential damages throughout the state for precipitation induced landslides, but only developed rough estimates due to data limitations (Wills et al. 2014). Discussions were held between the research team and the California Geological Survey landslide modelers

⁷ <http://www.sangis.org/>

regarding the opportunity to model extreme rainfall events overlaid with potential changes in wildfire risk areas and slope analysis. These discussions concluded that there is currently insufficient research basis for undertaking this analysis and as such no further research on the potential for climate change impacts to precipitation induced landslides risk was undertaken.

Available data do not consider any potential effects of climate change (such as changes in precipitation). Consultations with California Geological Survey staff revealed that the relationship between potential climate-change driven changes in rainfall distribution and intensity may be an important driver of future landslide hazard that is worthy of future research.

2.3.5.2 Phase 2—Hazard scenario changes/adjustments

The research team utilized the GIS data from San Diego County, which is based on the landslide data and work undertaken by the California Geological Survey and documented in the San Diego County Multi-Jurisdictional Hazard Mitigation Plan (San Diego County, 2010).

2.3.5.3 Phase 3—GIS Exposure Analysis

The research team downloaded the SANGIS Geohazard data, geoprocessed the data to prepare it for analysis, performed a GIS intersect function between the gas asset layers and the hazard layers, and then tabulated the exposed assets. The team processed the SANGIS Geohazards maps to exclude those geohazards that do not have the potential for a climate-related trigger, as outlined above. Specifically, the maps for *Fault Zones*, *Liquefaction*, and *All Other Conditions* were excluded. In addition, maps for *Coastal Bluffs* were also removed to reduce the potential for double-counting of hazard exposure with the coastal erosion hazard assessment (Section 2.3.1). Consequently, the SANGIS *Landslides* and *Slide Prone Formation* hazard layers were used as inputs to analyze exposure with geographic information system (GIS) analysis. The research team conducted quality control by cross-checking map results against the tabular data for a selection of features.

2.4 Evaluation of Direct and Indirect Impacts

To understand potential direct and indirect impacts from climate hazards, the research team combined research from the literature review with SoCalGas expertise and modeling the impacts of a climate change scenario on natural gas demand, supply, and market prices. This provided the study with perspectives from natural gas asset owners across the country, specifics of potential direct impacts for gas assets and operations, and quantitative estimates of potential indirect impacts to the utility and their customers. Direct impacts refer to damage to infrastructure and the interruptions in service that would result from the projected exposure. Indirect impacts refer to impacts on gas supply, demand, and market prices. To evaluate direct impacts, the research team applied a two-pronged approach. Using GIS, the research team spatially overlaid the projected exposure with the location of gas assets, to identify which assets would be exposed. Then, building on background research, the research team held workshops with the utility representatives to ground truth the results and understand how their assets and service could be affected by the projected exposure. The research team also took a two-pronged approach to evaluating indirect impacts, first developing reference and climate change scenarios, then leveraging ICF's Gas Market Model to assess potential impacts on gas supply, demand, and market prices.

Notably, this is not a comprehensive vulnerability assessment where design information about individual assets is used to determine how specific assets could be affected, or how impacts to specific assets would precisely affect the larger system. Rather, this assessment explored potential impacts of climate change to a set of asset types, and also considered, at a general level, how the larger system could potentially be affected by exposure to climate change hazards.

2.4.1 Stakeholder-Driven Approach to Understanding Direct Impacts

The research team worked closely with SoCalGas experts to build upon the background research and to ground-truth and further characterize the specific potential direct impacts to SoCalGas assets based on the exposure analysis results. For this, the research team employed an approach that was primarily utility-stakeholder based. Information on the direct impacts of hazards to the natural gas system was obtained primarily through a workshop, *Natural Gas System Climate Change Exposure and Impacts*, held on May 25th 2017. This workshop convened representatives from across SoCalGas, including gas engineering, pipeline integrity, emergency services, and risk management. The research team presented results from the exposure analysis, then elicited information on potential sensitivities and impacts through facilitated discussions. Following the workshop, the research team conducted supplemental interviews with SoCalGas staff to further refine the final set of potential direct impacts, as well as desk research that built upon the foundational literature conducted earlier in the study. The impacts information presented in Section 3.1 comes primarily from the workshop and follow-up interviews, except where otherwise noted.

2.4.2 Quantitative Analysis of Potential Gas Market Impacts from Climate Change

The approach to analyzing indirect impacts to SoCalGas and customers from climate change hazards leveraged the ICF Gas Market Model (GMM®) to determine potential impacts to demand, supply availability, and market prices. The analysis modeled two scenarios for the natural gas market through 2050 using the ICF GMM. By comparing the scenarios – one a reference scenario that does not incorporate changing climate conditions and the other a climate hazard scenario that explicitly includes projected gradual change in climate as well as an extreme climate hazard year – the results show the potential indirect impacts to SoCalGas and customers due to changes in the natural gas market.

The research team worked with SDG&E and SoCalGas to define a specific climate hazard scenario to model. The scenario considers supply and demand aspects of the natural gas system. From a demand perspective, warming due to climate change is projected to increase the number of cooling degree days (CDD) and decrease the number of heating degree days (HDD). Without considering other factors, the increased demand for cooling could lead to an increase in demand for natural gas given the reliance of natural gas for generating electricity to meet peak demand in the SDG&E Service Area. From a supply perspective, climate change could lead to spikes in demand in other regions, possibly impacting the available supply or market price.

The ICF Gas Market Model (GMM) is an internationally recognized modeling and market analysis system for the North American gas market. GMM is a full supply/demand equilibrium model of the North American gas market. The model solves for monthly natural gas prices throughout North America, given different supply/demand conditions, the assumptions for which are specified by the user. The GMM does not provide temporal resolution to capture daily peak gas demands. For example, the GMM does not capture the short-term impacts of a

one-day spike in demand may lead to curtailment. Looking at monthly averages can understate the impacts of short-term spikes in demand.

The GMM was developed in the mid-1990s to provide forecasts of the North American natural gas market under different assumptions. Since then, the GMM has been used to complete strategic planning studies for governments, non-government associations, utilities, and private sector companies. The different types of studies include:

- analysis of pipeline expansions;
- measuring the impact of gas-fired power generation growth;
- assessing the impact of low and high gas supply; and,
- assessing the impact of different regulatory environments.

See Appendix C for more details on GMM details and parameters.

2.5 Identification of Adaptation Measures and Pathways

2.5.1 Overview of Approach

Evaluation of adaptation measures in the context of a continuously changing risk environment – such as the non-linear change in SLR – poses a challenge to typical project planning, design, and execution. Despite significant improvements in climate science, uncertainties regarding the timing and magnitude of change remain. In addition, many other things can change between now and the time that climate change impacts are experienced. For example, demographics and energy use will change, land-use decisions may affect infrastructure locations and types, technology will advance, and other features of the gas system may change.

To help guide SoCalGas in adapting to climate change in the face of uncertainty about the future, the research team took a flexible adaptation pathways approach to identify and evaluate both short- and long-term adaptation measures (Wise et al. 2014; Haasnoot et al. 2013; Wilby and Dessai 2010). The research team selected this approach for its applicability to managing risk given significant uncertainty over long time horizons and in complex systems; engagements with SoCalGas suggested a willingness to explore non-traditional techniques for investment planning.

The research team elicited information from stakeholders, with this engagement focused around two distinct but complementary workshops (detailed methodology on the workshops is described in the next subsection). The first workshop occurred under this contract, and the second one occurred under a parallel study that focused on the electricity sector. Having these two workshops several weeks apart allowed the research team to test different approaches to identifying and evaluating adaptation measures. Both workshops provided insights that are applicable to both the natural gas and electricity sectors.

Together, these workshops assisted the research team in identifying and evaluating elements important to constructing viable flexible adaptation pathways. These elements included: a feasible set of potential hardening and planning adaptation measures; criteria that should be used when making decisions about adaptation; existing decision-making processes that could help foster adaptation decision making; and, information about the time horizon of potential

thresholds that trigger adaptation decision-making processes. Based on the input gathered at these workshops, the research team constructed several feasible flexible adaptation pathways, as well as priority adaptation actions to undertake. These pathways and actions are presented in Section 3.3.

2.5.2 What are Flexible Adaptation Pathways and Why Use Flexible Adaptation Pathways for this Study?

Flexible adaptation pathways can be used in adaptation planning and implementation to explicitly address the challenge of taking adaptation action in the face of uncertainty. Flexible adaptation pathways are designed to enable adjustment in implementing adaptation strategies in response to new information and changing circumstances, in ways that are as efficient and transparent as possible. Flexible adaptation pathways were used originally in the United Kingdom to develop a long-term tidal flood risk management plan for London and the Thames Estuary through the Thames2100 initiative (Reeder and Ranger 2012; McGahey and Sayers, 2008). The approach has also been used by New York City and New York State (Rosenzweig and Solecki 2014), piloted in Australia (Fisk and Kay 2010), and referred to in adaptation guidance produced by the New Zealand government (New Zealand Ministry for the Environment 2014).

Flexible adaptation pathways use a risk-based decision framework based on concepts of acceptable and unacceptable levels of risk, with the requirement that if adaptation is pursued, risk will be kept at an acceptable level (Moss and Martin 2012). The technique seeks to set thresholds that establish limits on the exceedance of pre-determined levels of risks that would lead to severe impacts and potentially irreversible consequences. Signposts are also established that help to assess information that should be collected to determine whether an adaptation plan is meeting the conditions for its success and if alternative adaptation pathways should be taken if thresholds are being neared (Haasnoot, 2013).

Low- and no-regrets adaptation actions can also be incorporated into planning using flexible adaptation pathways with the implication that these can be implemented now, while further research is conducted to enable informed flexible pathways to be established for longer-term aims.

Finally, a key benefit of the approach is that it is designed to be changed rather than a 'set and forget' approach, which simply plans for a single future outcome that ignores uncertainty.

The application of flexible adaptation pathways is particularly relevant for organizations and contexts where there is good understanding of risk management approaches (Moss and Martin 2012). Given the embedding of enterprise risk management and a strong engineering risk assessment culture, SoCalGas is ideally placed to test this approach.

2.5.3 Methodology for Adaptation Workshops

Two adaptation planning workshops were undertaken. The first focused on the natural gas sector and used a 'top down' multi-criteria approach for evaluating adaptation measures. The outcomes from this workshop informed the second workshop (held under a parallel study focused on electricity) that used a 'bottom-up' approach that drew from the skills and expertise of utility staff.

2.5.3.1 Workshop 1

The first workshop provided the opportunity to test a multi-criteria approach to align adaptation efforts with existing SDG&E/SoCalGas risk assessment and mitigation processes, and also explore how adaptation measures could be evaluated against a set of criteria. The research team based the adaptation measure prioritization process from the joint SDG&E/SoCalGas risk assessment processes outlined in the joint Risk Assessment and Mitigation Phase (RAMP) Report (Sempra Energy 2016). This allowed an explicit test of a system-wide, multi-criteria approach to identify and evaluate adaptation measures.

The research team first presented an overview of projected exposure and potential impacts across the SDG&E Service Area, then focused in on specific geographic areas and assets to help frame a more specific discussion around impacts. Using small-group breakout sessions organized around hazard types, workshop facilitators walked participants through exercises meant to evaluate a previously vetted set of adaptation measures based on impacts avoided, barriers to implementation, and a discussion on timing and urgency. The purpose was to test how feasible it was to further vet and rank potential adaptation measures for a theoretical situation.

The research team developed an evaluation matrix that directly employs the RAMP assessment criteria, scoring approach, and criteria weighting. This evaluation matrix allowed the rating of the relative priority impact avoided for each adaptation measure. These descriptions were used to craft exercises to evaluate adaptation measures from the perspective of impacts avoided.

To rate priority, the user selects the timeframe within which the adaptation measure should be implemented. The timeframe should be based on when the hazard will begin to induce impacts, when it would be feasible for the agency to undertake the measure, and the order in which the measures need to be implemented. The five timeframes discussed were: less than 2 years, 2 - 5 years, 6 - 10 years, 11 - 20 years, and beyond 20 years.

To rate impact avoided, the user uses SDGE'S RAMP impact matrix, which includes a seven-tier impact scale (*negligible* to *catastrophic*) and associated definitions for four impact criteria (Health, Safety, & Environmental; Operational and Reliability; Regulatory, Legal, & Compliance; and Financial).

2.5.3.2 Workshop 2

Integrating the lessons learned from the first workshop with SoCalGas, and working in consultation with SDG&E, Workshop 2 took a different approach for working through adaptation measures and approaches that were drawn from the expertise of workshop participants. Although this workshop focused on electricity assets, the approach tested could also have been applied to gas assets. This approach used a structured approach that drew from the knowledge and experience of SDG&E utility engineers, risk managers, and meteorologists regarding measures and approaches that are currently in place to manage climate-driven hazards, how these could be adjusted to integrate climate change factors, and what new adaptation options could be implemented.

The process adopted for the workshop first reviewed results of the climate change exposure and impact assessment undertaken through the project. Doing so enabled participants to be aware of the level and location of risks. The categorization of adaptation measures used in the study were then described, namely: Physical Protection; Operational Adjustments; and Recovery

Efforts. A small number of adaptation examples in each of these categories were presented as “thought starters” to help participants structure their ideas. Participants were then asked to record their initial proposals/ideas for adaptation measures on paper color-coded by: Generation; Transmission; and Distribution. This technique enabled adaptation measures from participants to be quickly captured and provide a structure for their subsequent analysis in small-group and plenary sessions.

Working on the elicited adaptation measures, workshop participants worked through structured discussion questions to discuss the feasibility and barriers to implementation. Finally, workshop participants were asked to provide input into the pathways to implementing adaptation measures discussed.

3: Findings

This section discusses the exposure results and corresponding potential impacts to natural gas infrastructure; these findings are organized by climate hazards, coastal hazards, wildfire, extreme heat, inland flooding, and landslides. This section also discusses potential *indirect* impacts, including economic impacts to customers and potential impacts to interdependent critical systems and customers. Finally, this section discusses potential flexible adaptation pathways that SoCalGas and other IOUs could follow in order to minimize the direct and indirect impacts.

As described in Section 2.3 Exposure Analysis, the potential impact analysis focuses on the mid-century scenario of 0.5 m (1.6 ft.) sea level, plus storm events, by around 2050 at SDG&E/SoCalGas’s recommendation.

3.1 Exposure and Direct Impacts

3.1.1 Overview

Overall, the natural gas system is likely to experience limited direct impacts from the climate hazards investigated. The relatively low level of system-wide impacts relates to limited projected exposure to climate change hazards, combined with relatively low system-sensitivity when exposure does occur. More specifically, the results indicate that impacts that do occur are likely to be localized and affect a small number of customers, or will be gradual repair/maintenance impacts – rather than widespread service disruptions. However, the fact that localized impacts could occur, and that maintenance and repair costs could rise indicates a need for adaptation measures in order to ensure continued resiliency of the system into the future.

The projected exposure assumes that no adaptive measures are taken by organizations with coastal management responsibilities, such as city governments. Such adaptive measures could include implementing enhanced beach nourishment or upgrading protection measures as sea levels rise. The research team decided to assume no such third-party adaptive measures are implemented to ensure that a full picture of potential exposure is provided. This allows for exploration of gas asset exposure to coastal climate change hazards should other parties fail to implement adaptive measures due to funding constraints, policy limitations, or other reasons.

Table 3 summarizes the potential climate change impacts, by hazard, facing the natural gas system in the SDG&E Service Area.

Table 3. Overview of Potential Impacts, by Hazard

Hazard	Overview of Potential Impacts
Coastal Hazards	A large number of assets potentially exposed, but overall pipelines are not considered highly sensitive to coastal hazards, particularly coastal wave flooding and coastal inundation hazard. Water crossings represent the assets where impacts are most likely to occur, although sensitivity is still considered fairly low. Coastal erosion could cause physical damages, but exposure is limited. Large number of service connections in projected exposure zones could result in costs to utility to either repair damaged connections and to reconnect customers, or cap ones that become abandoned.
Wildfire	Infrastructure generally has low projected exposure and sensitivity. The most significant impacts from wildfire could be from the costs associated with restoring service connections after wildfire events.
Extreme Heat	Infrastructure overall has low projected exposure and sensitivity. Impacts could be experienced in the form of additional cooling costs for compressor stations, increased wear and tear on compressor equipment, and outdoor worker safety precautions.
Inland Flooding	Pipelines are generally not very exposed or sensitive, and overall impacts are expected to be low, but could increase if flooding increases in the future. Two major transmission assets are in flood zones, as well as two regulator stations serving populous areas. Water crossings also represent assets that are likely to be impacted, although sensitivity is still considered to be fairly low.
Landslides	Again, there is an overall low system exposure and limited potential impacts. Landslides are currently uncommon, but may change in both frequency and extent in the future due to changes in extreme precipitation. Landslides tend to affect only a small number of customers, but when this occurs impacts are significant.

Although system-wide impacts are expected to be low overall, it is important to note that there is limited redundancy in some aspects of supply. If a major transmission line, or a compressor station, became inoperable, a large number of customers could be temporarily affected. Thus, although the exposure and sensitivity of the natural gas system tends to be low, the adaptive capacity of the natural gas supply network is low in some areas. Section 3.3 explores appropriate measures to increase resiliency, which could include efforts to make the supply network more resilient.

It is also important to note that SoCalGas is well-equipped to handle many of these hazards, given today's exposure. The utility's existing processes and risk management measures designed to mitigate the impacts of current levels of climate risks may also help to mitigate impacts as the climate changes. However, the potential for impacts will increase as the climate changes, making exposure to these hazards more frequent and/or severe. Section 3.3 explores opportunities for ensuring the natural gas system stays resilient to these hazards as the climate changes.

The subsections below provide more detail about the potential impacts from each climate hazard.

3.1.2 Coastal Hazards

The research team evaluated the coastal hazards of coastal wave flooding, coastal erosion, and tidal inundation (Figure 4, below). The team modeled sea level rise exposure for two scenarios, namely 0.5 and 2.0 m (1.6 and 6.6 ft.) of global sea level rise, and both 1-year and 100-year storm events. For the purposes of discussing impacts, the workshop and this analysis focus on the mid-century scenario of 0.5 m (1.6 ft.), plus storm events, by 2050 at SDG&E/SoCalGas's recommendation because: (1) planning horizons generally do not go beyond mid-century and (2) the energy systems – including supply, demand, and infrastructure – are likely to change significantly by end-of-century, so SDG&E and SoCalGas stakeholders stressed that it is difficult to draw conclusions today about what impacts could occur by end-of-century.

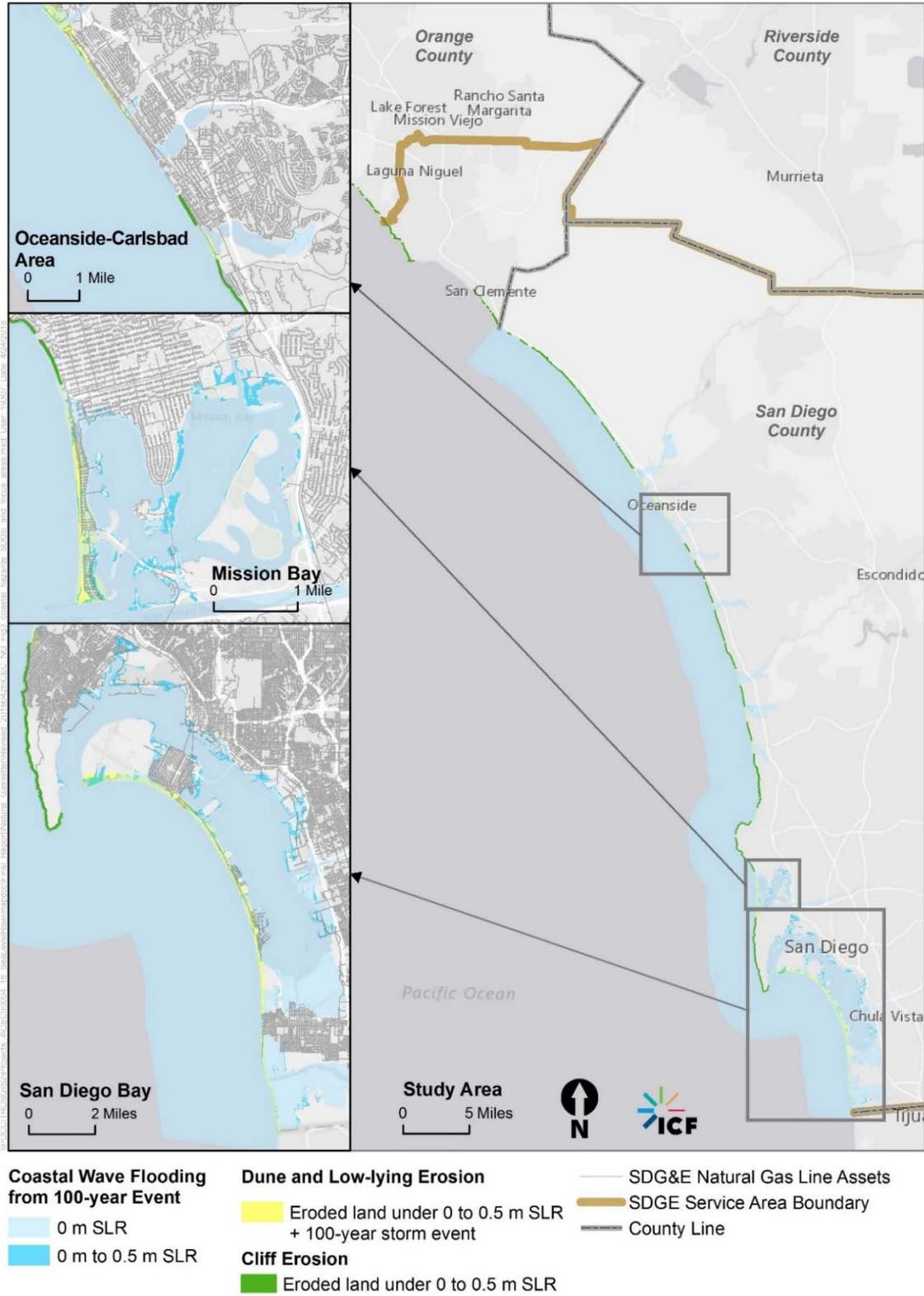


Figure 4. Natural gas line assets and coastal hazards analyzed in the SDG&E Service Area.
Sources: SDG&E and SoCalGas; USGS; SPAWAR; ESRI

Because SoCalGas natural gas assets are concentrated along coastal areas, a large number of assets are projected to be exposed to coastal hazards, particularly coastal wave flooding. The greatest exposure occurs around bays and inlets where there is significant development in low-lying coastal areas. However, even in exposed areas, SoCalGas indicates that they believe coastal hazards will have limited impacts on the natural gas system. The impacts are expected to be low overall at a system level, but still existent, because pipeline infrastructure is not very sensitive to coastal flooding given that the pipelines are both buried and pressurized. Water crossings are among the more sensitive types of infrastructure, and the utility could incur costs associated with repairing damaged, or capping abandoned, service connections due to coastal exposure. There are significantly fewer gas assets exposed to coastal erosion and the number of erosion-exposed assets is also greatly reduced in scenarios with erosion control (i.e., armoring in the 'hold the line' scenario). Importantly, assets exposed to erosion could experience physical damage, potentially creating service disruptions.

These potential impacts associated with pipelines, regulators, buildings, and service connections are described in the subsections that follow. As noted previously, projected information for some coastal hazards was not available for Orange County; the results presented here are for the study area (i.e. San Diego County) rather than the full SDG&E Service Area.

3.1.2.1 Pipelines

A singular transmission line running from Los Angeles to San Diego is a major pipeline asset that is potentially exposed to projected coastal hazards. Not only is it potentially exposed at various points to all of the coastal hazards modeled, it is also one of the oldest pipelines in the network. It runs right along the coast, along the back of the beach and along the coastal roadways. It is an important pipeline because it serves the coastal beach communities along about half of the San Diego coastline. While many service connections and customers depend exclusively on this transmission line for gas supply, SoCalGas and SDG&E consider this line to have low sensitivity overall. The line is backfed (i.e., supplied from both northern and southern ends), which would limit service disruptions if segments of the line were damaged. To create a disruption or failure in part of the line, the pipeline would need to be damaged and then have saltwater covering it – a combination of events considered unlikely by the research team (though the probability increases as sea level rises).

Most coastal aboveground pipelines are unlikely to be adversely affected by exposure to saltwater during wave run-up events due to their flexibility, being made of material not affected

Coastal Impacts Summary

Pipelines: Overall, impacts are expected to be low (though risk could increase) for both belowground and aboveground pipelines since they are not very sensitive to water. Water crossings are where the pipelines are most sensitive.

Regulators: Overall, impacts expected to be low.

Buildings: Older buildings more likely to experience impacts because of older building codes. Upcoming new building codes will account for sea level rise, but it's unclear whether or not these codes will be sufficient for the specific exposure modeled in SDG&E Service Area.

Service Connections: Where periodic flooding may occur, the utility may incur costs to repair/replace service connections. If buildings relocate out of flood zones, utility will incur costs to cap the connection. The large number of connections gives potential for significant costs to the utility.

by corrosion (i.e., plastic) or steel with protective coating. Furthermore, SoCalGas and SDG&E have internal operating procedures that seek not to depressurize pipelines during flood events, which have caused water to infiltrate the natural gas system during flood events as experienced by utilities in other parts of the country.

However, pipelines that run along bridges, such as those that cross lagoons, may experience negative impacts. SoCalGas highlighted that aboveground river crossings are among the natural gas assets that are most sensitive to coastal hazards. Should sea level rise to the height of the pipelines, the water may cause the pipelines to float along the bridge, damaging the hangers. In addition, the bridge structures on which the pipes are mounted may experience damage that would, in turn, impact pipeline integrity. Currently, there are 0.91 mi. of pipeline (1.46 km, and <0.01% of pipeline in the study area) attached to bridges and potentially exposed to coastal inundation. Exposure is projected to increase slightly (by 0.02 mi. or 0.03 km) by mid-century, and by 0.20 mi. (0.32 km) between mid- and end-of-century. At current and mid-century sea levels, 0.8 mi. (1.3 km) are potentially exposed to annual tidal flooding and 0.9 mi. (1.4 km) are potentially exposed to 100-year event coastal wave flooding. At end-of-century sea levels, 0.9 mi. (1.4 km) are potentially exposed to annual tidal flooding and 1.1 mi. (1.8 km) are potentially exposed to 100-year event coastal wave flooding. At all time periods (present day, mid-century, and end-of-century) and for both annual and 100-year event flooding, approximately 60% of potentially exposed pipelines are high pressure and approximately 40% are medium pressure.

While coastal belowground pipelines may be exposed to saltwater inundation, they are unlikely to experience negative impacts from limited saltwater exposure as they are primarily composed of plastic and cathodically protected steel, unlike older systems which are primarily bare cast iron. Liquefaction from saltwater intrusion is not believed to negatively affect the pipelines as they have a degree of flexibility and historically have not failed due to liquefaction with the exception of intense liquefaction induced by earthquakes. However, it is worth noting that some recent research indicates that rising sea levels and the associated effect of raising water tables in coastal areas could increase the effect of earthquake liquefaction along coastal areas.⁸ There is limited research on the extent to which this is a risk in the San Diego area, and more research on the topic may be warranted.

The coastal hazard impacts identified in this study generally align with those identified by Radke et al. (2017). Radke et al. (2017) focus on pipeline vulnerability to SLR and storm surge, and determine that inundation may damage pipelines through erosion, scouring, and debris flow, as well as corrosion, impeded access, and increased hydrostatic load. However, this study does not identify hydrostatic load as a probable 21st century impact as SDG&E and SoCalGas indicated that their pipelines can withstand pressure from over 10 ft. of inundation, a height which exceeds all but the most extreme sea level scenario considered plausible by 2100 (OPC 2018, Pierce et al. 2018).

The characteristics which heighten pipeline impacts from coastal hazards identified by this study also generally align with those identified by Radke et al. (2017). For instance, both studies conclude that pipelines nearby waterways are generally most susceptible to impacts from

⁸ For example: Risket et al. 2015; SF BCDC 2011; Mimura 2013

inundation, that older pipelines are more susceptible to damage, and that increased burial depth reduces risk of damage from erosion or scour.

3.1.2.2 Regulators

Between now and mid-century, there are two aboveground regulators exposed to coastal hazards, both of which are in the San Diego Bay area, as shown in Figure 5, below. Under current sea levels, one is potentially exposed to 100-year event coastal wave flooding, and the other is potentially exposed to dune erosion. Under mid-century sea levels (0.5 m or 1.6 ft. SLR), one is potentially exposed to annual tidal wave flooding, and the other is potentially exposed to 100-year event coastal wave flooding. Because this infrastructure tends to be more mechanical than electrical in nature, it can withstand temporary exposure, though some parts may experience more corrosion and thus need more frequent repair or replacement.

Belowground regulators are in vaults and water can accumulate after rain events which is a common problem when performing maintenance as the regulator stations do not have installed dewatering systems. However, regulators are mechanical. Thus, temporary exposure to inundation is not likely to cause significant impacts. The release valves are designed to address temporary flood events but are not designed to address instances where the regulators are in permanent inundation zones. Furthermore, long-term exposure to saltwater can lead to corrosion and thus increased maintenance needs. Currently, there are two belowground regulators that are projected to be exposed to 100-year event coastal wave flooding. By mid-century, this number triples so that six could be exposed to 100-year event coastal wave flooding, and two could be exposed to low-lying erosion.

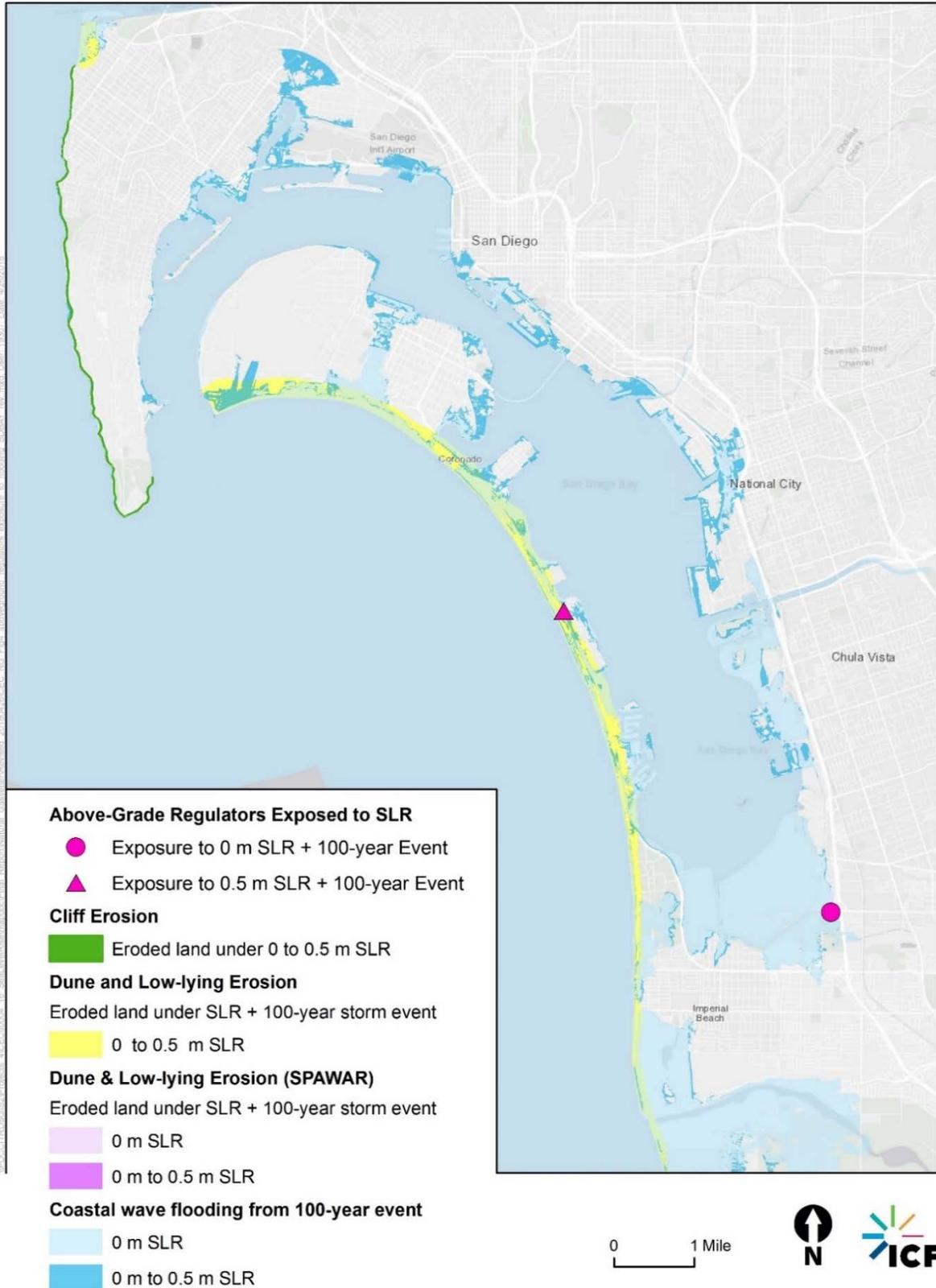


Figure 5. Aboveground regulators exposed to 100-year coastal wave flooding. Sources: SDG&E and SoCalGas; USGS; SPAWAR; ESRI

3.1.2.3 Buildings

SDG&E and SoCalGas representatives indicated that newer above-ground building assets are less likely to be adversely affected by sea level rise than older buildings. This is because American Society of Civil Engineers (ASCE) building codes have been, and will continue to be, periodically updated. These ongoing updates to buildings codes will mean that as new buildings are built, they may partially adjust to slow-changing hazards such as sea level rise. Currently, the ASCE building code standard requires that a building be built to withstand an event of magnitude mean plus one standard deviation, and the FEMA standards require that buildings be able to withstand present day one-in-100 year events. Older buildings would have been built to older standards less equipped to deal with the rising sea levels.

Neither the ASCE nor the FEMA codes, however, proactively account for sea level rise in building design, and it is not clear how the buildings built to these standards would fare in the face of sea level rise. Future infrastructure may be subject to guidance that is currently under development by the State of California per AB 2800, which will create recommendations for integrating climate change considerations into planning, designing, building, operating, maintaining, and investing in state infrastructure. AB 2800 guidance will include climate change needs for building codes that, if incorporated into code updates, would exceed the current standards (CA-AB 2800 2016). The AB 2800 recommendations are currently in the process of development; however, an example of building design guidelines that incorporate sea level rise and climate change considerations can be found in New York City's Climate Resiliency Design Guidelines. The Guidelines, developed in response to Hurricane Sandy, provide step-by-step instructions for incorporating climate model projections into the design of New York City capital projects (NYC Mayor's Office of Recovery and Resiliency 2018). It is important to note that the utility in this study could voluntarily exceed design standards if it felt the additional cost would be justified and suitable revenue sources identified; this is an area where additional research into the efficacy of any new design standards is needed given the projected climate hazard exposure in the SDG&E Service Area.

3.1.2.4 Service Connections

The exposure analysis indicates that several thousand service connections (i.e., connections to houses or businesses) could experience permanent or temporary inundation due to sea level rise, or be subject to coastal erosion. Currently, there are 2,934 and 5,197 service connections in the annual tidal inundation and 100-year coastal wave flooding zones, respectively; these values represent 0.4% and 0.6% of service connections within the study area, respectively. These numbers increase 29% and 51%, so that by mid-century, 4,432 service connections could be exposed to annual tidal inundation (a proxy for near-permanent inundation) and 6,695 could be exposed to a 100-year coastal wave flooding (representing 0.5% and 0.8% of the study area's service connections). Currently, no service connections are in the erosion zones, but by mid-century, 8 service connections could be subject to cliff erosion, and 3,425 and 3,862 service connections could be subject to low-lying erosion during the 1-year and 100-year events, respectively (these values represent 0.001%, 0.4%, and 0.5% of the study area's service connections). Practically, this means that thousands of customers have service connections that could be impacted by these coastal hazards by mid-century.

This exposure could result in cost impacts to the utility. Where only periodic flooding occurs, building owners may choose to repair/rebuild after events, meaning the service connections will still be needed but will need to be repaired after each event if damaged, incurring costs to the utility.

Over the long-run, customers may either implement adaptation measures to avoid inundation or relocate, rendering the service connections no longer necessary. That is, if a building is unable to continue to exist in a coastal location, then the utility will not need to ensure natural gas service to that building; meanwhile, if the building owners take adaptive measures (such as building flood barriers), then those protective measures may well protect the gas infrastructure as well. However, in cases where service connections are no longer needed, they must be capped or removed, which represents a cost to the utility.⁹ There are a large number of service connections in the exposure zones.

3.1.3 Wildfire

The research team determined the natural gas asset exposure to future wildfire hazards by considering projected change in the area burned

(Figure 6 showing the model ensemble average, Figure 7 showing the minimum model, and Figure 8 showing the maximum model, below) and existing fire fuel by vegetation type (Figure 9, below). Natural gas assets are primarily located toward the coast.

However, the most intense increases in wildfire area burned are projected to occur inland. Furthermore, aboveground assets are primarily located in urbanized areas, which tend to have lower wildfire risks to begin with (though those risks still exist, as evidenced by the 2017 Santa Rosa fire). Thus, overall, the natural gas system will likely experience limited impacts from increases in future wildfire because much of the system is underground (where it is not exposed to wildfire) and near the coast (where increases in wildfire are projected to be less intense).

The primary assets of concern are the meters or service connections, which are almost always aboveground.

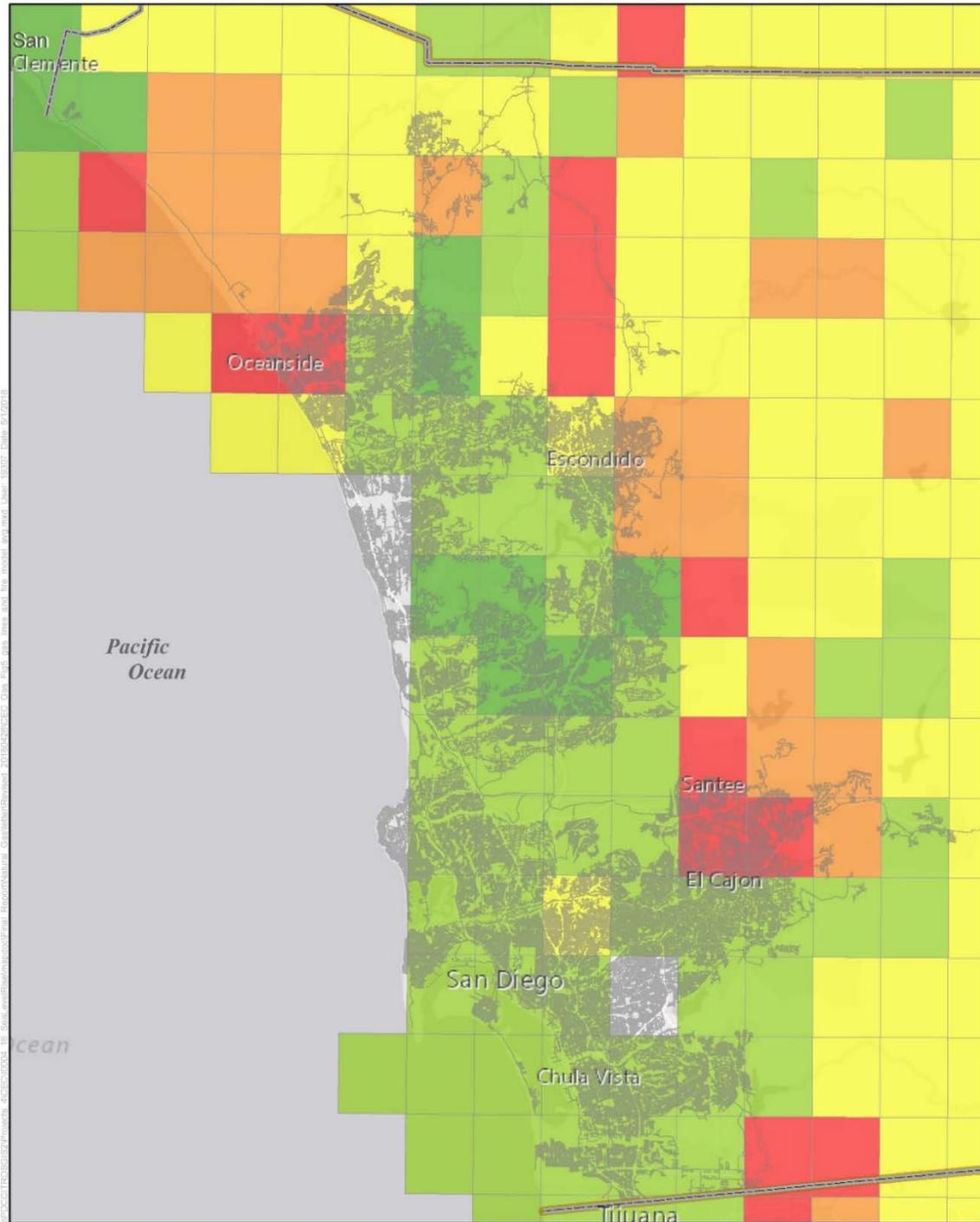
Wildfire Impacts Summary

Aboveground Pipes: Low impacts anticipated due to low exposure and sensitivity.

Regulators: Low impacts anticipated due to low sensitivity and low number of customers served by exposed aboveground regulators.

Meters: Costs to restore service to customers when wildfire damages customer buildings. Service restoration can be time consuming.

⁹ The research team was unable to quantify the cost of capping or removing the service connections, as costs are not tracked in this manner.



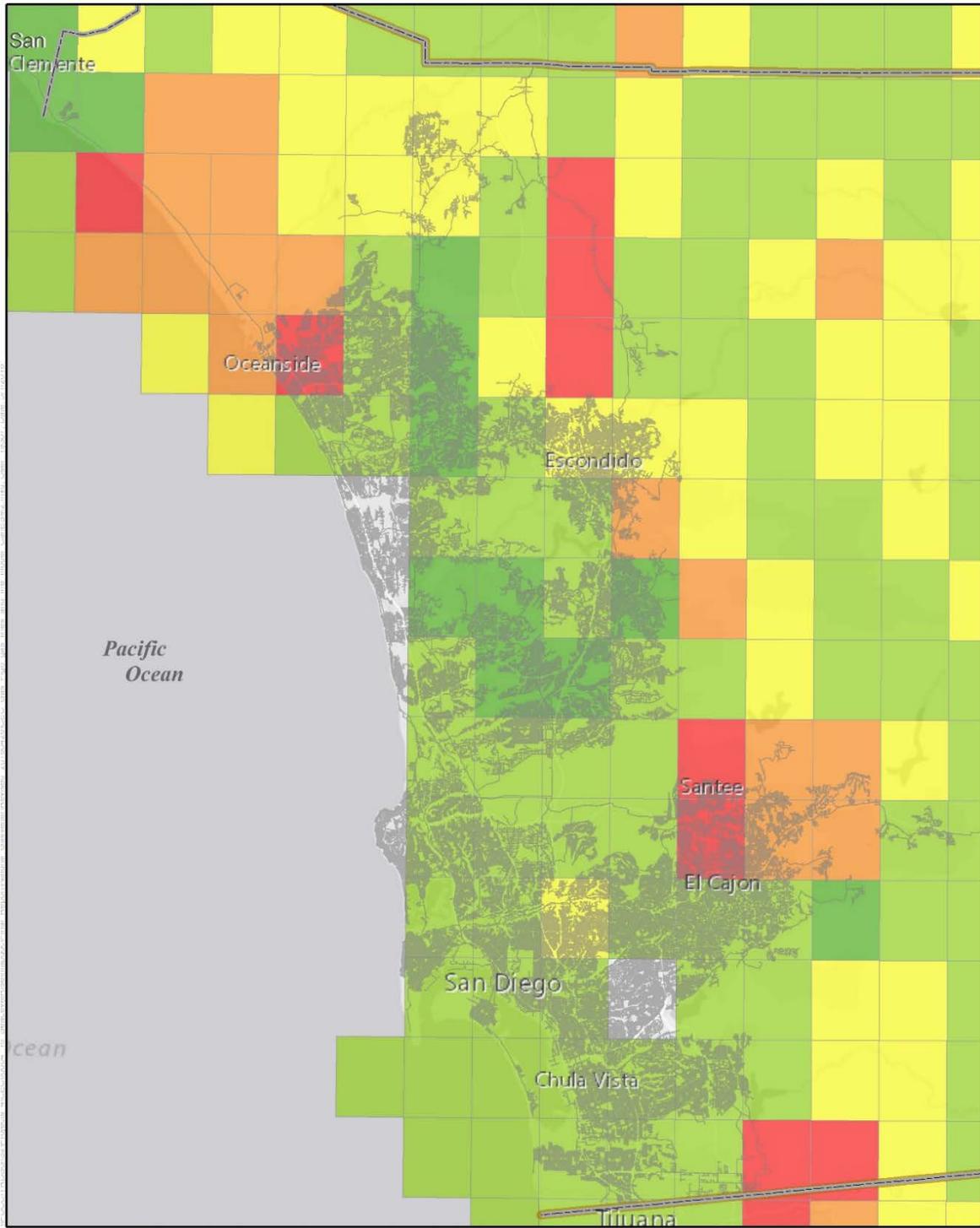
Projected Change in Area Burned (hectares): Average

- -35.0 - -15.0
- - 15.0 - 0.0
- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 27.0

- Natural Gas Line Assets
- County Line
- SDG&E Service Area Boundary

0 5 Miles

Figure 6. Projected change in area burned (model ensemble average) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI



Projected Change in Area Burned (hectares): CanESM2

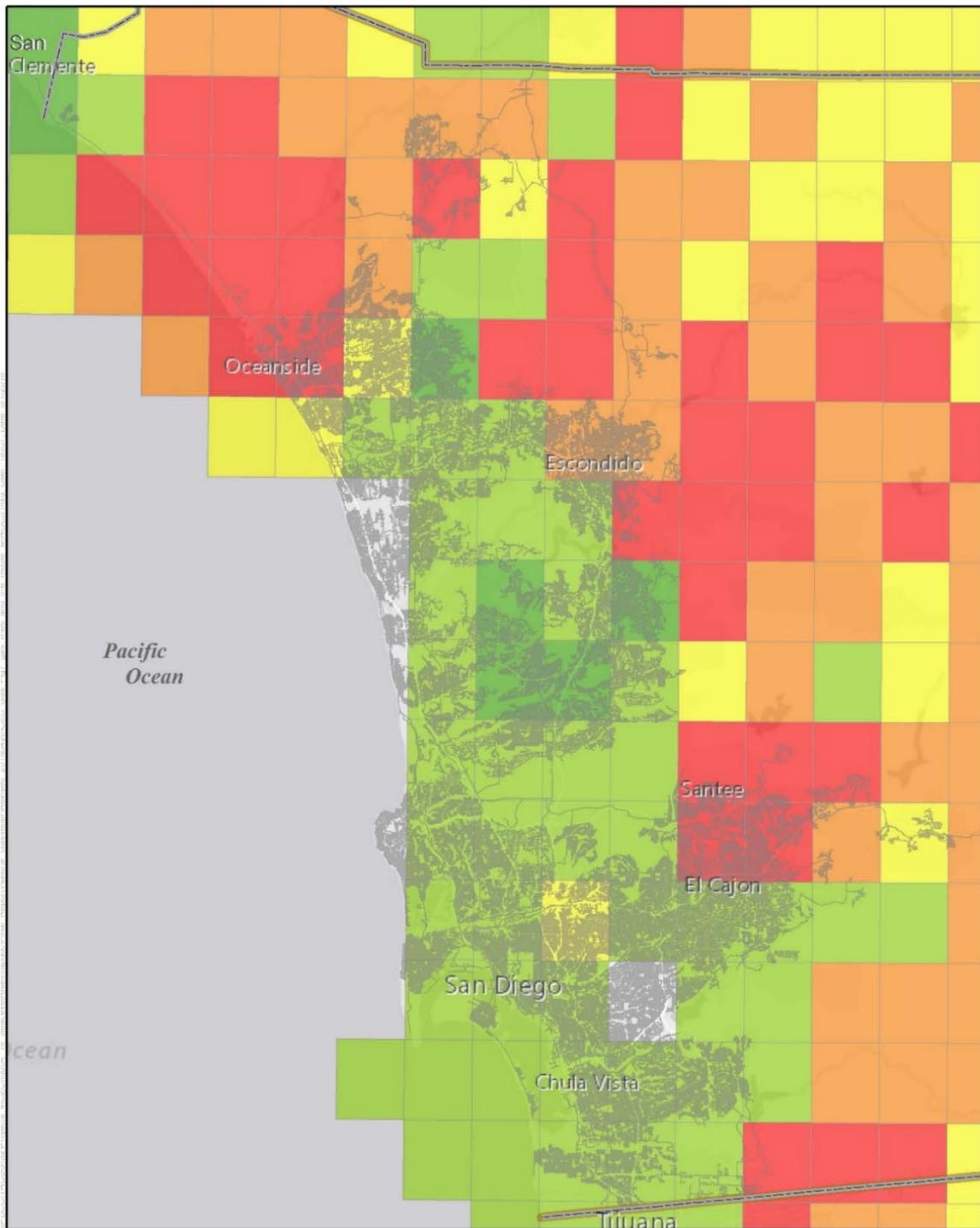
- -38.0 - -15.0
- -15.0 - 0.0
- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 29.0

- Natural Gas Line Assets
- County Line
- SDGE Service Area Boundary

0 5 Miles



Figure 7. Projected change in area burned (minimum model projected, CanESM2) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI



Projected Change in Area Burned (hectares): MIROC5

- -31.0 - -15.0
- -15.0 - 0.0
- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 26.0

- Natural Gas Line Assets
- County Line
- SDGE Service Area Boundary

0 5 Miles



Figure 8. Projected change in area burned (maximum model projection, MIROC5) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

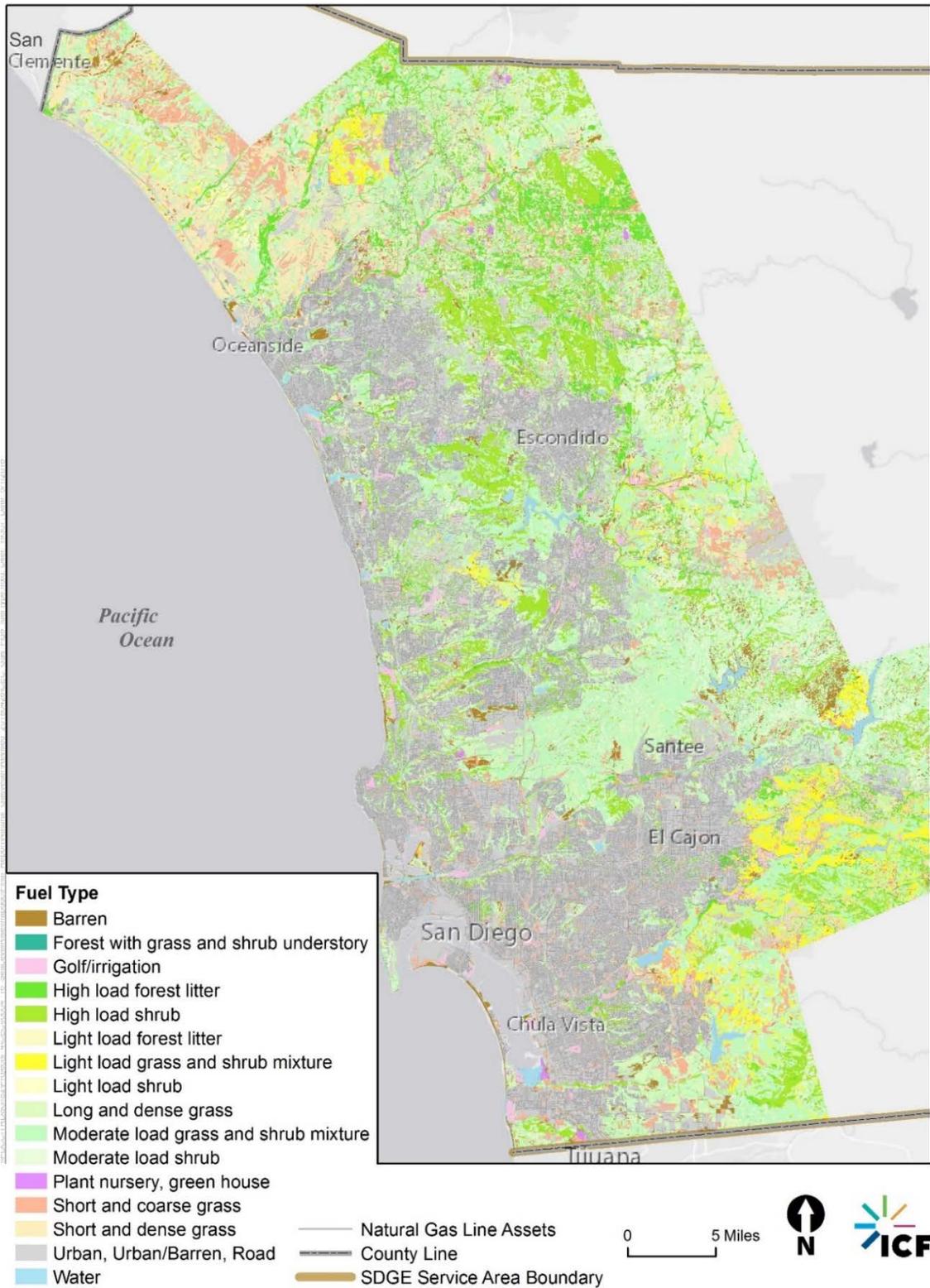


Figure 9. Fuel type and natural gas line assets in the SDG&E Service Area. Sources: SoCalGas; SDG&E; ESRI

3.1.3.1 Aboveground pipes

Aboveground pipes are almost always steel, which is naturally resilient to high temperatures. Where needed, such as in wildfire-prone areas – additional coatings are applied to the pipelines to make them more resilient to atmospheric corrosion. Sometimes, pipelines are run across deep canyons by using cable bridges. These bridges are more susceptible to wildfire impacts because they are very sensitive to stress yields; however, SoCalGas reports that such cable bridges are designed to withstand wildfires through selection of appropriate steel grades and the addition of corrosion resistant coatings.

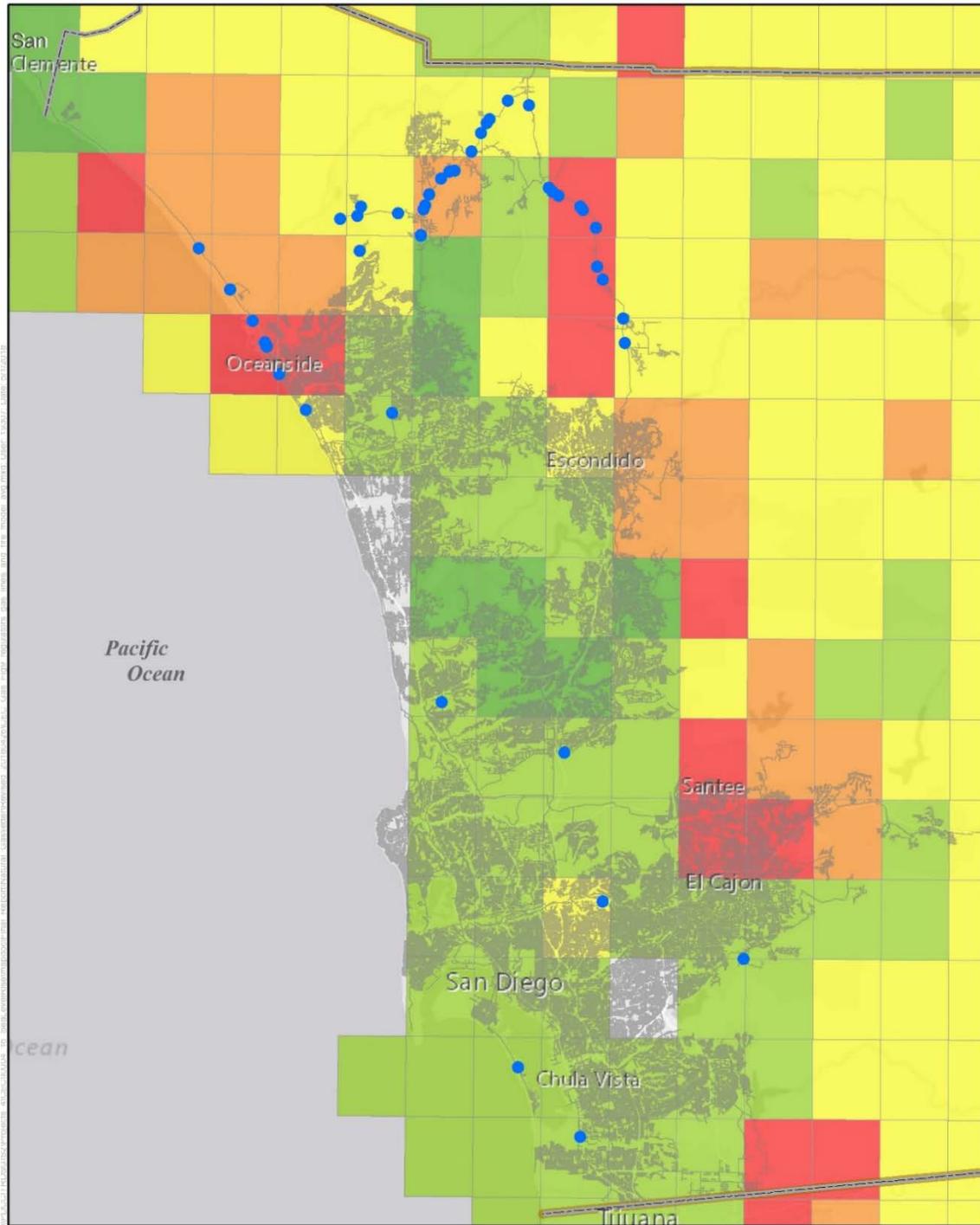
3.1.3.2 Regulators

There are 38 aboveground regulators (representing 6% of SDG&E Service Area regulators) located within grid cells that are projected to experience an increase in area burned, depicted in Figure 10, below. Of these, approximately one quarter (22 to 30%¹⁰) lie within areas that are projected to experience no change or a decrease in annual area burned by wildfire. Regulator stations are critical assets, as they connect the transmission system to the distribution system.

Aboveground regulator stations may experience diaphragm¹¹ failures during wildfires, which could impact a large number of customers. However, nearly all (37 of the 38) are in the northern areas of the Service Area where they serve a relatively small number of customers. Moreover, the utility reports almost no history of damage to regulators due to wildfire, in large part because of vegetation control practices which drastically limit the amount of burnable material around the regulator stations; thus, fires rarely reach the stations. Also, most aboveground equipment is situated on concrete pedestals, which are heat resistant. Finally, the utility makes use of isolation valves that allow isolation of natural gas infrastructure if there is a fire so that there is not infrastructure aboveground that is full of natural gas near a wildfire. In addition, regulator station design calls for shutoff valves both upstream and downstream of the regulator station in the case that an emergency shutdown is required (SoCalGas, Personal Communication).

¹⁰ Range reflects range of model projections. Minimum reflects CNRM-CM5 (cool/wet) while maximum reflects MIROC5 (complement).

¹¹ Diaphragms are a component of regulators. They reduce unbalanced forces acting on the valve plug, thereby increasing the accuracy and sensitivity of the regulator's response to pressure changes. If diaphragms are damaged, the regulator may not be able to control the pressure of the gas being delivered. Importantly, each regulator station has two regulators that control the flow of gas. For a station to fail or to cause over pressure both regulators would have to fail.



Projected Change in Area Burned (hectares): Average

- -35.0 - -15.0
- - 15.0 - 0.0
- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 27.0

- Above Grade Regulator
- Natural Gas Line Assets
- County Line
- SDGE Service Area Boundary

0 5 Miles

Figure 10. Aboveground regulators and projected change in area burned. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

3.1.3.3 Meters and Service Connections

Meters are almost all aboveground, and would be damaged if exposed to wildfire. However, the damage would affect service only to the customer served at that meter point. Furthermore, if the meter is damaged, the adjoining structure will also likely be damaged, meaning the customer may not need service until the structure can be repaired or rebuilt after the fire.

However, restoring service can be time consuming, and could represent a significant cost to the utility when a large number of service connections are shut off or damaged, and could potentially disrupt service to affect customers for weeks.

If a home is significantly damaged by fire, the meters are damaged and the utility must physically cut and cap the pipeline running to that house. The pipelines are excavated at the property, but will then need to be replaced once the house is rebuilt. In some cases, the utility will isolate the gas main that shuts down gas service to an entire street by using valves or cutting it off in one spot on the gas main. However, to bring the main line back into service, the individual homes will have to be disconnected and then reconnected to the main. Once gas must be shut off, additional customers are typically impacted, as each customer typically does not have a unique shut off valve. Communities with a large number of newer homes are less sensitive, as homes built within the past 10 years typically have a unique shut off valve.

Shutting off gas can also stress operations, as restoring service is time consuming, requiring that the utility purge the system of air, introduce gas or nitrogen slug, and restore service one connection at a time. This requires a significant amount of time and planning, depending on the size of the area. In some cases, it can take multiple weeks to completely restore service. Thus, one of the most notable sensitivities of the utility to wildfire is the cost and time of the workforce to restore service.

Wildfires can also burden operations by causing customers to preemptively shut off gas. This requires that utility staff go to each house to restore gas and check appliances.

As wildfire increases in the future, the utility may experience increased costs to restore service. Also, additional planning may be necessary to ensure it can effectively and quickly deploy crews to restore service after wildfire events.

3.1.4 Extreme Heat

The research team analyzed the projected change in days exceeding the extreme heat threshold. Although some areas may experience significant increases in heat, the greatest increases are projected to occur inland, where gas infrastructure is more limited. Most assets (around 55% of point assets and line asset length) are projected to experience a 5 to 10 day increase in extreme heat days per year, and around 20% of point assets and line asset length are projected to experience a 10 to 15 day increase in extreme heat days per year.

Overall, the infrastructure is expected to not experience significant increase in impacts due to low exposure and low sensitivity. The utility may

Extreme Heat Impacts Summary

Infrastructure: Limited impacts expected. Some increased wear-and-tear on equipment.

Operations: Potential for increased costs to adequately cool compressor stations, and costs associated with outdoor worker safety.

experience some cost impacts related to operations, specifically costs related to compressor station cooling and worker safety.

Although much of the natural gas infrastructure is not likely to experience direct impacts from extreme heat, the utility could still experience *indirect* impacts from the effects of extreme heat on natural gas demand, which are discussed in Section 3.2.

3.1.4.1 Infrastructure

Much of the natural gas system is underground and coastal, whereas the greatest potential heat increases are expected to occur inland, where there is limited infrastructure, as depicted in Figure 11, below. Furthermore, the infrastructure itself is not very sensitive to heat impacts.

Therefore, the projected increases in heat are not likely to have a significant direct impact on natural gas infrastructure.

Some impacts may occur in the form of wear-and-tear in compressor stations. Natural gas density is likely to decrease due to warmer temperatures, reducing the energy intensity of a given volume of natural gas, and increasing the volume of natural gas that must be delivered to meet demand (FHWA 2014). The required additional throughput causes more wear and tear on compressor equipment, which can shorten equipment lifespan.

3.1.4.2 Operations

Natural gas system operations may experience a number of direct impacts from extreme heat. For instance, compressor station buildings – many of which are located in the inland areas expected to experience more dramatic increases in heat – are likely to experience increased space cooling and decreased heating requirements. Thus, there may be increased energy costs to run the building cooling systems, as well as additional costs to upgrade systems that are not sufficient for the projected temperatures. Meanwhile, outdoor workers are likely to require more frequent breaks to prevent heat exhaustion and dehydration.

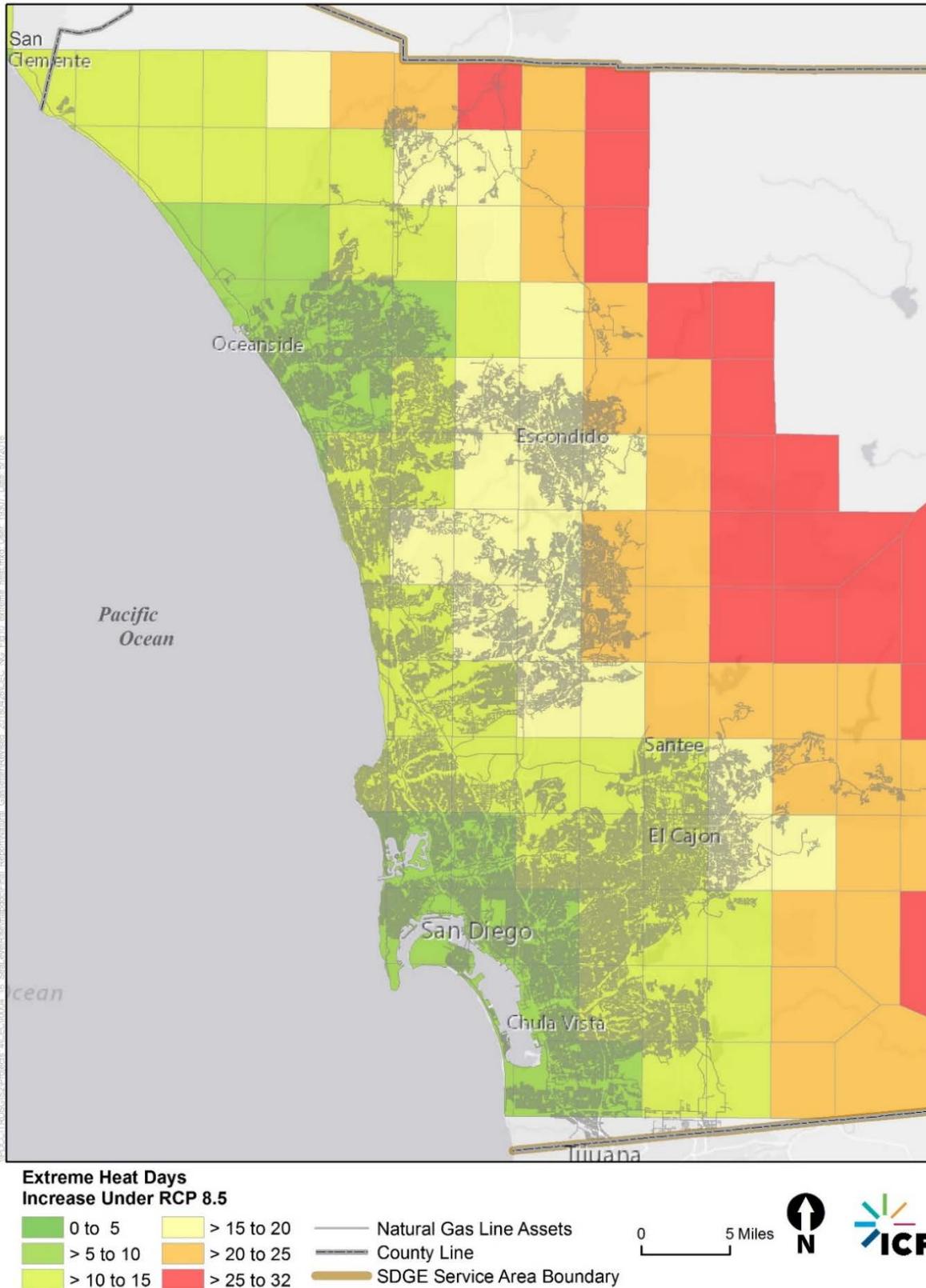


Figure 11. Projected change in extreme heat and natural gas line assets in the SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

3.1.5 Inland Flooding

The research team used the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) Flood Insurance Rate Maps (FIRM) for 100-year and 500-year floods to analyze gas asset exposure to inland flooding.¹² The exposure modeling indicates that only 5% of natural gas assets in the SDG&E Service Area are in flood zones; however, two critical transmission assets pass through these floodplains. Note that since projection information was not available for how these floodplains may change in the future, this report is not able to quantify the extent to which this exposure may increase in the future.

The research team used the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP) Flood Insurance Rate Maps (FIRM) for 100-year and 500-year floods to analyze gas asset exposure to inland flooding. The exposure modeling indicates that only 5% of natural gas assets (48,000 point assets and 860 mi. of line length) in the SDG&E Service Area are in flood zones; however, two critical transmission assets pass through these floodplains, and a number of distribution assets are also located in these floodplains. Note that since projection information was not available for how these floodplains may change in the future, this report is not able to quantify the extent to which this exposure may increase in the future.

Overall, the impacts from inland flooding (assuming current floodplains are a reasonable proxy for future flood areas) are expected to be low, since much of the system is underground, and even the aboveground assets have limited sensitivity to flood events. The assets most likely to experience damage are the water crossings. It is worth noting, however, that although direct impacts may be low, there is a potential for more significant indirect impacts if supply were to be disrupted. Potential indirect impacts are discussed in Section 3.2.

3.1.5.1 Pipelines

Because much of the natural gas system is underground, it is somewhat protected from still-water inland flooding. The primary way inland flooding could impact natural gas infrastructure in the SDG&E Service Area is by causing damage at water crossings.

For example, flooding can lead to scouring at water crossings, which can uncover and expose underground pipelines. Exposed pipelines are more sensitive to damage from scouring or washouts, flotation, and damage from debris and other objects carried by the flood waters. Dry and sandy soils are particularly susceptible to scouring during flooding events (FHWA 2014). There are at least 13 pipelines which are buried underneath rivers, one of which is capped by concrete.

Inland Flooding Impacts Summary

Pipelines: Low impacts overall due to low sensitivity. Water crossings most likely to experience impacts.

Regulators: Low impacts due to low exposure and sensitivity.

Other: Potential impacts from disruptions to communication systems or accessing right-of-ways, but impacts expected to be low overall.

¹² Changes to the floodplains due to climate change are unknown at this time. Thus, the current floodplains are used as a proxy to estimate potential extent of exposure.

In the SDG&E Service Area, there are at least 32 aboveground pipelines attached to or under bridges at water crossings; flood events can scour and cause other damage to those bridges, causing an indirect risk to the pipelines if major damage to the bridge would occur.

Even less major scour events could have impacts on service; although the utility does not maintain bridges, it may need to temporarily suspend service at a bridge to accommodate bridge repairs. The utility currently has a Flood Evaluation project evaluating pipelines located at select river crossings, with the purpose of identifying and mitigating potential impacts before they become a problem.

One important asset which passes through 100-year floodplains is a transmission main in Escondido. Within these floodplains, the line also crosses Escondido Creek and Lake Hodges. The line is directionally drilled beneath Lake Hodges, and due to the depth at which it is buried beneath the lake, it is unlikely to be scoured. Another critical transmission asset is located in FEMA Zone D, which is considered an “undetermined but possible flood hazard” zone. Within this zone, the line also crosses Los Flores Creek, San Onofre Creek, San Mateo Creek, and San Juan Creek. At these crossings, buried segments of the pipeline could experience scouring and subsequent direct damage from debris carried by floodwaters, and those that are attached to bridges could become buoyant due to flood waters and cause hanger damage and become exposed to damage from debris within floodwaters.

3.1.5.2 Regulators

Aboveground regulator stations may experience diaphragm failures during flooding events, which could impact a large number of customers. However, only a small percentage of regulator stations are aboveground. Of those, two are within a 100-year floodplain, and eight are within an area of FEMA Zone D “undetermined but possible flood hazards”, as shown in Figure 12, below. The majority of these ten regulator stations are in the northern areas of the Service Area where they serve a small number of customers. However, one of the regulators in the 100-year floodplain and one of the ones in FEMA Zone D are located in the more populous areas of Imperial Beach and Coronado. As the inland flooding risk increases in the future, these populous areas may face an increased risk.

Belowground regulators, as noted in the section on coastal hazards, are in vaults and are generally protected. Most have pumps to keep out any water that may seep in, and the mechanical (not electrical) nature of the regulators means they have low sensitivity. However, pumps can theoretically fail, which would leave the regulator stations susceptible to inundation, and long-term exposure can lead to corrosion and increased maintenance needs.

Overall, impacts are expected to be low, but the risk could increase as flooding increases in frequency or in geographic reach.

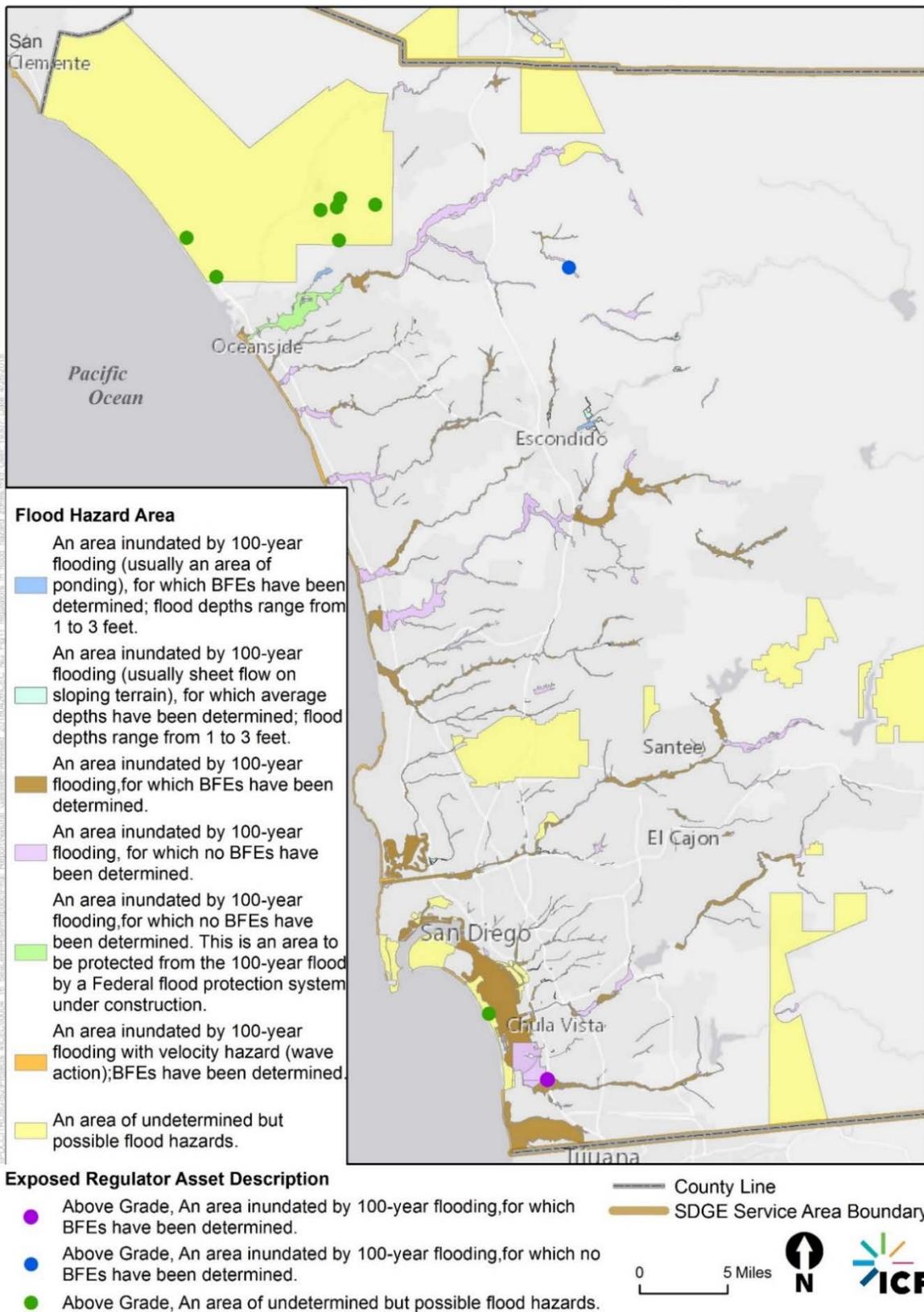


Figure 12. Aboveground regulators in flood hazard areas. Sources: SDG&E and SoCalGas; FEMA; ESRI

3.1.5.3 Other

In general, there are several other types of direct impacts that could occur. Communication, monitoring, and electronic systems may be disrupted during floods, negatively affecting operations (FHWA 2014). In addition, flooding can prevent access to right of ways or temporarily close roads and thus inhibit workers from accessing areas they need (FHWA 2014). However, there is no history of significant impacts from such events, and engagement with SDG&E and SoCalGas did not uncover anything to indicate that the potential impacts from such disruptions will be particularly significant.

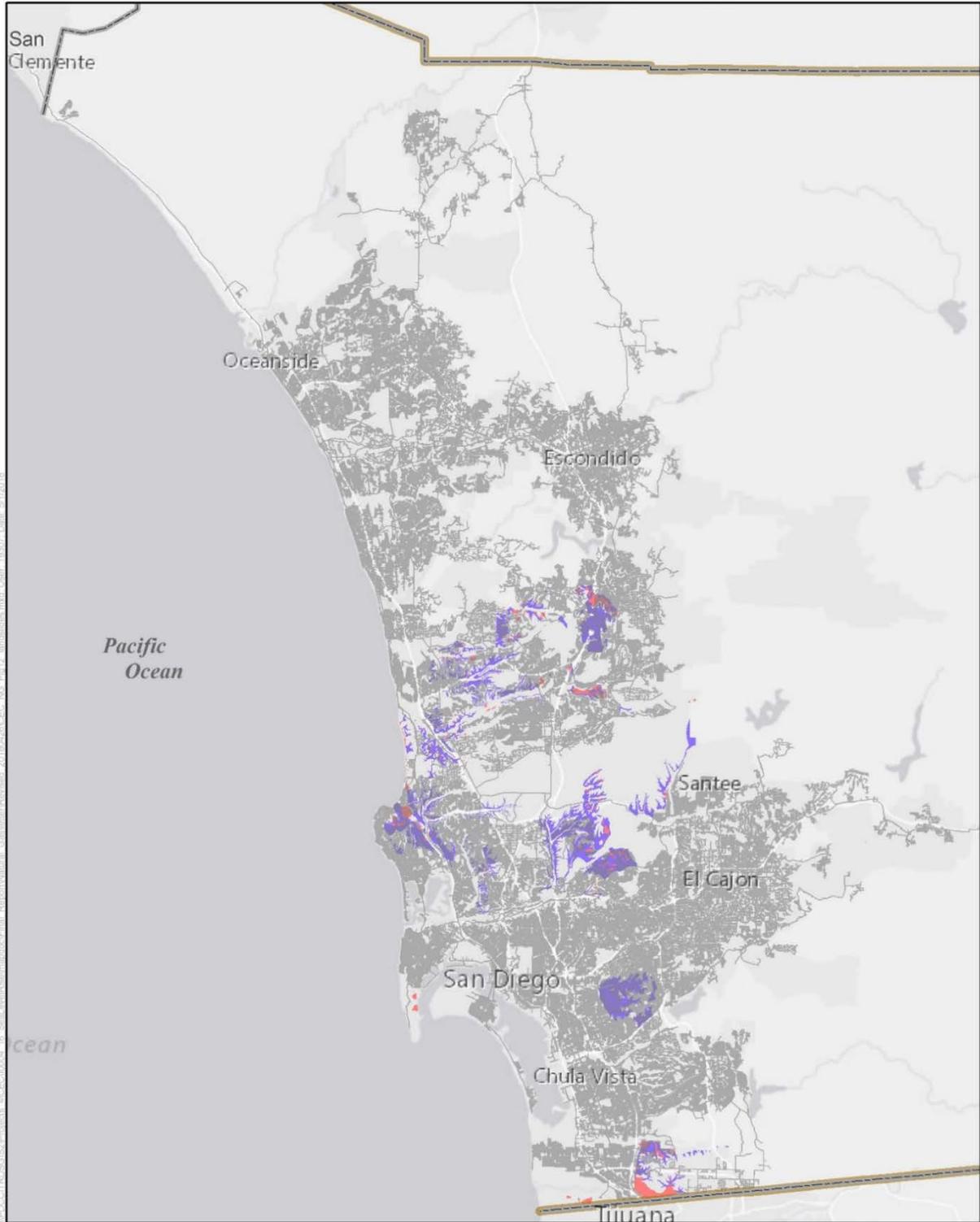
The most significant inland flooding risk to the SDG&E Service Area may come in the form of downstream impacts if a compressor station is ever compromised from flooding. There is at least one compressor station located in a flood zone that, although located outside the study zone, is a critical asset in supplying natural gas to the SDG&E Service Area. Disruptions to this station could cause significant disruptions to natural gas supply to the SDG&E Service Area. In general, there is limited redundancy in terms of supply, particularly in the system that moves gas from east to west, meaning that disruptions to supply (such as loss of use of the compressor station), could have significant impacts across the Service Area. In such an event, power plants and industrial and commercial customers would likely lose gas supply first, due to their position in a customer prioritization tier system. Residential customers and customers that serve a core function for the community (such as hospitals) would probably retain supply longer, but could also be adversely impacted.

3.1.6 Landslides

Extreme precipitation can destabilize land, causing landslides. Landslides are particularly a concern after periods of dry weather are followed by intense precipitation events. Although it is difficult to project areas where future landslides may occur, the research team was able to use the California Geologic Survey data on landslides and slide-prone formations to understand where natural gas assets might be exposed, shown in Figure 13, below. The results (which assume the current landslide and slide-prone formation areas are reasonable proxies for future exposure) indicate that over 43,000 (about 4%) of point assets and about 350 mi. (about 2%) of line assets are located within geological hazard areas. Of the assets, the vast majority (>90%) are within slide prone formations, while about 10% are within landslide areas. Most of the exposed point assets (86%, about 37,200 assets) are service connections. Most of the line assets (96%, 616 mi. or 991 km) are medium pressure pipe, with a smaller proportion (3%, 19 mi. or 31 km) being high pressure pipe. Although overall exposure may be low, landslide events can cause significant disruptions at a local scale; that is, only a small number of customers may be affected, but their service may be completely disrupted until repairs can be made.

Landslides Impacts Summary

Impacts to the system overall are expected to be low, albeit with the potential for low-probability events to affect the system. Though a number of assets are in the exposed zones, actual landslide events are localized, currently rare, and affect a small number of customers during each event. However, when landslides do occur, impacts are significant. The risk may increase in the future, and steps may need to be taken to protect critical assets in exposed areas.



Hazard Type

- Landslide Areas
- Slide-prone Formation Areas

Natural Gas Line Assets
 County Line
 SDGE Service Area Boundary

0 5 Miles

↑
N
✦
ICF

Figure 13. Landslides and slide-prone formations in the SDG&E Service Area. Sources: SDG&E and SoCalGas; SANGIS; ESRI

SDG&E and SoCalGas reports that landslides do occur, but not very often. On the occasions when the natural gas system is damaged by landslides, the impact is generally limited to a small number of customers that are immediately within a landslide area. Utility staff recall the most major landslide recent history within the SDG&E Service Area being the La Jolla 2007 event during which a minor gas leak occurred and service was cut off to about a dozen customers (San Diego Union Tribune 2007). Since then, SoCalGas installed two emergency valves and the City removed several homes and stabilized the area. More recently, North of the SDG&E Service Area, the January 9th 2018 Montecito landslides led to 2,900 SoCalGas customers to lose gas service (SoCalGas, 2018). Existing data documented this area as having low to high landslide risk (CA Department of Conservation, 2015). The large number of customers impacted by this event was due to unprecedented levels of localized scour – of up to 8 feet – in creeks where the landslides carved out creek beds where one gas transmission pipeline was damaged, and another was proactively de-pressured as a precautionary measure.

The utility has taken steps to reduce the sensitivity of aboveground service connections. Service connections that have experienced ground settling are often fitted with flexible connections installed on the customer side of the meter, allowing for some limited movement. Additionally, high pressure pipelines located within limited-access slide zones in steep canyons have been replaced. As landslides may increase in the future due to climate change, the utility may find it necessary to increasingly use these adaptation measures.

As previously discussed in 2.3.5, current models for precipitation induced landslides are restricted to broad, state-level assessments. The research team recommends that further research, data collection, and modeling that incorporates climate projection data be performed to identify local hazards associated with precipitation induced landslides.

3.2 Indirect Impacts

To analyze indirect impacts to the utility and its customers from climate change hazards the ICF Gas Market Model (GMM®) was used to determine potential impacts to demand, supply availability, and market prices. The research team worked with SDG&E and SoCalGas to define two scenarios for the natural gas market through 2050: one a reference scenario that does not incorporate changing climate conditions, and the other a climate hazard scenario that explicitly includes projected gradual change in climate as well as an extreme climate hazard, or “shock” year.¹³

The analysis of potential indirect impacts to the natural gas system supply indicates that the system has the capacity to adapt to projected changes. Results from the GMM analysis highlight that due to overall declining demand due to market forces such as California’s Renewable

¹³ The average monthly capacity values reflected in these charts assume that capacity is fully available and that there are not any reductions to capacity due to line outages, facility closures, integrity management, operational flow orders that result in loss of capacity, and/or force majeure events. Should such events occur, the pipeline capacity that is shown may not be fully available, and system flow conditions could be adversely impacted.

Portfolio Standard¹⁴, there is sufficient natural gas supply for California throughout the projection in both the reference case and the climate hazard case, although gas prices could spike above \$10 per MMBtu in a future extreme climate year. Impacts from the price increase could potentially indirectly cause energy costs to increase for customers, although gas is projected to be available to meet demand given the pipeline capacity and overall decline in future demand.

In the reference case, as gas demand declines, the system is projected to have surplus capacity and small increases in gas prices. The overall trends shown herein generally project declines in demand over time, and the annual average flow into the SDG&E area is projected to decline with demand to approximately 0.30 Bcfd by 2035 (Figure 14). The GMM projects monthly values; it is not a daily model and does not project daily peak demand. As such, the model does not capture how daily peak demands could potentially change over time as a result of climate impacts.

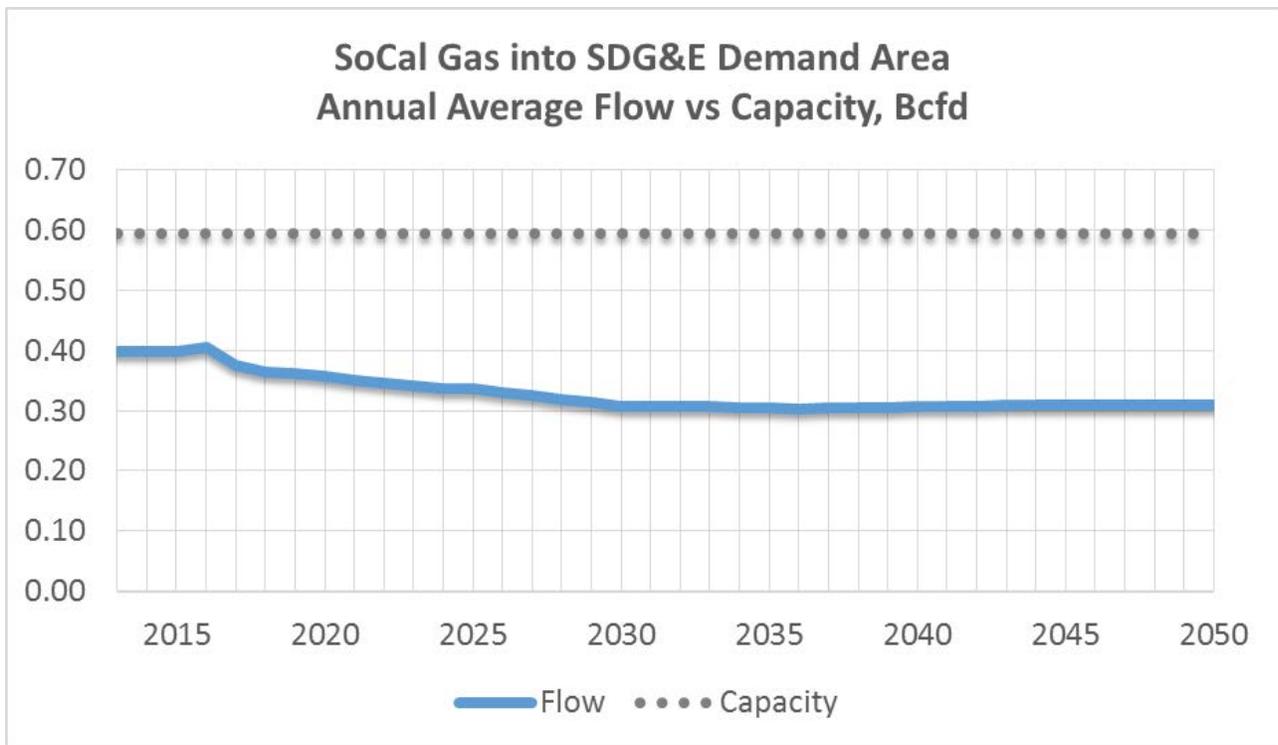


Figure 14. Projected SoCal gas pipeline capacity and annual average flow into the SDG&E area for GMM reference case

¹⁴ ICF GMM adapts California Gas Report 2016 (California Gas and Electric Utilities 2016) assumptions on California total and renewable electric generation. The renewable generation penetration is consistent with the Renewables Portfolio Standard (RPS) of 50 percent by 2030.

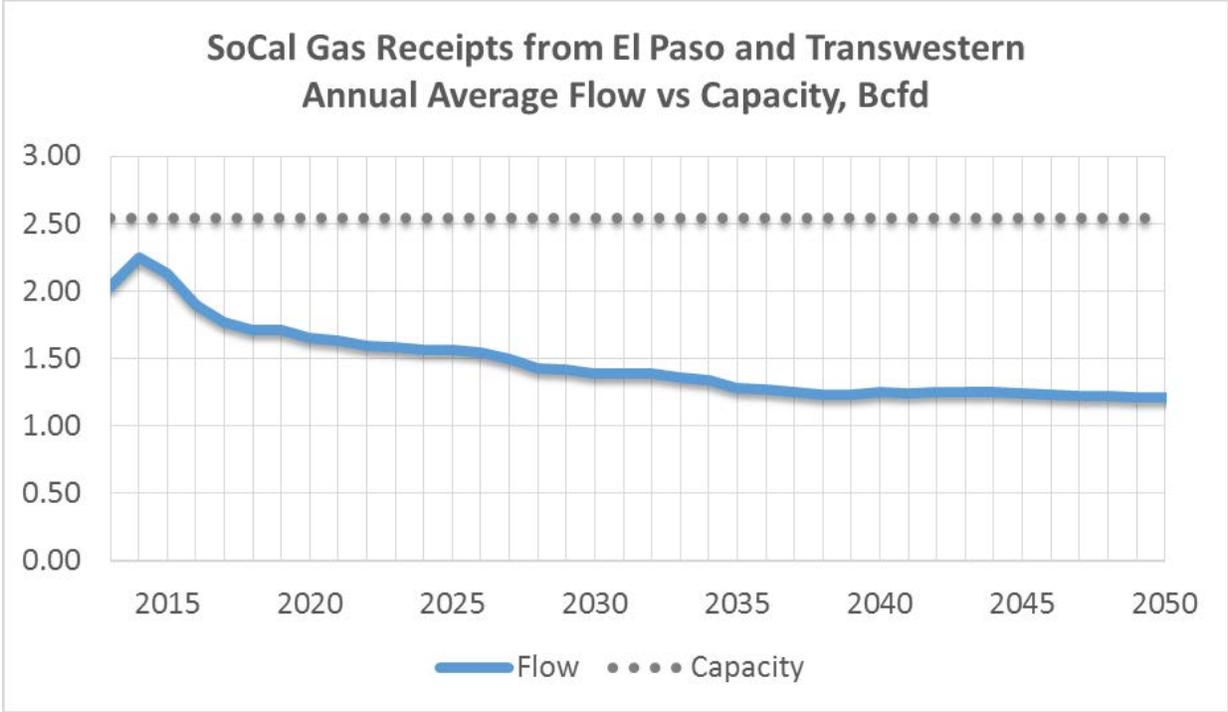


Figure 15. Projected SoCal gas receipts from El Paso and Transwestern for GMM reference case

Gas prices are projected to increase to nearly \$6 per MMBtu for Henry Hub, with a slightly smaller increase at SoCalGas (Figure 16).

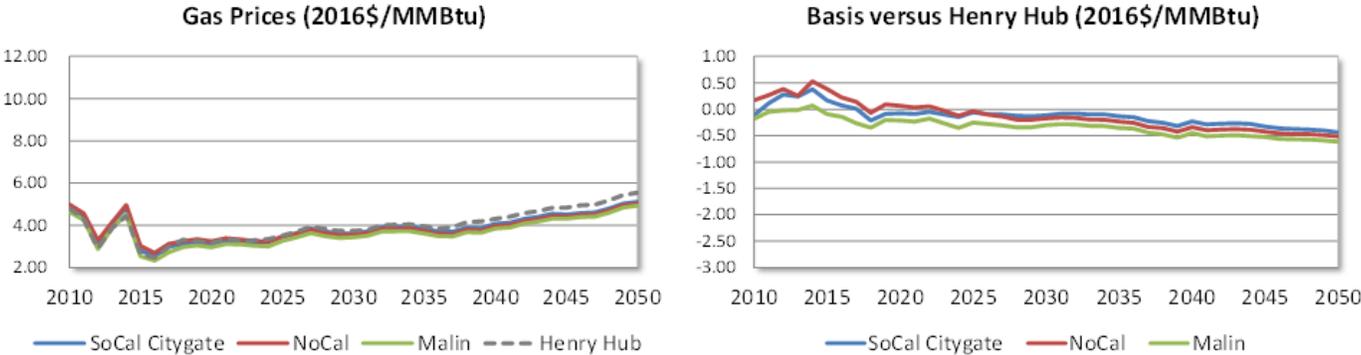


Figure 16. Projected Natural gas prices until 2050 in GMM reference case

For the climate hazard case, the changes in demand due to increases in CDD and the changes in available hydropower introduce greater variability in the projected gas prices, but the system is projected to have excess capacity, assuming no pipeline retirements, on an average annual basis. The annual average flow is projected to closely mirror that of the reference case (Figure 17 and Figure 13).

In the climate hazard case, there is relatively little change in California gas demand versus the reference case, as increases in gas demand for power generation due to increases in CDDs is

offset by decreases in gas use in other sectors due to higher natural gas prices and lower space heating requirements.

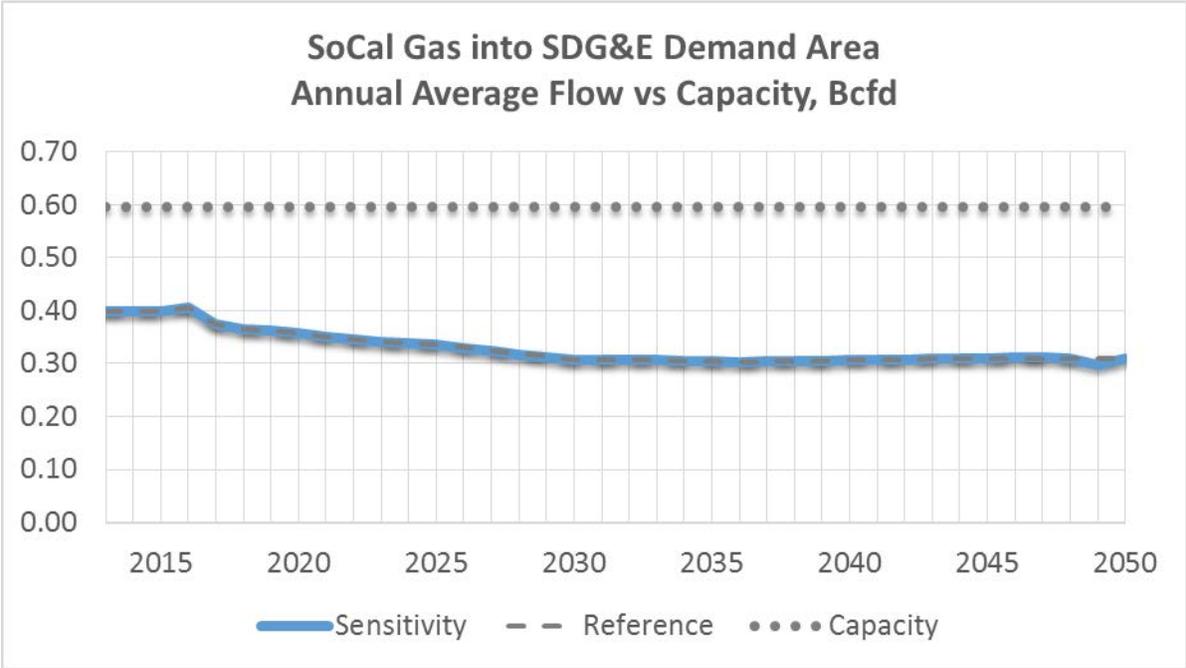


Figure 17. Projected SoCal gas pipeline capacity and annual average flow into the SDG&E area for GMM climate hazard (“Sensitivity”) case

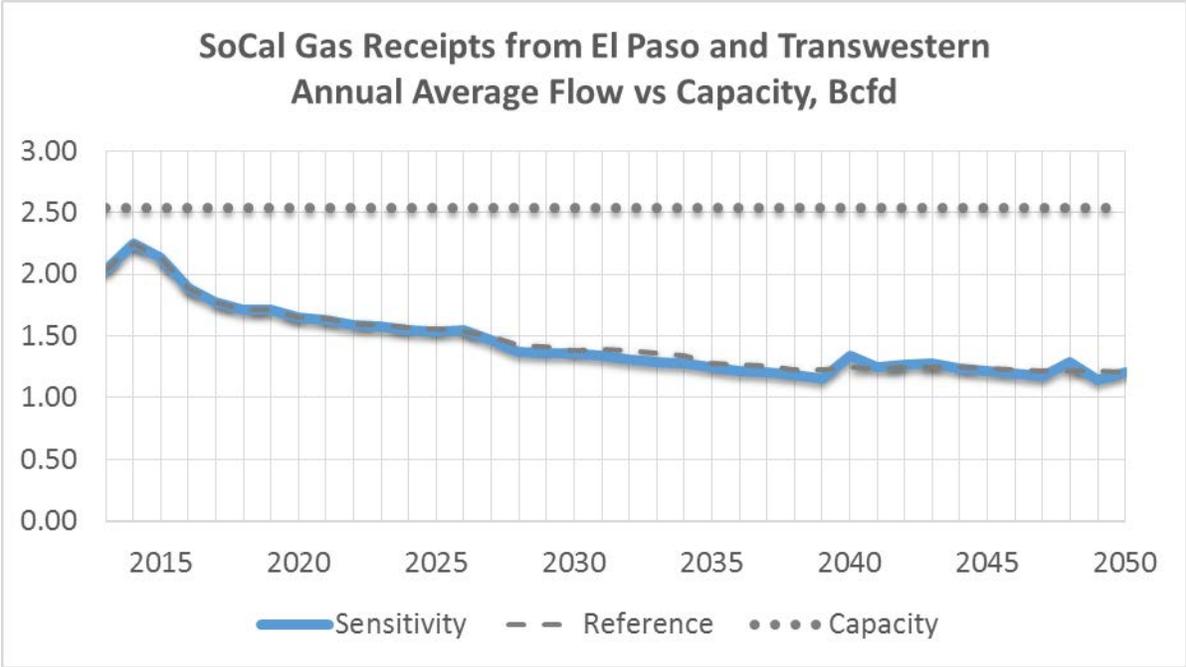


Figure 18. Projected SoCal gas receipts from El Paso and Transwestern for GMM climate hazard (“Sensitivity”) case

There are higher natural gas prices in the climate hazard case due to increased gas demand for power generation. Average 2020-2050 gas price at Henry Hub is increased by \$1.25 per MMBtu (real 2016\$).

The climate extreme “shock” in 2050, based on assumptions of extreme conditions in California and elsewhere, drives the gas prices above \$10 per MMBtu, as shown in Figure 19. This is approximately \$4 per MMBtu higher than projected prices under the reference case. This one-year extreme case provides perspective on impacts to gas prices under a plausible extreme scenario; the one-year case would not necessarily lead to changes in prices in subsequent years and should not be interpreted as part of a linear increasing trend. Long-term supply contracts would likely limit the amount of impact a one-year spike would have, as short-term changes tend to average out over time, although it could provide precedence for an increase in negotiated price for future contracts. The extreme shock year results in a price spike, but does not pose an overall supply availability risk, as California gas demand in 2050 is well below the current level.

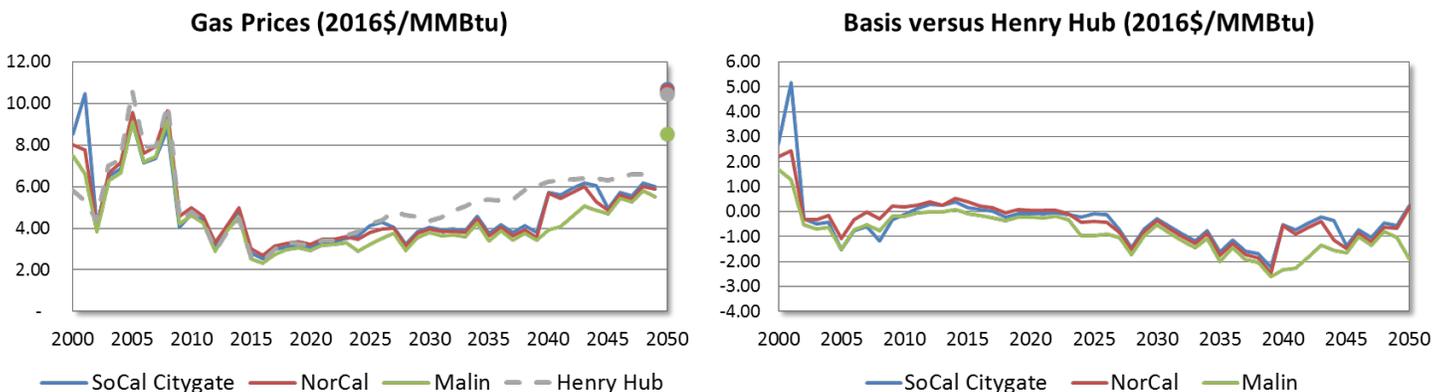


Figure 19. Projected future gas prices in the climate scenario, including 2050 climate extreme "shock" (Note: the 2050 values are for a modeled one year extreme case and should not be interpreted as part of a linear trend).

3.3 Flexible Adaptation Pathways

This section first discusses key findings from the adaptation workshops, and then presents potential flexible adaptation pathways that SoCalGas could employ.

3.3.1 Key Findings from Workshops

A key finding of Workshop 1 was that a system-wide, ‘top-down’ multi-criteria approach for selecting, evaluating, and prioritizing adaptation measures did not seem to be the best approach. In practice, the appropriate action is often very situation-specific, and discussing adaptation in high-level strategic-level terms was problematic. More importantly, a limited number of site- and context-specific conditions may drive the appropriate adaptation measure and alternative adaptation measures out of consideration based on those conditions. Therefore, evaluating each adaptation measure against a pre-determined set of criteria with the intention of then comparing and selecting adaptation measures was not necessary, as usually one or two criteria were the actual drivers in determining which measure was most appropriate.

Overall, introducing a scoring system to rank the prioritization of adaptation measures was not helpful as the utility seems well aware of appropriate adaptation measures for a given hazard and location based on experience in managing impacts from climate-driven hazards, such as wildfire and river flooding. Consequently, additional climate change adaptation measures can be evaluated using current systems. Importantly, effectively integrating climate change adaptation into existing decision-making systems will require those undertaking relevant technical analyses to have ready access to credible and up-to-date climate impact information.

Rather than introducing a new scoring system, therefore, it may be more beneficial to ensure the appropriate information and decision-making frameworks are in place that would allow existing risk-management systems to include climate change considerations. Integrating climate change considerations into risk-management would allow SoCalGas to continually monitor climate change risks and update climate data without overhauling existing risk management systems.

The research team found, based on workshop discussions, that SoCalGas has the ability to evaluate risk mitigation measures based on situation-specific factors, but requires robust climate hazard information to support adaptation decision making. A key finding of Workshop 2 was that adaptation barriers related to conceptual engineering or technology solutions are fairly low, but more work is needed on integrating the concept of climate adaptation throughout their decision making processes to support implementation. The research team found that SoCalGas's internal engineering design, risk management, and disaster preparedness systems generally function well enough to address current climate risks, with several examples from the management of wildfire risk. Importantly, enhancements to the forecasting of climate hazards were noted as being valuable for both managing current levels of risks and also as an important prerequisite to systematic long-term adaptation investments.

The research team found that SoCalGas equipment damage would incur damage progressively over time, such as through corrosion, and impacts would be in the form of increased maintenance, repair, and replacement costs. Therefore, most adaptation upgrades could happen gradually and opportunistically.

The research team found that there is an important shared responsibility for climate change and their local communities to make adaptation decisions that complement each other. For example, the identification of inland flood exposure for regulator stations highlights broader community exposure to these hazards and, as a result, any adaptation measures applied to enhancing the resiliency of infrastructure would be embedded within a broader response to adaptation by the surrounding community. Statistics on supply interruptions and maintenance call-outs due to repeated flooding could trigger a broader discussion about the potential to relocate critical infrastructure to higher ground. Implementation of specific adaptation measures, including detailed design, timing, and cost sharing would likely be taken jointly with other public and private sector organizations (particularly local governments) and with the communities themselves. While such a joint decision-making process would require time and effort to coordinate and would likely face significant regulatory challenges and planning approvals, it would likely yield the most effective outcomes, including in terms of cost-effective outcomes.

For SoCalGas, while the workshops drew together a sample of staff from across the organization for the purposes of the current research study, a programmatic approach will be needed to embed and sustain climate adaptation implementation. Such a programmatic approach would enable the formalization of points of contact across the utility to help ensure the success of

implementation by establishing clear reporting lines. A potential pathway to achieving such a programmatic approach is outlined in Section 3.3.2.

Finally, taking a programmatic approach in collaboration with other stakeholders is vital for choosing a portfolio of adaptation measures that is optimal both for SoCalGas and for the community. If adaptation decisions are made without broader considerations, the selected adaptation measures may not be the most appropriate options, and could even have unintended impacts of their own. For example, gas assets exposed to coastal hazards may be situated alongside other important community assets. The most cost-effective response may be for the community to implement protective structures or beach nourishment that would protect both utility and non-utility assets; in comparison, implementing measures that exclusively protect gas assets may be less cost-effective and less effective at enhancing asset resilience. Other adaptation may result in unintended consequences. For example, building a protective flood wall might protect a given asset, but could raise aesthetic concerns in the community or eliminate an important community recreational resource. Similarly, intense efforts to increase redundancy or harden infrastructure might successfully increase resilience but reduce funds available for other priority activities. It is therefore important that adaptation decisions consider the broader context and that they are made in coordination with the larger community. For these reasons, the priority adaptation actions discussed in the following section focus on first ensuring that appropriate methods, data access, and collaborative partnerships are in place before making specific decisions on whether and how to harden or relocate infrastructure, or undertake other specific adaptation measures.

3.3.2 Key Findings on Potential Flexible Adaptation Pathways at SoCalGas

Based on the study research and workshops, the research team identified eight potential adaptation *actions* as outlined in Table 4. Four of these actions are considered priority near-term actions (see bolded actions in Table 4, below). It should be noted that SoCalGas and SDG&E have several adaptation efforts currently in place, which are detailed in Appendix E.

Table 4: Illustrative Adaptation Actions and Indicative Implementation Steps, with Priority Actions Bolded

Action Code	Action Description	Adaptation Actions
A	Upgrade infrastructure design and maintenance specifications	<p>Based on inputs from Action D, Regional Consultation, and any other appropriate data sources, review engineering design and maintenance specifications for how enhanced standards will maintain current levels of system resilience to climate change hazards.</p> <p>Engage with national and state standard-setting bodies to ensure a coordinated process and to minimize the potential for over/under-design in response to climate change threats, including cost-benefit analysis.</p> <p>Implement enhanced standards for the design of new gas infrastructure and operations of existing systems.</p> <p>Monitor and evaluate standard implementation against defined signposts and thresholds (Action C).</p>
B	Integrate climate change hazard maps into planning and operations	<p>Review hazard risk mapping undertaken through the study and enhance as appropriate to align with SoCalGas GIS systems.</p> <p>Import hazard risk mapping align with SoCalGas GIS systems.</p> <p>Undertake internal training and awareness raising on new risk mapping with key user groups. Tailor training to support specific decisions.</p> <p>Evaluate system usage through regular system use statistics and user feedback.</p>
C	Signposts & thresholds assessment	Develop of suite of signposts and thresholds that determine when a transfer of adaptation actions is approaching (signpost) or reached (threshold).
D	Regional consultation	Discuss with regional stakeholders broader plans for opportunities and constraints that would contribute to community-wide resilience (e.g., any community-level adaptation investment planning led by cities/counties).

Action Code	Action Description	Adaptation Actions
E	Cost-benefit analysis methods	<p>Identify an appropriate process or methodology for evaluating costs and benefits of individual measures, including for supporting General Rate Case applications, recognizing that traditional economic techniques may need to be adjusted to account for multiple future scenarios.</p> <p>Use inputs from the enhanced hazard mapping (Action B) to fine-tune cost-benefit analysis.</p> <p>Use regional consultation inputs (Action D) to refine plans for financing measures (e.g., ability to cost-share adaptation initiatives).</p>
F	Enhance system management technology	Enhance system management technologies (e.g. Smart Meters, remote-controlled valves) to heighten resiliency against anticipated risks.
G	Siting & Relocation	Using inputs from analysis undertaken through assessment of Actions B-E, relocate assets to locations with reduced exposure to climate hazards.
H	Adjust gas supply and storage system to enhance resiliency	<p>Identify locations where disruptions in existing natural gas supply lines would be especially problematic.</p> <p>Evaluate potential to mitigate supply risks through increased distributed storage.</p>

Figure 20 shows a preferred pathway that begins with four initial adaptation actions, namely Actions B, C, D, and E, as depicted by colored dots and lines. Actions A, F, G and H may also begin early on, though this is not preferred (as indicated by the grey dots and lines) because waiting for outcomes from priority actions can help improve the effectiveness of these higher-cost actions, thereby providing greater adaptation value and maximizing cost-effectiveness. The black circular transfer stations indicate points where triggers are reached and either (1) adaptation actions inform one another (e.g., black arrows with transfer stations on either end, such as those in the first column of transfer stations), or (2) outcomes from one adaptation action inform and initiate another (e.g., black arrows that point from a transfer station to an initiation point, such as the third column of transfer stations, where priority actions B and C initiate non-priority Actions A, F, G, and H). The transfer arrows between transfer stations indicate that outcomes from one adaptation action are used to enhance the efficiency or performance of another adaptation action. The black vertical lines are terminal stations which indicate that that an adaptation action is no longer needed or no longer viable. The terminal stations shown for Actions B, C, and E represent the completion date of these actions, all of which are assessments and analyses that feed into the other actions. In contrast, Actions A, D, F, G, and H are shown not to not have terminal stations, indicating that these actions are ongoing.

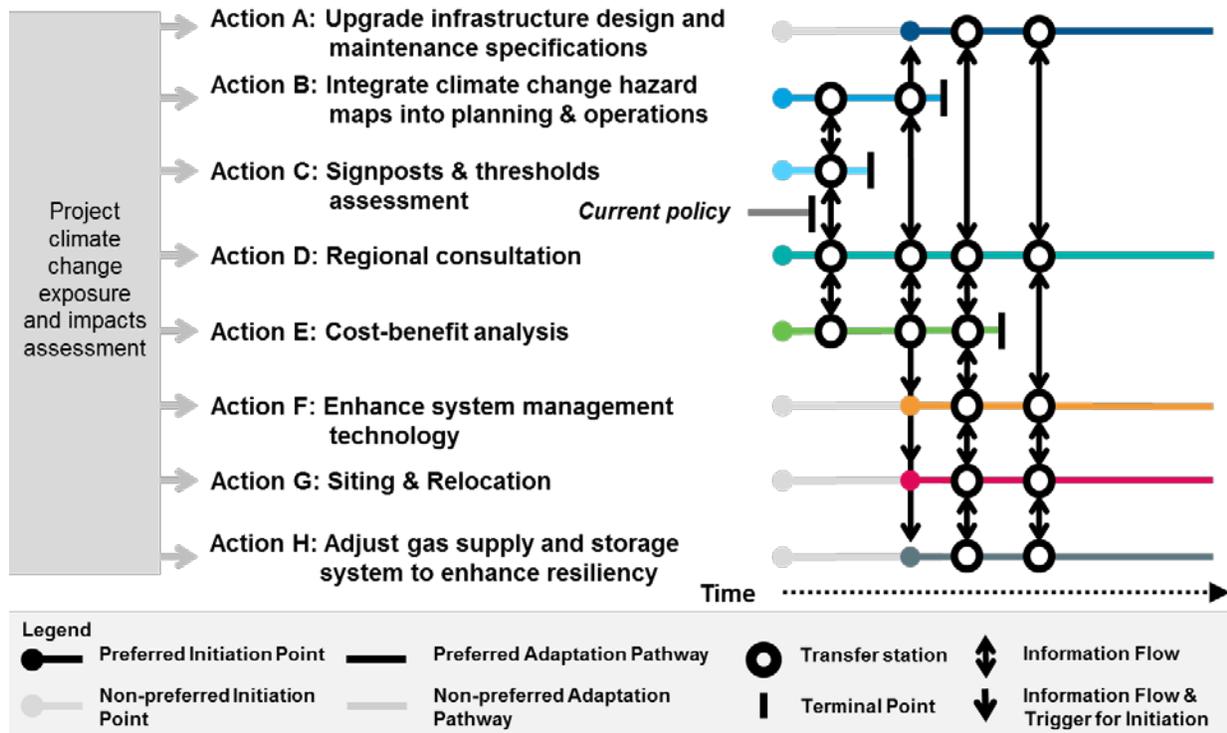


Figure 20: Initial flexible adaptation pathways map for immediate SoCalGas adaptation actions

These four initial adaptation actions – Action B: Integrate climate change hazard maps into planning & operations, Action C: Signposts & thresholds assessment, Action D: Regional Consultation and Action E: Cost-benefit analysis – are all “low regrets” climate change adaptation actions. That is, they enhance the ability of the utility to predict and manage present-day climate hazards in SDG&E Service Area (in a cost-effective and regionally engaged manner) that is valuable for both present, day-to-day disaster planning and also for managing future climate change impacts. In other words, there is little (or no) downside for implementing these actions. Conducting Actions B-E first will help improve the cost effectiveness of later implementing Actions A, F, G and H.

Action B (Integrate climate change hazard maps into planning & operations) will help SoCalGas make informed decisions on long-term adaptation investments by enhancing access to climate-related information alongside consideration of existing climate and geohazards. For example, the regulatory requirements of siting High-Pressure Gas pipelines require a geospatial analysis to assess pipe segmentation to address current natural hazards.

Action C (Signposts & thresholds assessment) involves the identification of appropriate adaptation thresholds and signposts recommended to be tracked to signal when a key decision point is imminent as climate change impacts emerge. The research team considered the workshop findings in concert with the policy and regulatory environment within which adaptation decision making occurs at present. An initial set of these adaptation thresholds, which could form the basis of analysis through Action C to determine when adaptive action is triggered, fall into four main categories:

1. Physical climate thresholds (e.g., exceedance of measured height of mean sea level rise at San Diego tide gauges; exceedance; # of nuisance flood days/year; increase in the geographic area of flooding; increase in landslide incidence).
2. Local and regional adaptation thresholds (i.e., lack of formal local zoning of landslide exposure by date XX).
3. Internal SoCalGas 'process/operational' thresholds (i.e., exceedance # of system outages/year due to flooding; lack of clear climate risk governance by date XX; lack of design standards that include climate by date XX).
4. External regulatory thresholds (e.g. regulatory agencies require system hardening to specific extreme heat levels).

Action D (Regional consultation) acknowledges that SoCalGas is already engaged in several key adaptation initiatives, as discussed in more detail in Appendix B. SoCalGas could continue these efforts and also continually review whether there are additional collaborative efforts in which to participate; for example, participating in LHMP and Catastrophic Plan updates. Doing so will enable SoCalGas to make adaptation decisions with a full understanding of complementary measures being taken by local and regional entities that could affect SoCalGas operations. This action will also give SoCalGas an opportunity to ensure that local and regional decisions are made with a full understanding of potential impacts on the energy system by communicating the results of this study and future research with San Diego County and others.

Ongoing regional consultation (Action D) is also envisaged as Actions A, F, G and H are implemented. SoCalGas's active on-ongoing engagement in local and regional climate adaptation efforts will be important, given that decisions that one player makes could affect the appropriate measures of another, and vice versa, at a given threshold point.

The fourth adaptation action recommended by the research team for priority implementation is to identify and begin implementing appropriate methods for conducting cost-benefit analyses of detailed adaptation actions (Action E). Critically, cost-benefit analyses must be cognizant of the fundamental basis of the flexible adaptation pathways approach that explicitly considers switching of adaptation actions, based on pre-defined thresholds. As such, traditional cost-benefit analysis approaches that assume only one policy outcome is undertaken will not be appropriate within an adaptive pathways framework (Schwartz and Trigeorgis 2004; Buurman and Babovic 2016). Rather, economic assessment techniques tailored to the pathways approach, such as are used in Real Options Analysis, will be better suited.¹⁵ However, these are techniques that are emerging and as such will require careful comparison prior to their selection and

¹⁵ Although transportation-focused, the Federal Highway Administration (FHWA) *Transportation Engineering Approaches for Climate Resiliency (TEACR)* project has completed research on economic analysis methods appropriate for climate change impact analyses (FHWA 2017). To help identify adaptation measures most appropriate across a range of plausible futures, the TEACR report details economic assessment approaches that explicitly recognize uncertainties associated with future climate, the resulting uncertainties in benefit/cost flows over time. For more information, see FHWA's *Transportation Engineering Approaches for Climate Resiliency (TEACR)* project (FHWA 2017).

application to cost-analysis and benefits assessment approaches currently used by SoCalGas to guide investments in risk mitigation (Sempra Energy 2016).

As shown on the left-hand side of Figure 20, the analysis undertaken throughout this study provides a sound basis for embarking on a program of adaptation actions. However, depending on when such a program is initiated, a re-assessment of the latest scientific research on climate change scenarios and assessments of their impacts in the SDG&E Service Area may be warranted.

Finally, investments in climate change adaptation by SoCalGas can be improved following completion of Action B, C and E, as well as receiving substantive inputs from regional stakeholders through Action D. Thus, implementing Actions B, C, D, and E early on will help make more cost-effective decisions about Actions A, F, G, and H. As shown in Figure 20, Actions B, and E eventually reach their 'sell-by date' (Haasnoot et al. 2013) in the future; that is, these actions eventually are no longer cost effective, and other actions (A, F, G and H) continue into the future instead.

A comprehensive list of adaptation measures that could be employed in support of various pathways (beyond just the pathways shown here) are included in Appendix D. The existing adaptation frameworks, partnerships, and programs that could help facilitate adaptation decision making are included in Appendix E.

4: Conclusion and Future Directions

This section summarizes key findings of the study, provides a brief discussion of study limitations, and concludes with suggestions for future research opportunities.

4.1 Key Study Findings

The primary findings from the study are:

1. Overall, natural gas assets and services are likely to experience limited impacts from the climate hazards investigated. Impacts may occur in the form of increased repair/maintenance needs or localized disruptions. The cumulative impacts of increased costs could not be quantified in this study, but could potentially be significant given the large number of assets potentially exposed. Widespread disruptions are not expected due to limited projected exposure to climate hazards, and existing physical protections that limit potential impacts.
2. The assets that are likely to experience the greatest impacts include:
 - assets located in low-lying areas around bays and estuaries and on the coastline adjacent to erodible cliffs and dunes (notably, the scale of projected exposure increases markedly between mid-century and end of century as sea level rises),
 - aboveground regulators in areas projected to experience an increase in wildfire area burned,
 - compressor stations in areas projected to experience large increases in extreme heat days,

- regulator stations and transmission assets within floodplains, and
 - pipelines along water crossings.
3. Based on the ICF Gas Market Model (GMM®) analysis of potential impacts to demand, supply availability, and market prices, the SoCalGas system has capacity to adapt to projected changes. Specifically, the climate extreme “shock” scenario in 2050, based on assumptions of extreme conditions in California and elsewhere, would not lead to shortfalls in regional supply, as there is sufficient pipeline capacity. However, the GMM does not provide temporal resolution to capture daily peak gas demands. For example, the GMM does not capture the short-term impacts of a one-day spike in demand that may lead to curtailment. Looking at monthly averages can understate the impacts of short-term spikes in demand. There also could be an increase in market price of natural gas above the reference case in the climate extreme “shock” scenario in 2050, with gas prices potentially spiking above \$10 per MMBtu.
 4. Though impacts may be limited overall, the gas system will likely experience impacts from climate change to some extent. Therefore, adaptation is warranted to ensure continued resiliency of the gas system in the future. The research team found that taking an iterative and flexible adaptation pathways approach to adaptation, rather than implementing a full suite of adaptation actions upfront, will allow SoCalGas to make better-informed decisions about adaptation investments as time goes on and more information is known about changes in climate, customer needs, the gas system, new technologies, and other factors.
 5. Immediate adaptation actions identified through this study for SoCalGas are:
 - a. Integrate climate change hazard maps into planning & operations;
 - b. Identify signposts and thresholds that can be used to determine when the need for an adaptation decision is approaching or reached;
 - c. Consult with regional stakeholders to identify opportunities to improve community-wide resilience; and
 - d. Adjust cost-benefit analysis techniques to account for unique features of climate change.

4.2 Limitations of This Study

While this study made several scientific advances, there are a number of limitations to the findings due to the scope of the study and available data, which should be considered when interpreting the findings. Specific limitations include:

- The exposure analysis assumes that the existing assets will still be the same through the middle of this century and beyond to late in the 21st century. In reality, the natural gas system will likely change over the next 80 years, just as it has changed over the past 80 years. It is difficult to predict how infrastructure will change due to changing demographics, technological advancements, and other factors.

- More analysis of the potential feedbacks between the gas system and the tightly connected electricity system would provide a fuller picture of potential impacts and adaptation related to the *energy sector* as a whole.
- This is not an engineering level study. Without providing detailed engineering analysis at the asset level, the research team was not able to specifically detail exact failure mechanisms for a given asset, nor make recommendations about engineering design changes for specific adaptation actions for a given asset.
- Due to security, data confidentiality and safety concerns, the research team was unable to either obtain or report on certain information that would have provided more specificity to the results. The research team was also unable to publicly identify specific lines or assets to ensure system security or, for reasons of confidentiality, to identify customers. Therefore, information on direct impacts is provided in a general way, rather than stating whether a specific, publicly identifiable asset could be damaged under a given scenario.
- The flexible adaptation pathways provide a framework and initial set of actions for SoCalGas to consider. Additional work is needed to expand on how these actions may best be implemented within the context of SoCalGas' existing decision-making processes, which may in turn uncover additional supporting actions that would be beneficial.
- An important limitation to note is that climate projection information was not available for certain hazards: inland flooding and landslides. Although projected changes in rainfall patterns could increase the frequency or severity of these hazards, more extensive modeling, which was outside the scope of this project, would be needed to quantify and spatially convey the change in exposure. Current floodplains and landslide risk areas were used as a proxy for areas that may be exposed to these hazards in the future, but may not capture the true extent of the risk.
- The research team had hoped to better quantify the potential costs of the impacts, but was unable to obtain specific cost information from SoCalGas. In many cases, it appears that cost information is not tracked in ways that would allow costs isolation associated with specific impacts. Rather, costs tend to be wrapped up in general operational/maintenance budgets, or aggregated in total costs associated with a large event. Additional research in this regard will be valuable.
- To the knowledge of the research team, this is the first long-term gas market analysis to explicitly consider a climate change extreme scenario. While these modeling results are informative for understanding potential adaptation to future conditions, additional research is needed to continue to develop a better understanding of these dynamics. There are many factors that influence gas prices over time, such as import/export activity, oil prices, and technology application for supply development, that are highly uncertain and can potentially have significant impact on gas price evolution. Thus, there is significant uncertainty around the overall gas price levels that are projected over time, and the magnitude of impact of climate change could be much greater or much less than what has been projected, depending on the specific market evolution. In addition, changes in peak demand and issues related to intraday ramping requirements may affect system requirements; such impacts are beyond the scope of the current study.

- Consideration was given to analyzing the indirect impacts to the natural gas system from loss of electricity, but through discussions it was determined that most of the critical assets (i.e., compressor stations, SCADA) that could be impacted by loss of electricity had backup systems; however, a deeper dive into this topic might be warranted at some point. Additionally, consideration was given to looking at the potential loss of the main transmission lines, but it was determined that this would require an effort beyond the scope of this study and the research team believes that such a scenario is unlikely as well.

4.3 Future Research Opportunities

In the course of this project, the research team identified several research topics that could significantly benefit adaptation efforts in the energy sector.

The scope of this study specifically covers the natural gas sector. However, natural gas is a major component, along with electricity, in the broader energy sector. In some situations, natural gas and electricity are theoretical substitutes for one another (for example, gas *or* electricity could be used to run stoves, water heaters, heating systems, etc. in residential buildings, and either one could be used to run some equipment types in non-residential settings). Therefore, to achieve the goal of a truly resilient *energy* system, it is important to consider whether the role of one (electricity or natural gas) should be expanded in some circumstances. This point is particularly important due to the fact that natural gas is expected to experience limited impacts due to a changing climate. Future research should consider the extent to which natural gas service should be expanded in order to increase energy resiliency, as well as the situations where doing so should be prioritized.

The flexible adaptation pathways approach underscores the fact that perfect information about the future is not needed in order to take action in the short term. There are initial actions that can be implemented today to begin the adaptation process. Adaptation actions can then be adjusted in the future to account for changes in climate, population growth and land use, energy needs, and technologies. Research that improves climate projection information is important; however, other research that focuses on how best to encourage implementation of short- and longer-term adaptation actions would be particularly valuable at this stage. For example, new research could investigate whether there are regulatory barriers to adaptation (e.g., rules surrounding cost recovery), and whether new regulations could help facilitate stronger adaptation actions (e.g., which processes and procedures should be required to incorporate future climate considerations).

Similarly, there is an opportunity through future research to strengthen understanding of how technology can be deployed in the gas supply and distribution system to optimize the already high levels of system resilience. Opportunities exist for technologies to play an enhanced role in increasing resilience, especially when linked to gas distribution compartmentalization based on assessments of hazard exposure and impacts. Emerging technologies, including those based on the considerable investments made by SoCalGas including building on investments in Advanced Meters, could be used to identify outages and remotely manage gas flow. However, there has been limited research as to where and how this technology should be deployed to optimize resilience. As technology upgrades are rolled out, exposure to climate change hazards could factor into the prioritization of the areas upgraded. Additional research could identify areas that are potentially exposed, have potential for technology upgrades, and where customers would most benefit from these upgrades. Moreover, it would be beneficial to study the impact that

existing technological upgrades have had thus far on gas system resilience in the face of climate hazards.

In addition, future research could investigate other changing factors that will affect climate impacts. Climate is not the only thing that will change in the future; population, demand, supply characteristics, and other factors mean that the gas system of the future may look and operate differently than today. Additional research is needed to inform plausible scenarios of changes in customers over time – including potential impacts and resilience – to help improve understanding of potential impacts from future climate conditions. Future research could also incorporate plausible socioeconomic scenarios and assumptions regarding the evolution of gas assets, including incorporation of adaptation actions. In this regard, the consideration of potential climate impacts on gas and electricity energy systems within the SDG&E Service Area – as well as their interdependency – is warranted to help optimize the overall climate resilience of energy distribution and supply.

Furthermore, future research could explore cost recovery mechanisms for extreme climate-related events. Outside of a general rate case, SoCalGas can recover expenses for unanticipated climate-related events through either a Catastrophic Event Memorandum Account (CEMA) or the Z-factor recovery mechanism. CEMAs apply when a state of emergency is declared due to the event. The Z-factor mechanism covers other events that meet eight specific criteria. For SDG&E, Z-factor events have a \$5 million deductible (SDG&E 2009). If events become more frequent and/or intense, there may be reason to revisit how costs are recovered. For example, is the \$5 million deductible still reasonable if multiple events are occurring in short order? Should there be more proactive cost recovery in advance of major events if the expectation is that frequency and/or intensity might increase? Are the rules written such that the utilities can recover costs in a reasonable timeframe, while also guaranteeing that ratepayers are paying for reasonable costs?

Future research could also investigate how to best define expectations for infrastructure design. Explicitly requiring a utility to build infrastructure to be resilient to future climate conditions can remove the burden of certain decisions from the utility itself. For example, stating that utilities are supposed to use certain sea level rise modeling datasets, or make specific other assumptions about how the other hazards might change in the future, can eliminate the cost and time associated with the utility making decisions about which future assumptions to make. Likewise, requiring that certain infrastructure be built to withstand specific future hazards can make it easier to design that infrastructure, as the utility has clear guidance and knows that associated costs would be considered reasonable. In a recent presentation, SDG&E and SoCalGas noted that resilience design standards, related either to technical information such as climate change projections or to equipment performance standards, would be useful in their resiliency efforts (Cho and Day 2015). The current work of the Climate-Safe Infrastructure Working Group, constituted under AB 2800 (Quirk), while focused on state-funded infrastructure, will likely provide useful insights in this regard.

A better understanding of appropriate metrics for heat and precipitation would allow Cal-Adapt to be customized to present climate data in a way better suited to the specific needs of natural gas utilities. Some research is already underway investigating these metrics, but more research is needed. As noted in Section 2.3.4, the research team found that appropriate metrics varied considerably depending on how the climate change projection information is being used. To identify the highest priority metrics for natural gas utilities, first a deeper look into how climate

projection data could be used by utilities is needed. This understanding may ultimately loop back to the adaptation pathways and signposts ultimately implemented by the utilities. A clearer understanding of the processes that rely on climate and weather data, and specifically how those data are used, as well as what information is needed to support the selected signposts, will drive what sort of metrics could be embedded in cal-adapt.org. If cal-adapt.org is able to process and output these metrics, it would lessen the data processing burden on the utilities.

Additional research on coastal climate-related hazards is also warranted. The study found important differences between the FEMA, CoSMoS, and SPAWAR models for the region and each model output has its strengths and weaknesses. For example, the extents and depths of flooding varied widely across the areas of overlap. In general, CoSMoS showed less extents of flooding and deeper depths than the SPAWAR data. SPAWAR also specifically mapped erosion hazards while CoSMoS had them imbedded in the coastal flooding. More discussion and details are available in Appendix B. Additional coastal process data collection and model calibration with historic storm events are needed to improve model projections and reduce uncertainties. Although the greatest gaps in understanding relate to the indirect impacts of climate hazards and the implementation of effective adaptation actions, additional research on coastal climate-related hazards is also warranted.

This study's scope does not include specific engineering design implications related to the climate hazards assessed. As a result, this research does not attempt to predict the impacts to or performance of specific assets during hazard events. Future research on SoCalGas and SDG&E's natural gas system could incorporate a projected performance assessment during hazard events for exposed assets identified in this report. This study is also limited to impacts to the natural gas system and indirect impacts to downstream customers. The scope does not include climate impacts to other services or infrastructure upstream of the utility's operations. Future research could include an examination of impacts to key services or interconnections the utility depends on, such as gas refineries outside of SoCalGas's control, and the associated impacts and adaptation solutions. This study did assess collaborative opportunities for the local community to work together in implementing adaptation solutions, which could help limit these upstream impacts.

Further, the scope of the report did not consider how individual climate hazards can combine to cause compounding impacts to natural gas assets. As the recent landslides in Santa Barbara County have demonstrated, climate-driven hazards compound each other – in this case drought leading to heightened wildfire risk, that then increased risk of landslides from intense rainfall events. The potential for changes in the intensity and frequency of such cascading events is worthy of future research.

Finally, while modelling of indirect impacts to gas supply and demand provided insights into gas capacity and potential price impacts due to a "climate shock" scenario, the temporal resolution of the model (average monthly) did not capture peak demands that occur on a daily scale. An important avenue for future research is to explore how potential future changes to daily peak gas demand could change over time as a result of climate impacts. For example, a one-day spike in demand may lead to curtailment. The outcomes of such research would be invaluable to long-term capacity planning to build resilience to both long-term changes in climate and also to short-term extreme conditions.

5: References

- Buurman, J., & Babovic, V. (2016). Adaptation Pathways and Real Options Analysis: An approach to deep uncertainty in climate change adaptation policies. *Policy and Society*, 35(2), 137-150.
- CA-AB 2800. (2016). Climate Change Infrastructure Planning. Session 2015-2016. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800
- cal-adapt.org Degree Days Tool. (2017). California Energy Commission (CEC). <http://cal-adapt.org/tools/degree-days/>
- cal-adapt.org Extreme Heat Tool. (2017). California Energy Commission. <http://cal-adapt.org/tools/extreme-heat/>
- CA-SB 246. (2015). Climate change adaptation. 2015-2016 Session. Retrieved from https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246
- CA-SB 379. (2015). Land use: general plan: safety element. 2015-2016 Session. Retrieved from https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB379CaLEMA
- CA Department of Conservation. (2015). CGS information warehouse: landslides. Retrieved from <http://maps.conservation.ca.gov/cgs/informationwarehouse/index.html?map=landslides>.
- California Gas and Electric Utilities. 2016. 2016 California Gas Report. Retrieved from http://docketpublic.energy.ca.gov/PublicDocuments/16-BSTD-06/TN212364_20160720T111050_2016_California_Gas_Report.pdf
- CA Governor's Office of Emergency Services (OES). (2018). Catastrophic planning. Retrieved from <http://www.caloes.ca.gov/cal-oes-divisions/planning-preparedness/catastrophic-planning>.
- Casola, J. and Zamuda, C. (2017). Watching for Wind: An Effort to Get the Upper Hand on Wildfire. U.S. Department of Energy. U.S. Climate Resilience Toolkit. Retrieved from <https://toolkit.climate.gov/case-studies/watching-wind-effort-get-upper-hand-wildfire>
- Cho, J. and Day, D. (2015). Climate Adaptation at SoCalGas and SDG&E. Retrieved from http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/Meetings_and_Events/Day_Cho_SDGE_SCG.pdf
- Climate Education Partners. (2017). Climate Education Partners: Our Project. University of San Diego. Retrieved from <http://www.sandiego.edu/climate/project/>
- CEC. (2017a). Transcript of 08/29/2017 IEPR Joint Agency Workshop on Climate Adaptation and Resiliency for the Energy System. California Energy Commission (CEC). Retrieved from http://docketpublic.energy.ca.gov/PublicDocuments/17-IEPR-09/TN221244_20170920T104023_Transcript_of_08292017_IEPR_Joint_Agency_Workshop_on_Climate_Ad.pdf

- CEC. (2017b). Use of CoSMoS to Explore Implications of Various SLR Increments Considered in Research Contributing for California's Fourth Climate Change Assessment: Memorandum issued: 7/7/2017. California Energy Commission (CEC).
- CEC. (2016). Notice of Proposed Awards (NOPA): Natural Gas Solicitation for Energy-Related Environmental Research GFO-15-507. November 22, 2016. California Energy Commission.
- CNRA. (2018). Safeguarding California Plan: 2018 Update, California's Climate Adaptation Strategy. California Natural Resources Agency (CNRA).
- CNRA. (2018). Local and Regional Actions and Projects. California Natural Resources Agency (CNRA). Retrieved from <http://resources.ca.gov/climate/safeguarding/local-action/>
- CNRA. (2016). Safeguarding California: Implementation Action Plans: Energy Sector Plan. California Natural Resources Agency (CNRA).
- Consolidated Edison. (2015). Storm Hardening and Resiliency: Collaborative Phase Three Report
- CPUC. (2018). What is a General Rate Case (GRC)? California Public Utilities Commission (CPUC). Retrieved from <http://www.cpuc.ca.gov/General.aspx?id=10431>
- CPUC. (2016). Climate Adaptation in the Electricity Sector: Vulnerability Assessments & Resiliency Plans. California Public Utilities Commission (CPUC). Retrieved from [http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_\(2014_forward\)/PPD%20-%20Climate%20Adaptation%20Plans.pdf](http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_(2014_forward)/PPD%20-%20Climate%20Adaptation%20Plans.pdf)
- CPUC. (1995). General Order No. 131-D: Rules relating to the planning and construction of electric generation, transmission/power/distribution line facilities and substations located in California. Adopted June, 1994. Decision 94-06-014. Modified August 11, 1995. Effective September 10, 1995. Decision 95-08-038.
- DOE. (2017). Partnership for Energy Sector Climate Resilience. U.S. Department of Energy (DOE). Retrieved from <https://energy.gov/policy/initiatives/partnership-energy-sector-climate-resilience>
- DOE. (2016a). Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning. U.S. Department of Energy (DOE) Office of Energy Policy and Systems Analysis.
- DOE. (2016b). Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise. U.S. Department of Energy (DOE) Office of Energy Policy and System Analysis.
- DOE. (2015a). An Assessment of Heating Fuels and Electricity Markets During the Winters of 2013-2014 and 2014-2015. U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability. https://energy.gov/sites/prod/files/2015/10/f27/DOE_OE_Two%20Winters%20Report_Final_10.19.15.pdf

- DOE. (2015b). Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions. U.S. Department of Energy (DOE) Office of Energy Policy and Systems Analysis.
- DOE. (2010). Hardening and Resiliency: U.S. Energy Industry Response to Recent Hurricane Seasons. U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability.
- FEMA. (2010). Southern California Catastrophic Earthquake Response Plan. California Emergency Management Agency (CalEMA) and Federal Emergency Management Agency (FEMA) Region IX. Retrieved from https://www.fema.gov/pdf/about/regions/regionix/ca_social_oplan_public.pdf
- FHWA. (2017). Transportation Engineering Approaches to Climate Resiliency (TEACR) Study. Federal Highway Administration (FHWA). Retrieved from https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/
- FHWA. (2014). Chapter 6, Evaluating Vulnerability of Pipelines. In Impact of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2. Prepared by ICF International on behalf of Federal Highway Administration (FHWA). FHWA-HEP-14-033.
- Fisk, G., and Kay, R. (2010). Dealing with uncertainty in climate change adaptation planning and developing triggers for future action. In: Climate Change 2010: Practical Responses to Climate Change (pp. 554-563). Engineers Australia: Barton, A.C.T.
- Franco, G., Anderson, J., Wilhelm, S., Bedsworth, L., and Anderson, M. (2017). Sea Level Rise Scenarios for California's Fourth Climate Change Assessment. Guidance memorandum provided to Fourth Assessment Teams: 1/21/2017.
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global environmental change*, 23(2), 485-498.
- Haine, S. (2016). How S-MAP and RAMP Relate to PG&E GRC. California Public Utilities Commission. Pacific Gas & Electric (PG&E) General Rate Case (GRC) Workshop.
- Hanschen, P. W., & Erspamer, G. P. (2004). A Public Utility's Obligation to Serve: Saber or Double-Edged Sword? *The Electricity Journal*, 17(10), 32-49.
- IPCC. (2014). WGII AR5 Annex II: Glossary. Retrieved from Cambridge, United Kingdom and New York, NY, USA: http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-AnnexII_FINAL.pdf
- Limber, P., Barnard, P., and Hapke, C. (2015). Towards projecting the retreat of California's coastal cliffs during the 21st century. In *The Proceedings of the Coastal Sediments 2015*.
- McGahey, C., Sayers, P.B. (2008). Long term planning – robust strategic decision making in the face of gross uncertainty – tools and application to the Thames. In: *Flood Risk Management: Research and Practice*. Proceedings of FLOODrisk 2008, Taylor & Francis, London, UK, pp. 1543-1553.

- Mimura, N. (2013). Sea level rise caused by climate change and its implications for society. Proc. Jpm. Acad., Ser. B 89. Retrieved from <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3758961/pdf/pjab-89-281.pdf>
- Moss, A. and Martin, S. (2012). Flexible Adaptation Pathways. Published on ClimateXChange, UK. Retrieved from http://www.climatechange.org.uk/files/9713/7365/7868/Flexible_adaptation_pathways.pdf
- Nature Conservancy. (2017). Coastal Natural Infrastructure: Technical Guidance. Prepared by Environmental Science Associates (ESA) for The Nature Conservancy. California's Fourth Climate Change Assessment.
- New Zealand Ministry for the Environment. (2014). New Zealand's Framework for Adapting to Climate Change. Publication reference no. INFO 723. Retrieved from <http://www.mfe.govt.nz/publications/climate-change/new-zealands-framework-adapting-climate-change>
- NWS. (2014). Winter Season Summary 2013-2014. National Weather Service (NWS). Retrieved from <https://www.weather.gov/buf/wintersummary1314>.
- NYC Mayor's Office of Recovery and Resiliency. (2018). Climate Resiliency Design Guidelines. Retrieved from http://www1.nyc.gov/assets/orr/pdf/NYC_Climate_Resiliency_Design_Guidelines_v2-0.pdf.
- OPC. (2018). Updating the State of California Sea-Level Rise Guidance Document. State of California Ocean Protection Council (OPC). Retrieved from <http://www.opc.ca.gov/climate-change/updating-californias-sea-level-rise-guidance/>
- OPR. (2017). General Plan Guidelines. California Governor's Office for Planning and Research. Retrieved from <http://opr.ca.gov/planning/general-plan/>
- PG&E. (2016a). Joint Proposal to Retire Diablo Canyon Nuclear Power Plant at Expiration of the Current Operating Licenses and Replace it with a Portfolio of GHG Free Resources. Pacific Gas and Electric Company (PG&E). Available at: <https://www.pge.com/includes/docs/pdfs/safety/dcpp/JointProposal.pdf>.
- PG&E. (2016b). Retirement of Diablo Canyon Power Plant, Implementation of the Joint Proposal, and Recovery of Associated Costs through Proposed Ratemaking Mechanisms. Pacific Gas and Electric Company (PG&E). Retrieved from <https://www.pge.com/includes/docs/pdfs/safety/dcpp/diablo-canyon-retirement-joint-proposal-application-prepared-testimony.pdf>
- Pierce, D.W., Kalansky, J. F. & D. R. Cayan. (2018). Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC-2018-006.

- Radke, J., Biging, G., Schmidt-Poolman, M., Foster, H., Roe, E., Ju, Y., Hoes, O., Beach, T., Alruheil, A., Meier, L., Hsu, Wei-Chen, Neuhausler, R., Fourt, W., Lang, W., Garcia, U., & Reeves, I. (2017). Assessment of California's Natural Gas Pipeline Vulnerability to Climate Change. White Paper from the California Energy Commission's Climate Change Center. CEC-500-2017-008. Retrieved from <http://www.energy.ca.gov/2017publications/CEC-500-2017-008/CEC-500-2017-008.pdf>
- Ready San Diego. 2018. Wildfire Hazard Map. San Diego County Office of Emergency Services and Homeland Security Ready.gov. Retrieved from <http://www.readysandiego.org/wildfire-hazard-map/>
- Reeder, T., Ranger, N (2012). How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project, World Resources Report Uncertainty Series, Washington, DC. http://www.wri.org/sites/default/files/uploads/wrr_reeder_and_ranger_uncertainty.pdf
- Rolinski, T., Capps, S. B., Fovell, R. G., Cao, Y., D'Agostino, B. J., & Vanderburg, S. (2016). The Santa Ana wildfire threat index: methodology and operational implementation. *Weather and Forecasting*, 31(6), 1881-1897.
- Rosenzweig, C. and Solecki, W. (2014). Hurricane Sandy and adaptation pathways in New York: Lessons from a first-responder city. *Global Environmental Change*, Volume 28, September 2014, p. 395-408
- San Diego County. (2018). About the Sustainable Groundwater Management Act (SGMA). Retrieved from: <https://www.sandiegocounty.gov/pds/SGMA.html>. The San Diego Union Tribune. (2007). 111 homes evacuated as landslide wreaks havoc in La Jolla. Retrieved from <http://www.sandiegouniontribune.com/sdut-111-homes-evacuated-as-landslide-wreaks-havoc-in-2007oct04-story.html>
- San Diego Region Climate Collaborative. (2017). San Diego Region Climate Collaborative Home Page. Retrieved from <https://www.sdclimatecollaborative.org/>
- Schwartz, E. S., & Trigeorgis, L. (Eds.). (2004). *Real options and investment under uncertainty: classical readings and recent contributions*. MIT press.
- Scripps Institution of Oceanography. (2017). Scripps Center for Climate Change Impacts and Adaptation. Retrieved from <https://scripps.ucsd.edu/centers/adaptation/>
- SDC OES. (2018). San Diego County Multi-jurisdictional Hazard Mitigation Plan. San Diego County Office of Emergency Services (SDC OES). Retrieved from http://www.sandiegocounty.gov/content/sdc/oes/emergency_management/oes_jl_mitplan.html
- SDG&E. (2018). Natural Gas System Operator Safety Plan. Retrieved from https://www.sdge.com/sites/default/files/regulatory/SDGE_2018_Gas_Safety_Plan.pdf

- SDG&E. (2015). U.S. Department of Energy, SDG&E Partner to Improve Resiliency of Nation's Electric Grid. San Diego Gas and Electric Company (SDG&E). Retrieved from <https://www.sdge.com/newsroom/press-releases/2015-04-29/us-department-energy-sdge-partner-improve-nation%E2%80%99s-electric-grid>
- SDG&E. (2013). SDG&E Weather Network Prepares San Diego for Santa Ana Conditions. San Diego Gas and Electric Company (SDG&E). Retrieved from <https://www.sdge.com/newsroom/press-releases/2013-09-29/sdge-weather-network-prepares-san-diego-santa-ana-conditions>
- SDG&E. (2009). Application of San Diego Gas & Electric Company (U 902 E) for Authorization to Recover Unforeseen Liability Insurance Premium and Deductible Expense Increases as a Z-factor Event. Retrieved from <https://www.sdge.com/sites/default/files/regulatory/Z-factorApp.pdf>
- Sempra Energy. (2018). 2017 Annual Report: Investing for the Future. Retrieved from http://www.sempra.com/sites/default/files/content/files/node-page/file-list/2018/2017_annualreport_sre.pdf
- Sempra Energy. (2016). Risk Assessment and Mitigation Phase Report of San Diego Gas & Electric Company and Southern California Gas Company. San Diego Gas and Electric Company (SDG&E) and Southern California Gas Company (SoCalGas). Retrieved from https://www.sdge.com/sites/default/files/documents/1647252733/SDGE_SCG_Risk_Assessment_Mitigation_Phase_Submission_Report.pdf
- Seattle City Light. (2016). Climate Change Vulnerability Assessment and Adaptation Plan. Retrieved from https://www.seattle.gov/light/enviro/docs/Seattle_City_Light_Climate_Change_Vulnerability_Assessment_and_Adaptation_Plan.pdf
- Sempra Energy. (2016). Risk Assessment and Mitigation Phase Report of San Diego Gas & Electricity Company and Southern California Gas Company. Docket Number I.16-10-015. Retrieved from https://www.sdge.com/sites/default/files/documents/1647252733/SDGE_SCG_Risk_Assessment_Mitigation_Phase_Submission_Report.pdf
- SF BCDC. (2011). Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project. San Francisco Bay Conservation and Development Commission (SF BCDC). Retrieved from https://mtc.ca.gov/sites/default/files/Rising_Tides_Briefing_Book.pdf
- SoCalGas. (2018). Natural Gas System Operator Safety Plan. Retrieved from <https://www.socalgas.com/regulatory/documents/r-11-02-019/SoCalGas%202018%20Gas%20Safety%20Plan.pdf>
- SoCalGas. (2016). Chapter SCG-4 Catastrophic Damage Involving a High-Pressure Gas Pipeline Failure. In Risk Assessment and Mitigation Phase Risk Mitigation Plan. Retrieved from https://socalgas.com/regulatory/documents/i-16-10-016/SCG-4_RAMP_Catastrophic_Damage_Involving_a_High-Pressure_Pipeline_Failure_FINAL.pdf

- SoCalGas. (2016). Risk Assessment and Mitigation Phase Risk Mitigation Plan: Climate Change Adaptation. Retrieved from <https://socalgas.com/regulatory/I16-10-016.shtml>
- SoCalGas, Montecito Updates, updated February 2, 2018, accessed February 20, 2018, <https://www.socalgas.com/newsroom/montecito>
- South Coast Climate Science Alliance. (2017). South Coast Climate Science Alliance Home Page. Retrieved from <http://www.climatesciencealliance.org/about-us>
- USGCRP (2016). Glossary. U.S. Global Change Research Program (USGCRP). <http://www.globalchange.gov/climate-change/glossary>.
- Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F. and Masui, T., 2011. The representative concentration pathways: an overview. *Climatic Change*, 109(1-2), 5.
- Vicuna, S. and Dracup, J. (2009). Climate Change impacts on the Operation of Two High-Elevation Hydropower Systems in California. California Climate Change Center. CEC-500-2009-019-D. Retrieved from <http://www.energy.ca.gov/2009publications/CEC-500-2009-019/CEC-500-2009-019-D.PDF>
- Vitousek, S., Barnard, P. L., Limber, P., Erikson, L., and Cole, B. (2017). A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research: Earth Surface*, 122(4), 782-806.
- Wilby, R. L., & Dessai, S. (2010). Robust adaptation to climate change. *Weather*, 65(7), 180-185.
- Wills, C., Perez, F., & Branum, D. (2014). New method for estimating landslide losses from major winter storms in California and application to the ArkStorm scenario. *Natural Hazards Review*, 17(4), A4014001.
- Wise, R. M., Fazey, I., Smith, M. S., Park, S. E., Eakin, H. C., Van Garderen, E. A., & Campbell, B. (2014). Reconceptualising adaptation to climate change as part of pathways of change and response. *Global Environmental Change*, 28, 325-336.

APPENDIX A: Detailed Coastal Hazard Exposure Methodology

The research team developed composite data sets to analyze the exposure of gas assets to coastal hazards. The models available to assess projected hazards each having strengths (e.g., ability to run scenarios with and without coastal armoring management scenarios) and weaknesses (e.g., underestimating hazard). An exhaustive assessment of each model was not possible since several did not have full technical documentation available or full suites of data products available (e.g., CoSMoS 3.0).

The research team was able to draw on experience working directly with several of the available models. The models available for the San Diego region include:

- Pacific Institute (2009)

In 2009, the Pacific Institute mapped a 100-year coastal wave flooding extent with 0.5 m (or 1.6 ft.) and 1.4 m (or 4.6 ft.). The 100-year coastal wave flooding was determined from the effective FEMA base flood elevations (BFE), and SLR was added. This runup elevation was mapped using a bathtub model which shows coastal flooding for all elevations below the 1% annual chance wave runup BFE.

Limitations—Model uses a single elevation of wave runup at the coast from 1980s science and “floods” the landscape using a bathtub elevation approach.

Use—The team deemed this dataset has been superseded by more recent efforts and did not rely on this dataset.

- Department of Defense SPAWAR (2014)

This project, funded by DoD, developed a methodology to evaluate impacts of SLR and coastal hazards to coastal military installations in San Diego, Naval Base Coronado, and Camp Pendleton over the next century. Model results mapped future projections of coastal erosion, coastal flooding, tidal inundation, and depth of flooding along with various recurrence intervals. SPAWAR combined four 0.50 m (1.6 ft.) SLR increments (four increments from 0 to 2 m or 0.0 to 6.6 ft.) and five different storm return periods (week, month, annual, 10-year, 100-year) to generate 20 different sea level elevation scenarios.

Limitations—No longshore sediment transport; assumes overtopping of structures causes them to fail; limited geographic extent to Naval Base Coronado to Imperial Beach and Marine Corp Base Camp Pendleton.

Use—The team deemed this dataset the best at representing observed historic storm event flood extents and used this dataset in the select areas for dune and low-lying inlet erosion where it was available (Coronado to Imperial Beach).

- USGS CoSMoS Model Version 1.0 (2011)

The USGS developed the Coastal Storm Modeling System (CoSMoS) for a pilot study conducted for the entire Southern California Bight from Point Conception to the U.S.-Mexico border. For Version 1.0, the modeling team hindcast a 10-year storm that

impacted the Southern California region during January 2010. The model then projected this 10-year storm for two SLR scenarios: 0.5 m (or 1.6 ft.) and 1.4 m (or 4.6 ft.) (Barnard et al 2009).

Limitations— Does not explicitly model embayments such as San Diego Bay and did not include an assessment of other coastal hazards such as coastal erosion or impacts to sandy and cliff-backed beaches.

Use— The team determined that this dataset has been superseded by more recent efforts and did not rely on this dataset.

- USGS CoSMoS Model Version 3.0 Phase 1 and Phase 2 (2017)

CoSMoS Version 3.0 has updated the model inputs using wind fields from downscaled global climate models to project future offshore waves, and to then transform those offshore waves into 100 m spacing along the Southern California Coast. This downscaling and nested modeling approach represents the state of the science to provide future coastal hazard forcing to the nearshore. This more recent version also includes specific modeling of San Diego Bay. CoSMoS 3.0 combines ten 0.25 m SLR increments (ten increments from 0-2 m and a single 5 m increment) and four different storm return periods (daily, annual, 20-year, 100-year) to generate 40 different sea level elevation scenarios. In addition, the modeling has expanded to include not only coastal wave flooding, but cliff erosion, coastal creek flooding, and long-term shoreline change. Finally, in some of the CoSMoS 3.0 modules (cliff erosion, and shoreline position), there are several management “scenarios” - with and without historic levels of nourishment, and with or without storm erosion able to erode into urbanized “non-erodible” landscapes (a proxy for armoring). The shoreline evolution module called CoSMoS Coast maps a future Mean High Water (MHW) shoreline position by using a historic data assimilation algorithm that considers longshore and cross-shore transport.

Limitations— Maps a dynamic wave set-up 2 minute inundation water level, NOT maximum wave runoff (commonly mapped by FEMA and other models as the 1% annual chance storm). Mapped flood extents for existing conditions do not match well with observed historic flood photos and extents. In general, the model seems to underpredict the potential extent of coastal flood hazards. In addition, the model assumes no longshore sediment transport, assumes no storm erosion of urban “non-erodible” shorelines, does not explicitly map long-term dune erosion, current cliff erosion hazards, limited technical documentation on specific assumptions, and relies on the use of a topographic lidar data set collected from a single day between 2009 and 2011.

Use— The team relied heavily on this dataset as it best matched the spatial extent of the study area. Given the underestimates of existing conditions and noted limitations, the research team used the maximum flood uncertainty for the exposure analysis. For low-lying areas that did not have any erosion extents mapped, the research team did some gap filling by adjusting the MHW shoreline outputs, as described in the following sections.

- Federal Emergency Management Agency (FEMA)

FEMA is currently updating the Pacific Coast coastal flood maps for FEMA Region IX. The California Coastal Analysis and Mapping Project is conducting updates to the coastal flood hazard mapping with best improved science, coastal engineering, and regional understanding. The project incorporates regional wave transformation modeling and new runup methods and will be revising the effective flood insurance rate maps for coastal flood hazard zones. These mapped hazards include coastal wave flooding for a 100-year storm event for existing conditions. Revisions will include updating the BFE including specifically the VE (wave velocity), AE (ponded water), and X (minimal flooding) zones. The anticipated completion date is 2017-18. The preliminary coastal hazard maps were not released until February 2017 and thus were not available in time for much of the analysis.

Limitations—No SLR, no storm induced coastal erosion, use of a topographic lidar dataset collected from a single day between 2009-2011, and does not follow FEMA Pacific Coast Guidelines to use a Most Likely Winter Profile.

Use— The team deemed this dataset insufficient since it did not incorporate SLR and was not available in time for this exposure work.

For the purposes of this study, the research team used several SLR scenarios, combined with an annual tidal inundation event (i.e., 1-year return interval), and 1% annual chance (i.e., 100-year return interval) coastal wave flooding event:

- 0.0 m (0.0 ft.) SLR (1-year and 100-year) – *baseline*
- 0.5 m (1.6 ft.) SLR (1-year and 100-year)
- 2.0 m (6.6 ft.) SLR (1-year and 100-year)

The team primarily used the USGS CoSMoS 3.0 (2017) model, augmented by other coastal hazard models and technical adjustments performed by the research team. Below is a summary of models used for each coastal hazard:

- Coastal Wave Flooding (episodic storm impacts)
 - USGS CoSMoS 3.0
- Coastal Erosion (potential loss of land and assets)
 - Cliff from USGS CoSMoS 3.0¹⁶
 - Erosion of dune and low-lying inlets from USGS CoSMoS 3.0 COAST (plus geomorphic interpretation¹⁷) and SPAWAR (see data gap filling below)
- Tidal Inundation (periodic flood impacts)

¹⁶ Note: CoSMoS cliff erosion data does not include a ‘baseline’ for existing erosion hazard conditions

¹⁷ Note: The CoSMoS data available at the time of analysis did not explicitly map dune erosion hazard extents or maximum wave run-up extents.

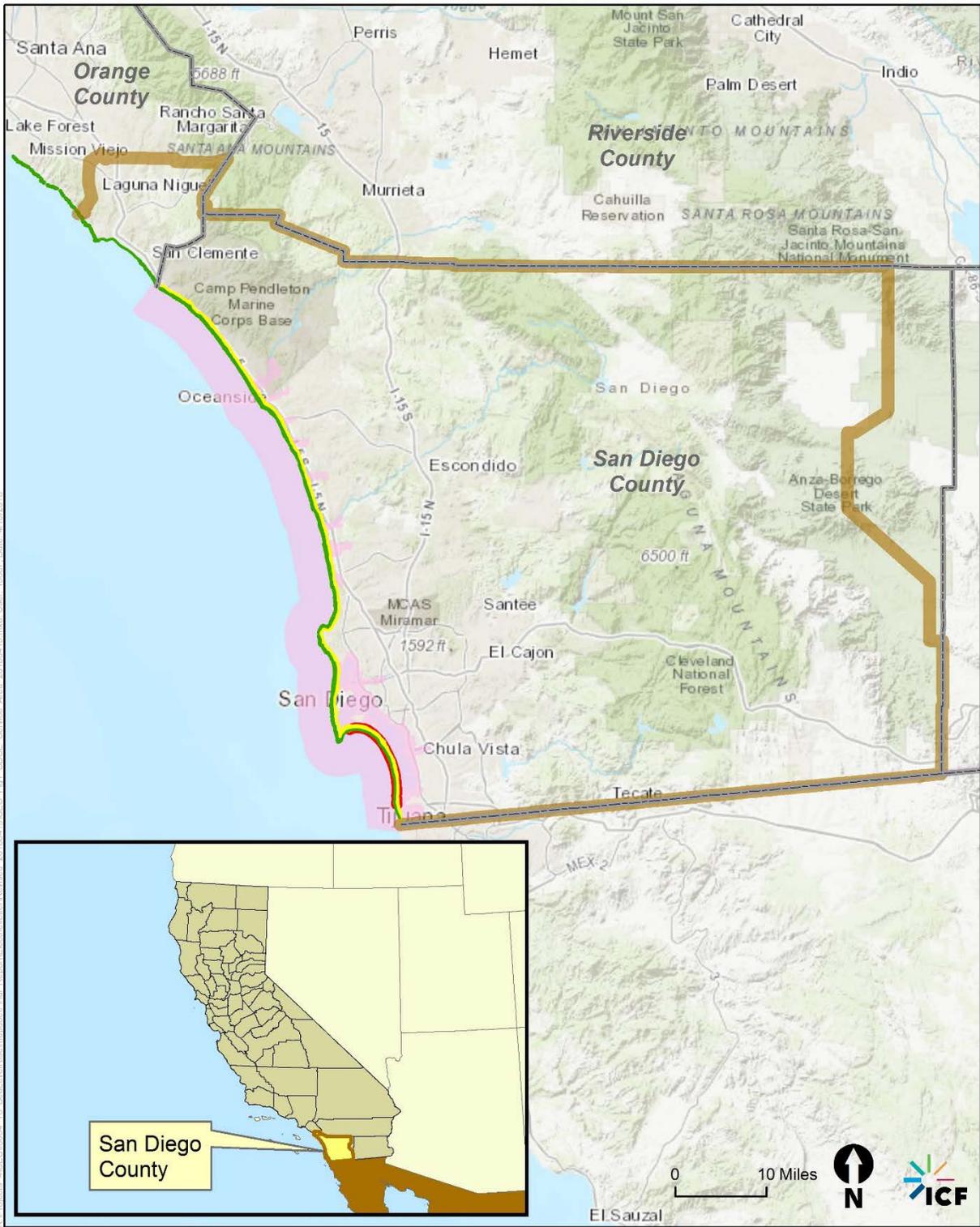
- USGS CoSMoS 3.0 (used average spring tide conditions with minor wave runup)

To enhance the specificity of the discussions with SDG&E regarding potential direct impacts, the research team supplemented the exposure analysis with additional analysis of potential depth of flooding at substation locations. The research team first developed geospatial polygons for the footprint of each substation. For each polygon, flood depths were extracted within the polygon and summarized statistically from the available raster flood depth data contained in the CoSMoS 3.0 modeling results.¹⁸ Given the uncertainty associated with wave and water level and elevation data (Erikson et al 2017), the results include the maximum flood depth in addition to the associated uncertainty (68 cm) from the CoSMoS 3.0 data.

¹⁸ The research team also calculated depths based on the SPAWAR data for comparison, however the SPAWAR data do not cover the entire study extent. In general, the COSMOS flood depths were deeper than the SPAWAR data for the evaluated locations.

APPENDIX B. Detailed Exposure Results

Using the hazard model information discussed above, and asset location data provided by SoCalGas, the research team used GIS to intersect the hazard zones with the natural gas point assets (controllable gas valves, excess flow valves, in-line meters, non-controllable fittings, non-controllable gas valves, regulators, service connection) and line assets (gas pipe casing, high pressure pipe, high pressure service pipe, miscellaneous gas line, medium pressure pipe, medium pressure service pipe) exposed to each coastal hazard scenario. The following section reports exposure results by asset type and scenario for values with at least one point asset or mi. (0.02 km) of line assets exposed. Figure B-1, below, depicts the spatial extents of the CoSMoS and SPAWAR data.



- USGS CoSMoS coastal wave flooding and tidal inundation extent
- USGS CoSMoS low-lying and dune erosion extent
- USGS CoSMoS cliff erosion extent
- SPAWAR extent
- SDGE Service Area Boundary
- County Line

Figure B-1. Extents of CoSMoS and SPAWAR data. Sources: USGS; SAPWAR; ESRI

B.1 Coastal Hazards

The sections below describe potential asset exposure to coastal wave flooding, coastal erosion, and tidal inundation.

B.1.1 Coastal Wave Flooding

As expected, because the hazard is only along the coastline, there is a large number or miles of assets exposed under the maximum exposure scenario for 2.0 m SLR plus a 100-year event, shown in Table B-1 and Table B-2, below. However, the total number of assets exposed by percentage is small. Specifically:

- 27 out of the 607 regulators are exposed.
- 28 mi. out of 582 mi. (45 km of 937 km) of high pressure pipe is exposed.
- Just over 137 mi. out of 7,769 mi. (221 km of 12,503 km) of medium pressure pipe is exposed.
- More than 13,500 service connections out of 816,977 are exposed.

Table B-1. Potential Point Asset Exposure to Coastal Wave Flooding (100-year Event)

Asset Type	System Total	0 m (0 ft.) SLR	0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	194	267	785
Excess Flow Valve	10,441	61	79	144
Non-Controllable Fitting	137,175	1102	1508	3541
Regulator	607	3	6	27
Service Connection	816,977	5,197	6,695	13,620

Table B-2. Potential Line Asset Exposure to Coastal Wave Flooding (100-Year Event)

Asset Type	System Total		0 m (0 ft.) SLR		0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
	mi.	km	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	3.93	6.32	6.18	9.95	12.6	20.28
HP Pipe	582	937	10.59	17.04	15.44	24.85	28.03	45.11
HP Service Pipe	2	3	0.08	0.13	0.18	0.29	0.51	0.82
MP Pipe	7,769	12,503	42.95	69.12	62.89	101.21	137.47	221.24
MP Service Pipe	6,831	10,993	30.51	49.10	41.39	66.61	92.57	148.98

B.1.2 Coastal Erosion

The research team found that a limited set of assets are exposed to coastal erosion, although several potential critical aboveground assets such as regulators are exposed; details are provided in Table B-3 and Table B-4, below. In addition, this analysis determined that there are multiple specific infrastructure within the CoSMoS Hold the Line data for cliff erosion and low-lying erosion scenarios, such as accreting cliffs and shorelines in front of the cliffs that move oceanward over time. The research team has alerted USGS to these issues. As a consequence, the research team is unable to present results for this scenario.

For cliff erosion, under the Do Not Hold the Line with 2.0 m SLR, 162 service connections and 1 mile (1.6 km) of medium pressure pipe is exposed.

Table B-3. Potential Point Asset Exposure to Coastal Cliff Erosion (Do Not Hold)

Asset Type	System Total	Potentially Exposed to SLR	
		0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	0	5
Non-Controllable Fitting	137,175	1	45
Service Connection	816,977	8	162

Table B-4. Potential Line Asset Exposure to Coastal Cliff Erosion (Do Not Hold)

Asset Type	System Total		Potentially Exposed to SLR			
			0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	0.02	0.03	0.08	0.13
HP Pipe	582	937	0.00	0.00	0.17	0.27
HP Service Pipe	2	3	0.00	0.00	0.01	0.02
MP Pipe	7,769	12,503	0.02	0.03	1.02	1.64
MP Service Pipe	6,831	10,993	0.12	0.19	1.51	2.43

For low-lying erosion from CoSMoS for San Diego County for Do Not Hold the Line management option with a 100-year event, the research team finds a variety of assets exposed, including:

- Four regulator stations, which may be key assets within the system (to be explored in subsequent tasks) are exposed; nearly 175 controllable gas valves, more than 100 excess flow valves, and 5,425 service connections are also exposed.
- Nearly 5 mi. (8 km) of high pressure pipe is exposed and 42 mi. (68 km) of medium pressure pipe is exposed.

Additional details of exposure results are provided in Table B-5, Table B-6, Table B-7, and Table B-8, below.

Table B-5. Potential Point Asset Exposure to Low-Lying Erosion (1-year event, Do Not Hold)

Asset Type	System Total	Potentially Exposed to SLR	
		0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	105	149
Excess Flow Valve	10,441	31	65
Non-Controllable Fitting	137,175	587	820
Regulator	607	3	4
Service Connection	816,977	3,425	4,604

Table B-6. Potential Point Asset Exposure to Low-Lying Erosion (100-year event, Do Not Hold)

Asset Type	System Total	Potentially Exposed to SLR	
		0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	123	173
Excess Flow Valve	10,441	49	101
Non-Controllable Fitting	137,175	682	943
Non-Controllable Gas Valve	5	0	2
Regulator	607	3	4
Service Connection	816,977	3,862	5,425

Table B-7. Potential Line Asset Exposure to Low-Lying Erosion (1-year event, Do Not Hold)

Asset Type	System Total		Potentially Exposed to SLR			
			0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	3.37	5.42	4.06	6.53
HP Pipe	582	937	1.48	2.38	3.1	4.99
MP Pipe	7,769	12,503	28.12	45.25	36.83	59.27
MP Service Pipe	6,831	10,993	18.96	30.51	25.76	41.46

Table B-8. Potential Line Asset Exposure to Low-Lying Erosion (100-year event, Do Not Hold)

Asset Type	System Total		Potentially Exposed to SLR			
			0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	3.59	5.78	4.59	7.39
HP Pipe	582	937	2.54	4.09	4.78	7.69
MP Pipe	7,769	12,503	31.83	51.23	42.09	67.74
MP Service Pipe	6,831	10,993	21.3	34.28	31.44	50.60

Table B-9, Table B-10, Table B-11, and Table B-12, below, present the SPAWAR data for dune and low-lying inlet erosion focused on a limited stretch of coast (San Diego Bay only: Coronado to Imperial Beach), reporting only the numbers of exposed assets rather than the percentage of overall assets. The results indicate a limited number of assets exposed in this portion of the Service Area:

- No regulators or excess flow valves are exposed.
- 1-year event: 322 service connections are exposed.
- 100-year event: 428 service connections are exposed.
- No high-pressure pipeline is exposed from either a 1-year or 100-year event for all sea level rise scenarios.
- 1-year event: 3 mi. (6 km) of medium pressure pipe is exposed.
- 100-year event: 6 mi. (9 km) of medium pressure pipe is exposed.

Table B-9. Potential Point Asset Exposure to Low-Lying Erosion (SPAWAR, 1-year event)

Asset Type	System Total	Potentially Exposed to SLR		
		0 m (0 ft.) SLR	0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	1	4	25
Non-Controllable Fitting	10,441	0	9	70
Service Connection	4	2	80	322

Table B-10. Potential Point Asset Exposure to Low-Lying Erosion (SPAWAR, 100-Year Event)

Asset Type	System Total	Potentially Exposed to SLR		
		0 m (0 ft.) SLR	0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	4	10	25
Non-Controllable Fitting	10,441	8	35	87
Service Connection	4	28	215	428

Table B-11. Potential Line Asset Exposure to Low-Lying Erosion (SPAWAR, 1-Year Event)

Asset Type	System Total		Potentially Exposed to SLR					
			0 m (0 ft.) SLR		0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	0.00	0.00	0.13	0.21	0.22	0.35
MP Pipe	7,769	12,503	0.00	0.00	0.32	0.51	3.47	5.58
MP Service Pipe	6,831	10,993	0.12	0.19	0.91	1.46	2.16	3.48

Table B-12. Potential Line Asset Exposure to Low-Lying Erosion (SPAWAR, 100-Year Event)

Asset Type	System Total		Potentially Exposed to SLR					
			0 m (0 ft.) SLR		0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	0.05	0.08	0.15	0.24	0.29	0.47
MP Pipe	7,769	12,503	0.27	0.43	1.57	2.53	5.60	9.01
MP Service Pipe	6,831	10,993	0.52	0.84	1.48	2.38	2.87	4.62

B.1.3 Tidal Inundation

Under the maximum inundation scenario of a 2.0 m of SLR, a limited percentage of assets are exposed, as shown in Table B-13 and Table B-14, below. However, over 118 mi. (190 km) of medium pressure pipe and 24 regulators, which could be important aboveground assets:

- 24 out of the 607 regulators are exposed.
- Just over 25 mi. of 582 mi. (41 km of 937 km) of high pressure pipe are exposed.
- Just over 118 mi. of the 7,769 mi. (190 km of 12,503 km) of medium pressure pipe is exposed.
- Over 11,000 out of 816,977 service connections are exposed.

Table B-13. Potential Point Asset Exposure to Tidal Inundation

Asset Type	System Total	Potentially Exposed to SLR		
		0 m (0 ft.) SLR	0.5 m (1.6 m) SLR	2.0 m (6.6 ft.) SLR
Controllable Gas Valve	24,224	87	160	678
Excess Flow Valve	10,441	26	44	109
Non-Controllable Fitting	137,175	569	975	3,008
Regulator	607	0	3	24
Service Connection	816,977	2,934	4,432	11,357

Table B-14. Potential Line Asset Exposure to Tidal Inundation

Asset Type	System Total		Potentially Exposed to SLR					
			0 m (0 ft.) SLR		0.5 m (1.6 m) SLR		2.0 m (6.6 ft.) SLR	
Units	mi.	km	mi.	km	mi.	km	mi.	km
Gas Pipe Casing	337	542	2.19	3.52	3.37	5.42	11.61	18.68
HP Pipe	582	937	6.96	11.20	10.28	16.54	25.53	41.09
HP Service Pipe	2	3	0.02	0.03	0.09	0.14	0.50	0.80
MP Pipe	7,769	12,503	20.38	32.80	36.29	58.40	118.07	190.01
MP Service Pipe	6,831	10,993	15.00	24.14	25.33	40.76	78.80	126.82

B.2 Wildfire

The current SDG&E wildfire fuel map provides a baseline for the wildfire hazards. In the SDG&E Service Area, two distinct fire-types are possible. The first is a grass-fuel driven fire, which is characterized by fast moving and lower temperature fires, compared to the second type, the shrub-fuel driven fire. By later this century, projections indicate:

- A 40% increase in wildfire area burned statewide (Bryant and Westerling 2012).
- That between 171,100 and 230,400 point assets and between 2,800 and 3,900 mi. (4,500 – 6,200 km) of line length are projected to experience an increase in wildfire area burned (representing 17 – 23% of point assets and 18 – 25% of line asset length). Detailed exposure statistics are provided in Table B-15, Table B-16, Table B-17, and Table B-18, below. Projected change in wildfire area burned is also depicted for the model ensemble average and for the four climate models used, being CanESM2 (average), CNRM-CM5 (cool/wet), HadGEM2-ES (warm/dry), and MIROC5 (complement). See Figure B-1, Figure B-2, Figure B-3, Figure B-4, and Figure B-5.

Table B-15. Point Assets by Fuel Type

Fuel Type	Controllable Gas Valve	Excess Flow Valve	In Line Meter	Non-Controllable Fitting	Regulator	Service Connection
System Total	24,224	10,441	4	137,175	607	816,977
High load forest litter	68	14	0	578	4	1,818
High load shrub	91	17	0	685	9	2,124
Light load forest litter	2	1	0	24	1	133
Light load grass and shrub mixture	8	64	0	122	1	299
Light load shrub	0	0	0	0	0	3
Long and dense grass	139	1,262	0	1,296	24	4,223
Moderate load grass and shrub mixture	311	695	0	2,774	34	9,724
Moderate load shrub	126	47	0	907	12	2,821
Short and coarse grass	170	305	1	1,238	10	3,669
Short and dense grass	100	23	0	584	24	1,816

Table B-16. Line Assets by Fuel Type

Fuel Type	Gas Pipe Casing		HP Pipe		HP Service Pipe		Misc. Gas Line		MP Pipe		MP Service Pipe	
	mi.	km	mi.	km	mi.	km	mi.	km	mi.	km	mi.	km
System Total	337	542	582	937	2	3	4	6	7,769	12,503	6,831	10,993
High load forest litter	0.5	0.8	9	14	0.03	0.05	0.05	0.08	36	58	28	45
High load shrub	0.8	1.3	7	11	0.09	0.14	0.11	0.18	45	72	32	51
Light load forest litter	0	0.0	1	2	0.00	0.00	0	0.00	2	3	3	5
Light load grass and shrub	0.1	0.2	1	2	0.00	0.00	0.02	0.03	8	13	4	6
Long and dense grass	0.3	0.5	15	24	0.00	0.00	0.12	0.19	47	76	27	43

Fuel Type	Gas Pipe Casing		HP Pipe		HP Service Pipe		Misc. Gas Line		MP Pipe		MP Service Pipe	
	mi.	km	mi.	km	mi.	km	mi.	km	mi.	km	mi.	km
Moderate load grass and shrub mixture	2.1	3.4	41	66	0.11	0.18	0.27	0.43	162	261	113	182
Moderate load shrub	0.6	1.0	12	19	0.02	0.03	0.02	0.03	52	84	36	58
Short and coarse grass	1.3	2.1	14	23	0.02	0.03	0.11	0.18	50	80	38	61
Short and dense grass	0.2	0.3	15	24	0.01	0.02	0.04	0.06	34	55	29	47

Table B-17. Point Assets within Areas Projected to Experience an Increase in Area Burned

Asset Type		Controllable Gas Valve	Excess Flow Valve	Non-Controllable Fitting	Regulator	Service Connection
System total		24,224	10,441	137,175	607	816,977
Assets within areas projected to increase in area burned	Model Ensemble Average	5,432	1,921	29,051	156	160,981
	CanESM2 (average)	4,899	1,501	25,538	140	139,052
	CNRM-CM5 (cool/wet)	5,162	1,570	26,811	133	147,253
	HadGEM2-ES (warm/dry)	5,432	1,921	29,051	156	160,981
	MIROC5 (complement)	6,013	2,126	33,721	181	188,327

Table B-18. Line Assets within Areas Projected to Experience an Increase in Area Burned

Asset Type		HP Pipe		HP Service Pipe		MP Pipe		MP Service Pipe	
		mi.	km	mi.	km	mi.	km	mi.	km
System total		582	937	2.5	4.0	7,769	12,503	6,831	10,993
Assets within areas projected to increase in area burned	Mode 1 Ensemble	150	241	0.4	0.7	7,769	12,503	6,831	10,993
	CanESM2 (average)	132	213	0.2	0.3	1,624	2,613	1,450	2,333
	CNRM-CM5 (cool/wet)	130	210	0.4	0.7	1,400	2,254	1,255	2,020
	HadGEM2-ES (warm/dry)	150	241	0.4	0.7	1,475	2,374	1,323	2,129
	MIROC5 (complement)	169	272	0.4	0.7	1,624	2,613	1,450	2,333

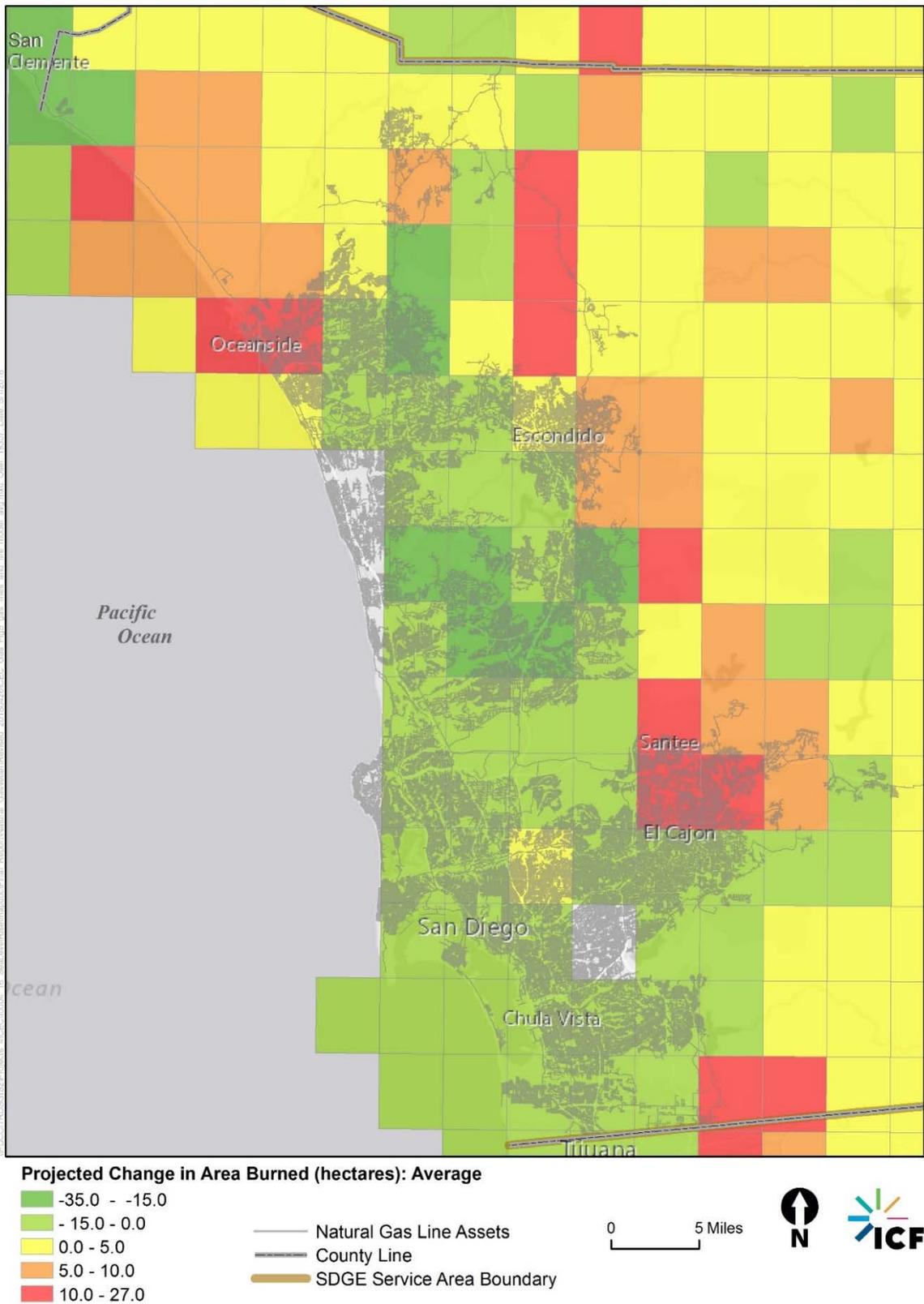


Figure B-1. Projected change in area burned (model ensemble average) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

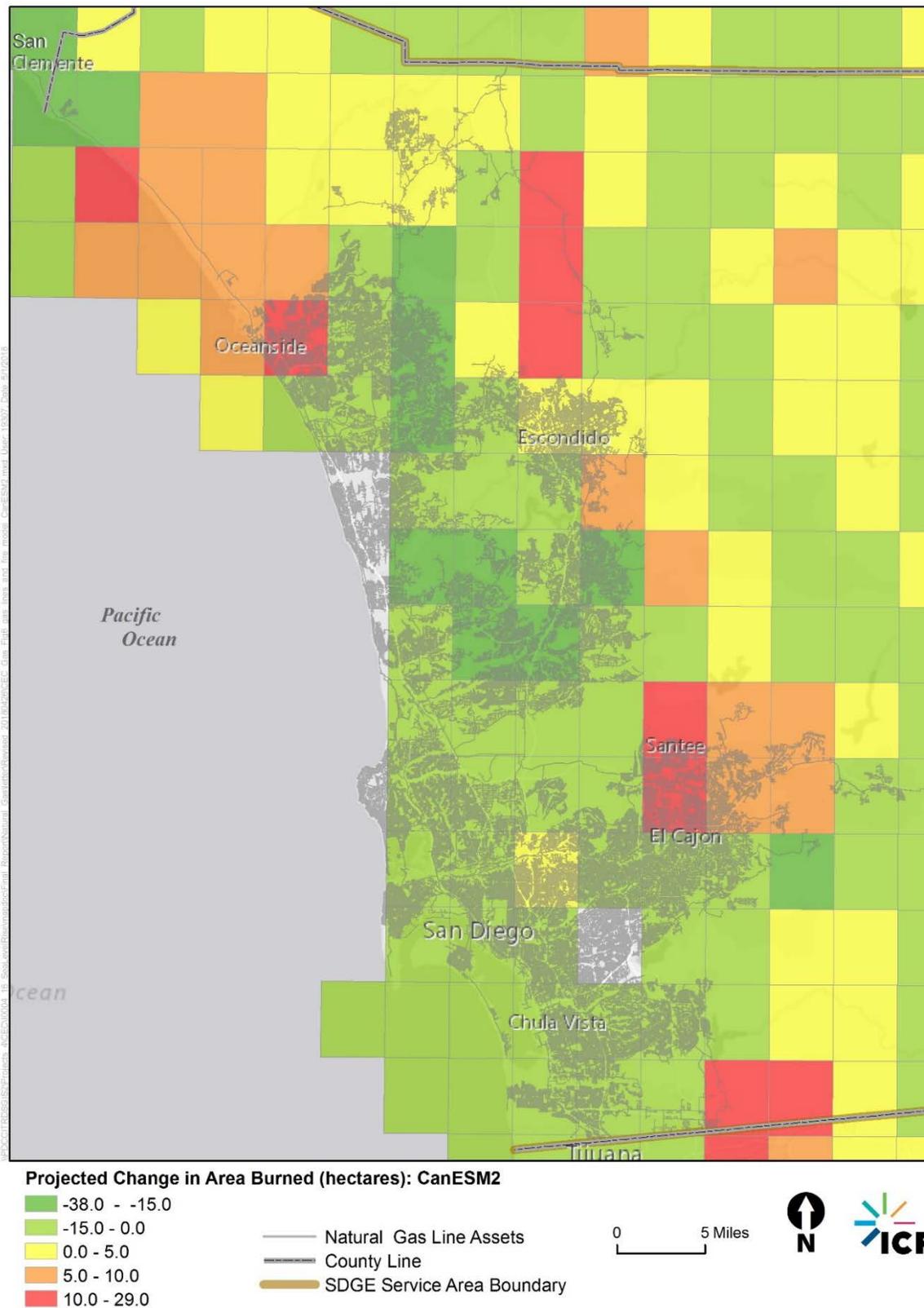
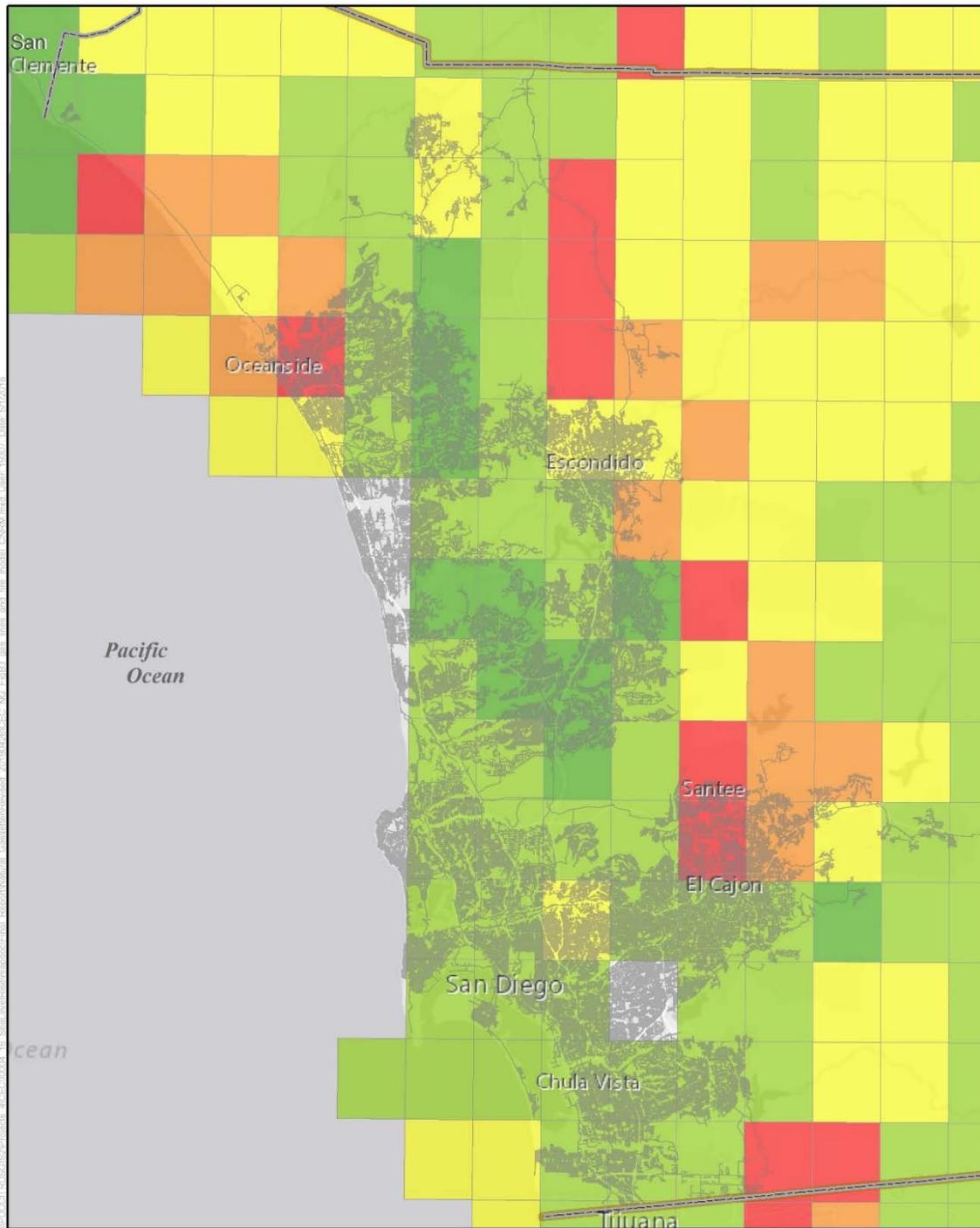


Figure B-2. Projected change in area burned (minimum model projected, CanESM2) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI



Projected Change in Area Burned (hectares): CNRM-CM5

- -35.0 - -15.0
- -15.0 - 0.0
- 0.0 - 5.0
- 5.0 - 10.0
- 10.0 - 23.0

- Natural Gas Line Assets
- County Line
- SDGE Service Area Boundary

0 5 Miles



Figure B-3. Projected change in area burned (CNRM-CM5) and natural gas line assets in SDG&E Service Area. Sources: SoCalGas; Cal-Adapt; ESRI

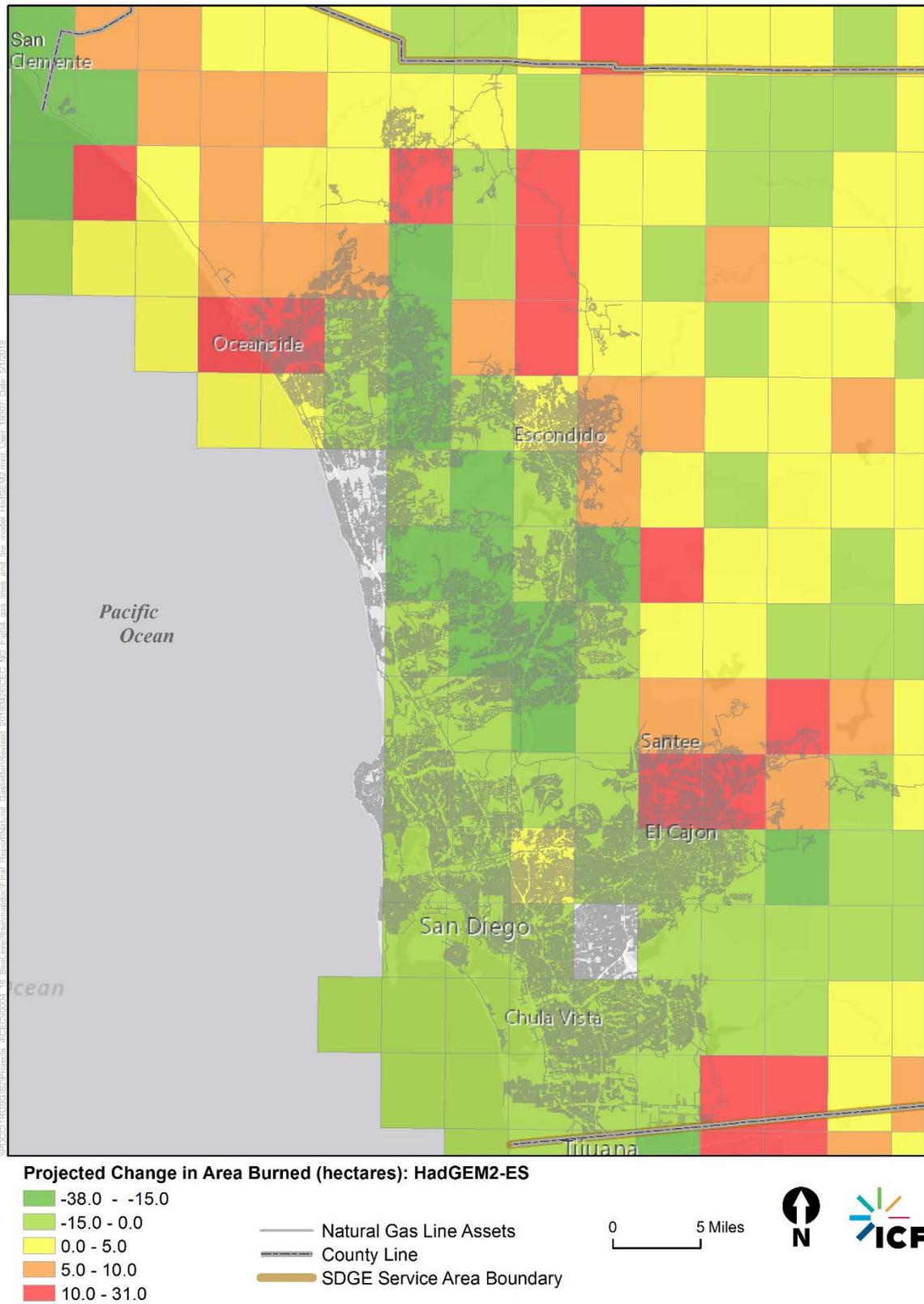


Figure B-4. Projected change in area burned (HadGEM2-ES) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

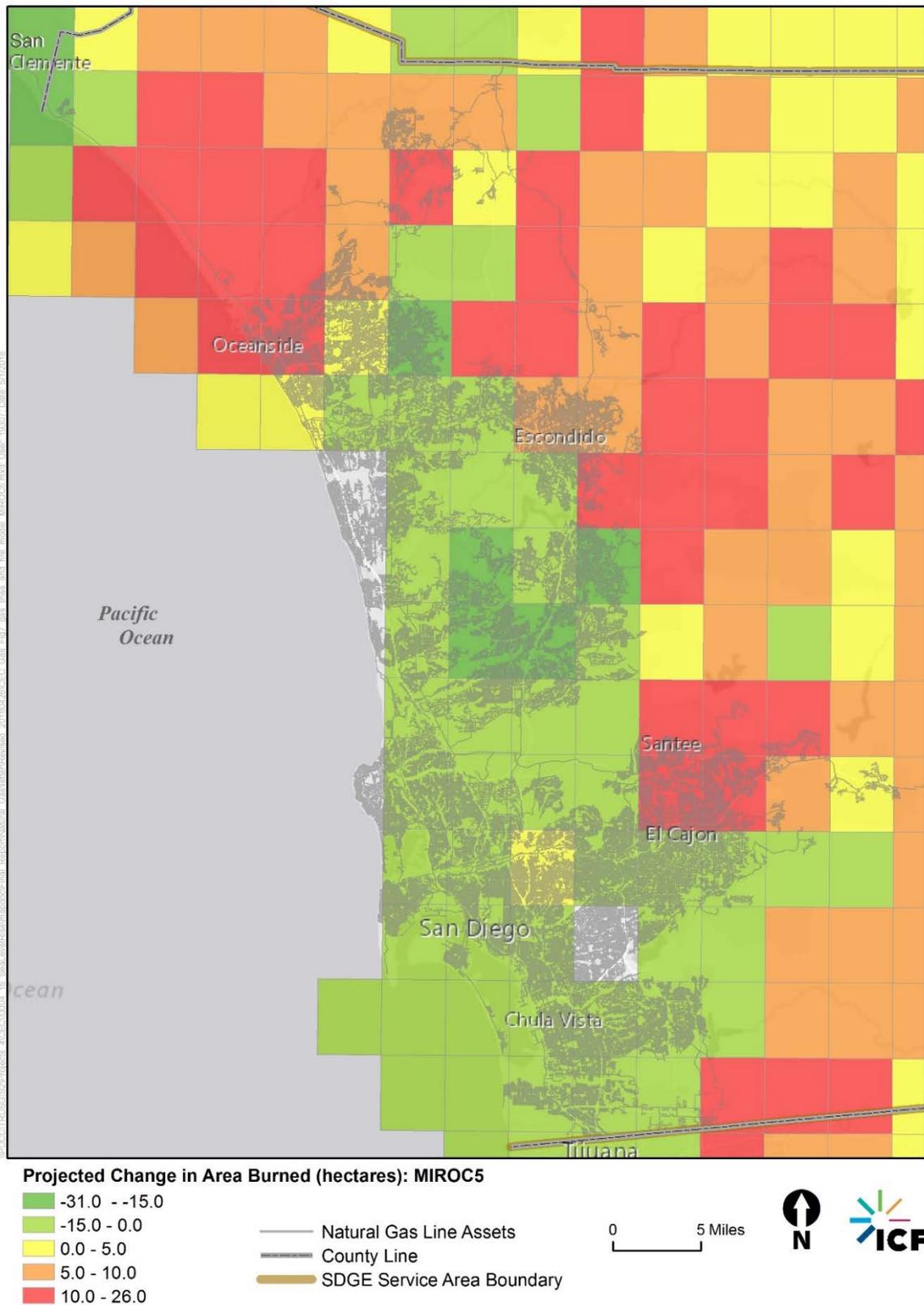


Figure B-5. Projected change in area burned (maximum model projection, MIROC5) and natural gas line assets in SDG&E Service Area. Sources: SDG&E and SoCalGas; Cal-Adapt; ESRI

B.3 Extreme Heat

The SDG&E Service Area is projected to undergo an increase in the number of days exceeding the extreme heat threshold, with the least change occurring along the coast and the greatest increases occurring inland. Gas assets within the SDG&E Service Area are projected to experience an increase of 0 to 14 extreme heat days per year under RCP 4.5 and an increase of 1 to 22 extreme heat days per year under RCP 8.5. Under RCP 4.5, the vast majority of gas assets are projected to undergo an increase of less than five extreme heat days (56% of total gas line length) or of 5 to 10 extreme heat days (33% of total gas line length). Under RCP 8.5, the majority of gas assets are projected to see an increase of 5 to 10 days (54% of total gas line length) or of 10 to 15 extreme heat days (21% of total gas line length), while a small amount (12% of total gas line length) is projected to experience an increase of 15 to 20 extreme heat days. Exposure to extreme heat is presented in Table B-19, Table B-20, and Table B-21, below.

Table B-19. Potential Line Asset Exposure to Extreme Heat

Projected Change in Extreme Heat Days	RCP 4.5		RCP 8.5	
	Length of Gas Lines (mi.)	Percent of Gas Lines	Length of Gas Lines (mi.)	Percent of Gas Lines
<5	8,619	56%	2,058	13%
5-10	5,132	33%	8,434	54%
10-15	1,774	11%	3,192	21%
15-20	0	0%	1,822	12%
20-25	0	0%	20	0.1%
Total	15,526	100%	15,526	100%

Table B-20. Potential Point Asset Exposure to Extreme Heat Under RCP 8.5

Additional Extreme Heat Days	Controllable Gas Valve	Excess Flow Valve	Non-Controllable Fitting	Regulator	Service Connection
<5	4,405	907	17,658	113	114,828
5-10	13,690	4,702	74,843	297	458,177
10-15	3,515	4,114	28,699	110	161,487
15-20	2,569	718	15,737	77	81,808
20-25	34	0	168	10	229
Total	24,213	10,441	137,105	607	816,529

Table B-21. Potential Line Asset Exposure to Extreme Heat Under RCP 8.5

Additional Extreme Heat Days	HP Pipe		HP Service Pipe		Misc. Gas Line		MP Pipe		MP Service Pipe	
	mi.	km	mi.	km	mi.	km	mi.	km	mi.	km
<5	75	121	1.0	1.7	0.6	0.9	919	1,478	878	1,414
5-10	312	503	1.1	1.7	2.5	4.0	4,220	6,791	3,766	6,060
10-15	112	180	0.2	0.4	0.9	1.5	1,683	2,708	1,384	2,227
15-20	73	118	0.1	0.1	0.4	0.7	941	1,514	800	1,287
20-25	10	15	0.1	0.1	0.0	0.1	7	11	3	5
Total	582	937	2.5	4.0	4.5	7.2	7,769	12,503	6,831	10,993

B.4 Inland Flooding

The FEMA NFIP FIRMs identify Special Flood Hazard Areas (SFHAs). There are two (2) basic SFHAs, commonly referred to as the 100-year and 500-year floodplain. A 100-year floodplain is an area subject to a 1 percent or greater chance of being equaled or exceeded during any given year. The 100-year floodplain areas actually have a 26 percent chance of occurring during a 30- year period. The 500-year floodplain has a 0.2 percent chance of being equaled or exceeded in any given year. Notably, these FEMA floodplains do not incorporate projected changes in climate, such as changes in precipitation. Based on these FEMA definitions, the FEMA NFIP FIRM provides the following hazard descriptions (or zones):

- 0.2 percent annual chance Flood Hazard
- 100-year flooding; flood depths range from 1 to 3 ft. (0.3 to 0.9 m)
- 100-year flooding, for which Base Flood Elevations (BFEs) have been determined
- 100-year flooding, for which no BFEs have been determined
- 100-year flooding protected from the 100-year flood by a Federal flood protection system
- 100-year flooding with velocity hazard
- An area of undetermined but possible flood hazards

The high-level results from the research team’s modeling determined that:

- Less than 5% of natural gas point assets are in the FEMA NFIP FIRM flood zones, of which over two thirds (3% of all point assets) are in the 500-year floodplain.
- Little over 5% of natural gas line assets are in the FEMA NFIP FIRM flood zones, of which nearly two thirds (3% of all line length) are in 500-yr floodplain.

Detailed exposure results are depicted in Table B-22 and Table B-23, below.

Table B-22. Potential Point Asset Exposure to Inland Flooding

FEMA Flood Hazard Description	Controllable Gas Valve	Excess Flow Valve	Non-Controllable Fitting	Non-Controllable Gas Valve	Regulator	Service Connection
System Total	24,224	10,441	137,175	5	607	816,977
0.2% annual Chance	833	134	5,105	0	28	24,392
100-year flooding; flood depths range from 1 to 3 ft. (0.3 to 0.9 m).	50	2	159	0	4	386
100-year flooding; flood depths range from 1 to 3 ft. (0.3 to 0.9 m).	107	1	447	0	4	1,451
100-year flooding, for which BFEs have been determined.	321	42	1,560	0	9	3,386
100-year flooding, for which no BFEs have been determined.	153	12	658	0	6	1,393
100-year flooding protected from the 100-year flood by a Federal flood protection system	107	0	489	1	1	2,503
100-year flooding with velocity hazard	1	0	0	0	0	1
An area of undetermined but possible flood hazards.	237	201	1,043	0	27	3,063
Total	1,809	392	9,461	1	79	36,575

Table B-23. Potential Line Asset Exposure to Inland Flooding

FEMA Flood Hazard Description	Gas Pipe Casing		HP Pipe		HP Service Pipe		Misc. Gas Line		MP Pipe		MP Service Pipe	
	mi.	km	mi.	km	mi.	k	mi.	k	mi.	km	mi.	km
System Total	337	542	582	937	2	3	4	6	7,769	12,503	6,831	10,993
0.2% annual Chance	6	10	22	35	0	0	0	0	242	389	194	312
100-year flooding; flood depths range from 1 to 3 ft.	0	0	1	2	0	0	0	0	5	8	4	6

FEMA Flood Hazard Description	Gas Pipe Casing		HP Pipe		HP Service Pipe		Misc. Gas Line		MP Pipe		MP Service Pipe	
	mi.	km	mi.	km	mi	k	mi	k	mi.	km	mi.	km
100-year flooding; flood depths range from 1 to 3 ft.	0	0	4	6	0	0	0	0	16	26	11	18
System Total (0.3 to 0.9 m).	337	542	582	937	2	3	4	6	7,769	12,503	6,831	10,993
100-year flooding, for which BFEs have been determined.	4	6	18	29	0	0	0	0	67	108	32	51
100-year flooding, for which no BFEs have been determined.	2	3	11	18	0	0	0	0	29	47	12	19
100-year flooding protected from the 100-year flood by a Federal flood protection system	0	1	2	3	0	0	0	0	30	48	21	34
100-year flooding with velocity hazard	0	0	0	0	0	0	0	0	0	0	0	0
An area of undetermined but possible flood hazards.	1	2	41	66	1	1	0	0	53	85	33	53
Total	13	21	98	158	1	1	1	1	443	713	307	494

B.5 Landslides

The California Geologic Survey data provides the following hazard descriptions:

- Landslide – confirmed, known, or highly suspected
- Landslide – possible or conjectured
- Slide Prone Formation – Ardath – neutral or favorable geologic structure
- Slide Prone Formation – Ardath – unfavorable geologic structure
- Slide Prone Formation – Friars – unfavorable geologic structure
- Slide Prone Formation – Friars – neutral or favorable geologic structure
- Slide Prone Formation – Otay – Sweetwater and others

The high-level results from the research team’s modeling determined that:

- Over 4% of the natural gas point assets are in landslide areas, the majority of which are in the slide prone formations, as shown in Table B-24, below.
- Over 8% of the natural gas line assets are landslide areas, the majority of which are in the slide prone formations as shown in Table B-25 below.

Table B-24. Potential Point Asset Exposure to Landslides

CGS Definitions	Controllable Gas Valve	Excess Flow Valve	Non Controllable Fitting	Regulator	Service Connection
System Total	24,224	10,441	137,175	607	816,977
Landslides	48	4	457	1	3,629
not steep slope	40	3	406	1	3,249
steep slope	8	1	51	0	380
Slide Prone Formations	696	195	4,807	19	33,543
not steep slope	634	173	4,454	13	32,476
steep slope	62	22	353	6	1,067
Total	744	199	5,264	20	37,172

Table B-25. Potential Line Asset Exposure to Landslides

CGS Definitions	Gas Pipe Casing		HP Pipe		Misc. Gas Line		MP Pipe	
	mi.	km	mi.	km	mi.	km	mi.	km
System Total	337	542	582	937	4	6	7,769	12,503
Landslides	0.5	0.8	0.6	1.0	0	0.0	32	51
not steep slope	0.4	0.6	0.4	0.6	0	0.0	29	47
steep slope	0.1	0.2	0.2	0.3	0	0.0	3	5
Slide Prone Formations	3.2	5.1	18	29.0	0.08	0.1	295	475
not steep slope	2.8	4.5	15	24.1	0.06	0.1	275	443
steep slope	0.4	0.6	4	6.4	0.02	0.0	19	31
Total	3.7	6.0	19	30.6	0.08	0.1	326	525

APPENDIX C: Detailed Methodology for Modeling Natural Gas Indirect Impacts

For the analysis of indirect impacts to gas assets within the SDG&E Service Area from climate hazards, the ICF Gas Market Model (GMM®) was used. Details on the modeling are provided below.

C.1 Reference Case

For the reference case, or baseline scenario, the research team assessed whether the assumptions for the base case were materially different from the assumptions in the ICF standard GMM reference case used to model the natural gas market without climate change. The research team reviewed available information on projected energy supply and demand for California. For California, total electricity demand is projected to decrease over time from 254,951 GWh in 2016 to 245,176 GWh in 2035 (Table C-1). In this study, California electricity demand is assumed flat after 2035. For the reference case, the research team updated assumptions for California consistent with projection from 2016 California Gas Report (PG&E 2016b). The research team updated California electricity demand, renewable generation, local production, and assumptions on Aliso Canyon working gas capacity. For example, the working gas capacity of the Aliso Canyon storage facility is assumed to be restricted to about 25 Bcf starting from 2016 consistent with EIA reported data (unrestricted capacity was 86 Bcf).¹⁹ This 25 Bcf represents 8% of total California storage working gas capacity of 315 Bcf from 2016. If no data is specified in the California Gas Report, ICF Base Case assumptions (e.g. nuclear generation) were used. The research team did not change assumptions outside of California.

Table C-1. Projected energy supply and demand information for California through 2035. Source: California Gas Report 2016 (PG&E 2016b)

	2016	2017	2018	2019	2020	2025	2030	2035
Electricity Demand (GWh)	254,951	253,808	251,995	250,857	250,201	249,154	247,036	245,176
Renewable Electric Generation (GWh)	63,738	68,528	73,078	77,766	82,556	103,339	123,518	122,558
Renewable Electric Generation Share	25%	27%	29%	31%	33%	42%	50%	50%

Utilities are assumed to phase out nuclear powered electricity generation by 2025 with an expansion of renewables over the next 15 years (PG&E 2016b). This assumption is adapted from the Pacific Gas & Electric announcement last year on the retirement of two Diablo Canyon units

¹⁹ This study relied upon information available at the time and it was beyond the scope of the study to comprehensively analyze implications of different capacity scenarios for the Aliso Canyon storage facility, or scenarios of gas supply availability and reliability with and without Aliso Canyon.

(PG&E 2016b) and their Joint Proposal (PG&E 2016a). For this analysis, the electric generation mix was assumed to remain at 2035 levels for the remainder of the study period (2050).

C.2 Climate Hazard Case

In addition to the exposure analysis results, the research team performed additional research on the supply and demand aspects of the natural gas system that are influenced by climate change to define a specific climate hazard case to model. The case includes changes to heating and cooling degree days, hydropower generation, and Mexican exports, as well as a “climate extreme” year in 2050. In this way, the climate hazard case captures long term trends as well as a potential future “event” driven by climate changes in the future consistent with best available science on projected future climate, as well as observed historical extremes.

Heating and Cooling Degree Days

Heating and cooling degree days are a common proxy for energy needed to heat and cool buildings, respectively. Heating degree days (HDD) refers to the number of degrees that a day’s average temperature exceeds a given temperature threshold, while cooling degree days (CDD) refer to the number of degrees that a day’s average temperature falls below a given temperature threshold. Using a 65°F (18°C) threshold for the SDG&E Service Area, the historical (1976-2005) annual number of CDD is 1,017 degree days, compared to 1,787 degree days for 2050 (RCP 8.5; 2036-2065) period. Table C-2 provides a monthly breakdown of historical (1976-2005) and 2050 (RCP 8.5; 2036-2065) CDDs for the SDG&E Service Area (Cal-adapt.org Degree Days Tool 2017).

Table C-2. Monthly breakdown of historical and future cooling degree days for SDG&E Service Area

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Historical	0	0	4	9	40	134	280	302	200	52	3	0
2050	5	0	9	27	89	245	409	446	355	174	27	6

Using the same threshold and time periods, the historical annual number of HDDs is 2,236 degree days, compared to 1,440 degree days for 2050 (RCP 8.5).

Hydropower Generation

Projections of future hydropower generation in California and the Northwest vary. In California, for example, climate change and variability is expected to decrease the average annual hydropower generation by 3.1% under RCP 4.5, but have negligible impact under RCP 8.5. While overall volume of future available water for energy production may be similar or higher, the delivery of this volume is expected to be significantly more variable in the future climate than the historical average, which has many implications for hydropower generation (Tarroja et al. 2016). A study of two high-elevation hydropower systems in California (Upper America River Project and Big Creek System) shows that generation may decrease -8.2% for Upper America River Project and -8% for Big Creek System by mid-21st century (2014-2070) for B1 and A2 emission scenarios (Vicuna and Dracup 2009).

Summer hydropower generation in the Northwest (Washington, Oregon, and Idaho) could decrease by 18-21% by 2080 compared to 20th century levels due to decreased flows under the

moderate (A1B) emissions scenario. Declining April 1st snowpack and earlier spring snowmelt is expected to shift peak streamflow timing in snowmelt-fed rivers, potentially reducing summer water availability and hydropower generation. Winter precipitation is expected to increase, with a greater fraction expected to fall as rain rather than as snow. Overall, annual average precipitation is expected to decline (DOE 2015b).

Mexican Exports

ICF GMM does not model Mexico endogenously. Natural gas exports to Mexico are input to the model. In the climate hazard case, gas exports to Mexico are assumed to increase linearly by +10 percent by 2050 due to increased CDD in the region. This assumption was based on average changes in the U.S. gas generation due to increased CDDs in the climate hazard case. In the 2050 Extreme Condition case, ICF GMM assumes an extreme hot summer in Mexico and increased exports by +15 percent (another +5 percent from the linear trend).

Extreme Conditions

In the SDG&E Service Area, the historical (1976-2005) annual number of extreme heat days (days exceeding 95.5°F or 35°C, which is historical 98th percentile) is 4.9, compared to 32 days for 2050 (RCP 8.5; 2036-2065) (Cal-adapt.org Extreme Heat Tool 2017).

During the winter for 2013-2014, a polar vortex caused the U.S. residential and commercial gas consumption to be 15% higher than the average of the prior five winters (DOE 2015a, NWS 2014).

ICF's GMM evaluated how the climate hazard scenario would affect the natural gas market compared to the reference case.

The GMM incorporates the following climate change assumptions, based on research outlined above, to inform the climate hazard case.

Changes to CDDs, HDDs, hydropower generation, and Mexican exports versus the Reference Case:

- For CDD in the Pacific region, increased by 67% and used monthly profile as specified in Table C-2 (above) for the SDG&E Service Area. For all other regions, increased CDD by 67% and used the historical monthly profiles.
- Decrease HDDs in the Pacific region linearly by -700 (-23%) through 2050. Implement same percentage decrease in other regions.
- Reduce hydropower generation throughout the U.S. linearly by -25% through 2050.
- Increase Mexico exports linearly by +10% through 2050 (based on average changes in U.S. gas generation due to increased CDDs).

Extreme Conditions in 2050:

- Extreme hot summer in California: Increase Pacific CDD by +800 (another +250 from the linear trend).
- Extreme cold winter/polar vortex in the Northeast, Midwest, and Southeast: Implement 2013-2014 HDD's.

- Very low hydro generation: Reduce by -1 standard deviation of historical data (by region) on top of the linear trend using expert judgement to capture potential extreme drought, similar to 2015, in addition to linear decline.
- Extreme hot summer in Mexico: Increase exports by +15% (another +5% from the linear trend).

In addition, the model makes several macroeconomic assumptions including a constant oil price beyond 2026; the influence of each could be explored through additional research. The macroeconomic assumptions for the reference case include are shown in Table C-3.

Table C-3. Gas Market Model Q3 2017 base case macroeconomic assumptions

Category	Reference Case Assumption
Economic Growth Rate (U.S. GDP Annual Growth Rate)	2017 = 2.35% 2018-25 = 2.1% 2026-2035 = 2.1%
Industrial Production Growth Rate	2.3% per year
Oil Price (Annual Average Refiners' Average Cost of Crude real 2016\$/bbl)	2017 = \$45 2018-2025 = \$45-\$75 2026-2035 = \$75
Inflation Rate	2016 = 1.4% 2017-2025 = 2.1% 2026-2035 = 2.1%
Demographics	Regional population growth based on U.S. Census Bureau projections U.S. average rate of growth is approximately 1% per year.

Weather Station Network

SDG&E operates a utility-owned weather network to track weather conditions and monitor fire risk (SDG&E 2013). The system is one of the largest and most sophisticated in the U.S., and includes approximately 170 weather stations throughout the San Diego region (Cho and Day 2015; SDG&E 2013). These stations measure variables such as temperature, humidity, wind speed, and solar radiation (SDG&E 2013). SDG&E provides this weather information to regional fire responders, including CAL FIRE and local fire agencies, providing real-time information to firefighters through a mobile application, enabling them to more effectively combat wildfires (SDG&E 2013). SDG&E is also collaborating with universities and government agencies to use the data to study the Santa Ana winds (SDG&E 2013).

At the adaptation workshop, participants noted that this wildfire monitoring system can be used as a model to implement a coastal flooding monitoring system, which would track tidal and wave conditions and provide forecasts about which areas and assets are at risk of coastal inundation.

APPENDIX D: Potential Adaptation Measures

As the adaptation pathways are implemented, SoCalGas will need to make decisions about how to implement adaptation at the asset level. When beginning the assessment of what measures to take for a given asset, it is helpful to understand the range of possible adaptation measures.

Therefore, the research team undertook a literature review to identify adaptation measures applicable to the gas sector. The literature review assessed RAMP filings, other utility Vulnerability Assessments & Resilience Plans, the California Adaptation Planning Guide, and reports produced through the U.S. Department of Energy's Partnership for Energy Sector Climate Resilience (the Partnership). One Partnership document, *Climate Change and the Electric Sector: Guide for Climate Change Resiliency Planning* (DOE 2016a) provided a useful categorization of energy system adaptation measures. While developed with a focus on electricity systems, the categorization scheme is applicable to other energy systems, such as natural gas systems, as well. The *Partnership* document categorizes adaptation measures into:

- **System hardening**—reducing the probability of damage or disruption e.g., elevating, retrofitting, and relocating assets; enhancing distributed generation.
- **Planning and modifying operations**—e.g., updating designs and resource plans; enhancing communications and monitoring technologies; implementing energy efficiency programs; deploying demand response management tools; mutual aid agreements; risk transfer/insurance.

The list of adaptation measures developed through the Partnership is shown in Table D-1 together with specific inputs gained through the study. The adaptation measures were divided by the Research Team into those adaptation measures within the purview of SDG&E implementation (Table D-1) and adaptation measures that require regional collaboration (Table D-1). It is important to note that the general range and example costings of adaptation measures are drawn from the Partnership only and that specific discussion on the cost/benefit of adaptation measures was not undertaken with SoCalGas for this study. However, the Partnership's costing estimates are retained for ease of reference.

It is also important to note that the adaptation measures listed are not expected to be solely implemented by SDG&E. Rather, as outlined in the body of this report, it is suggested that SDG&E collaborate with regional stakeholders to develop a suite of adaptation actions that, when taken together, create an integrated adaptation response to the risks posed by climate change hazards. This will require careful deliberation over the relative contributions to adaptation efforts by organizations in the region, and the identification of specific responsibilities for mitigating risks of climate change-driven hazards. It will also require the consideration of potential unintended impacts that may result from such actions. For example, the implementation of a coastal protection structure to reduce coastal hazard risk may limit a recreational amenity and disrupt the flow of beach sand, resulting in erosion of down-drift beaches (USACE 2013). As a result, an action which is appropriate may in fact be mal-adaptive, reducing resilience elsewhere, or negatively impacting the community in another manner. For this reason, Action D: Regional consultation is suggested as an initial adaptation action in Section 3.3.2. Consultation and collaboration can build off of existing partnerships, such as those described in Appendix E.

Furthermore, engaging regulatory organizations in regional collaboration will be critical to ensure that existing regulatory hurdles are recognized and overcome. This will require regulatory agencies in the energy sector, including CPUC and CEC, to work closely with agencies with coastal hazard management responsibilities, such as the California Coastal Commission. CEC and other agencies may wish to consider additional research to better understand how regulations might currently inadvertently inhibit resiliency efforts, and where newly policies and regulations could encourage utilities to undertake resiliency efforts. For example, future research could explore whether rules related to cost recovery, building standards, or smart grid technology are hindering or helping resilience goals.

It is also important to note that this table is meant to be inclusive of a broad range of adaptation measures that could be applicable to natural gas utilities in general, with the intention that this table could serve as a resource for utilities besides SoCalGas. Not all of these measures are necessarily appropriate for the SDG&E Service Area. Where possible, Table D-1 indicates whether the adaptation measure is being actively pursued or considered by SoCalGas.

Table D-1. Natural Gas Adaptation Measures

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
System Hardening								
Harden assets	Install flexible connections at meter. ²⁰	Impacts workshop					x	Y
	Install shut-off valves at property lines in wildfire high risk areas.	Impacts workshop		x				N
	Elevate regulators.	Adaptation workshop	x			x		Y
	Select an appropriate grade of steel and apply flame retardant and protective coatings to aboveground pipelines at risk of wildfire exposure, particularly cable bridges.	Adaptation workshop		x				Y
	Install protection devices for vent lines of high-pressure regulators to prevent water infiltration and resulting over-pressurization of downstream customer equipment, or loss of customer pilot lights.	Consolidated Edison 2015	x			x		N
	Harden remotely controlled valve (RCV) equipment to prevent water intrusion, including (a) replacing wire in hollow conduit with solid cables and cable glands that are rated for wet and dry use, eliminating the water migration path, and (b) replacing analog actuators with digital actuators.	Consolidated Edison 2015	x				x	N

²⁰ Applicable to minor land settlement only, recognizing meter connections follow American National Standards Institute B109, which requires the meter connections withstanding certain torsional and bending moment tests and that flexible connectors would not withstand major landslide movement.

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Harden remotely controlled valve (RCV) manhole vaults by (a) removing existing casting and install storm-hardened bolt-down inner pan and casting where feasible, (b) excavate as necessary to expose all vault penetrations and interface between vault wall and ceiling, then apply waterproof coating over these elements, (c) apply waterproof coating inside of manhole, (d) install or replace penetration seals as needed, € rebuild vent post system and manhole walls if they appear to be a major source of water infiltration. ¹⁷	Consolidated Edison 2015	x			x		N
Protective new construction	Complete road and storm drainage improvements.	Sempra RAMP Filing 2016				x	x	Y
	Implement construction storm water management plans.	Sempra RAMP Filing 2016				x		Y
	Alter or create channel or drainage paths.	Sempra RAMP Filing 2016				x		Y
	Install protective structural walls or retention ponds.	Sempra RAMP Filing 2016				x		Y
	Install a firewall around equipment at risk of being exposed to wildfire.	Adaptation workshop		x				N
	Install control valves, if possible remotely controlled, for systems at risk of being exposed to wildfire to allow for isolation ¹⁸ .	Adaptation workshop		x				Y
	Install tie-back systems (soil nails) coupled with shotcrete.	Sempra RAMP Filing 2016					x	Y

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Install Riprap, shot rock, or vegetation.	Sempra RAMP Filing 2016	x			x		Y
	Install floodwall(s).	DOE 2010	x					N
	Install levee(s).	DOE 2010	x			x		N
	Install berm(s).	DOE 2010	x			x		N
Natural Infrastructure	Marsh Creation.	DOE 2016a	x					N
	Vegetated dunes. Adding vegetation to dunes causes more sand to be trapped and deposited, causing the dune to grow. Vegetating dunes is an option to enhance resilience of SoCalGas assets that are along a shore lined by sandy beaches with dunes are threatened by coastal flooding.	The Nature Conservancy 2017 ¹⁹	x					N
	Cobble berms or dynamic revetments. Cobble berms are mounds of rounded rocks, and are referred to as dynamic revetments in areas where they do not occur naturally. Cobble berms are appropriate in areas where coastal cliff erosion threatens gas assets, and where coastal flooding threatens gas assets that are along a shore lined by beach.	The Nature Conservancy 2017	x					N
	Tidal benches. Tidal benches are gently-sloping beaches that extend from mean or low tide level to the backshore, and act as wind wave breaks. Tidal benches are appropriate for areas with assets at risk of exposure to coastal wave flooding.	The Nature Conservancy 2017	x					N

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Oyster reef. Oyster reefs reduce shoreline erosion potential and dissipate wave energy. These reefs are appropriate in bays and estuaries, nearby assets that are threatened by low-lying erosion or wave run-up.	The Nature Conservancy 2017	x					N
	Eelgrass beds. Eelgrass beds help dissipate wave energy at low tide. Because the beds do not provide this benefit at high tide, they are not recommended as a primary adaptation measure for assets threatened by coastal inundation, rather would be beneficial as a component of a portfolio of measures.	The Nature Conservancy 2017	x					N
	Lagoon mouth management. Lagoon estuary water levels are typically higher than ocean water levels, and are affected by mouth management, which can lower lagoon water levels. This measure is appropriate for gas assets that are threatened by coastal flooding and are nearby lagoons.	The Nature Conservancy 2017	x					N
Relocate assets	Relocate existing assets in high risk areas. Note that relocating regulator stations or other major infrastructure is very difficult and expensive.	The Nature Conservancy 2017, DOE 2016b, DOE 2010	x	x		x	x	N
	Reroute pipeline (more feasible than relocating major point assets like regulator stations).	Adaptation workshop	x				Y	
Planning and Operations								
Enhance monitoring	Increase pipeline patrols.	Sempra RAMP Filing 2016					x	Y
	Implement satellite monitoring in the areas identified.	Sempra RAMP Filing 2016					x	Y

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Install strain gauges in area identified.	Sempra RAMP Filing 2016					x	Y
	Enhance monitoring for coastal and inland flooding, wildfire, and heat.	DOE 2016a	x	x	x	x		Y ²⁰
	Monitor cathodic protection (corrosion) system.	PG&E 2016			x			Y
	Monitor equipment for heat damage.	PG&E 2016			x			Y
	Enhance heat wave prediction systems and predictions of increased gas demand from gas-fired power plants.	Adaptation workshop			x			N
	Conduct regular inspection of assets threatened by coastal flooding or erosion.	DOE 2010, Adaptation workshop	x		x	x	x	Y
Harden workforce	Educate workforce on importance of managing heat stress, and provide water, sunscreen, shade areas, and increased breaks, and ensure that staff are looking out for one another.	Adaptation workshop			x			Y
	Arrange a method to procure additional staff to help during emergencies when a large number of staff is needed (e.g., during a wildfire, flood, etc.).	Adaptation workshop	x	x		x		N
Harden operations	Manage vegetation surrounding assets in areas at risk of experiencing wildfire.	Adaptation workshop		x				Y
	Warn customers not to turn off gas preemptively.	Impacts workshop		x				Y
	Enhance equipment for corrosion inspections.	Adaptation workshop	x			x		Y
	Procure, pre-position, pre-wire portable generators for equipment reliant on electricity.	DOE 2010	x	x	x	x	x	Y

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
Enhance supply	Diversify gas supply sources (e.g., LNG, biogas, power to gas from renewables) for periods during which there are supply shortages.	Adaptation workshop, DOE 2010	x	x	x	x	x	Y
Reduce demand	Demand reduction programs.	DOE 2016a	x	x	x	x	x	N
	Electricity workshop participants discussed opportunities to notify customers when supply shortages are expected and request increased conservation. When appropriate, collaborate with local governments to accurate information and improve public perception. SoCalGas already has a notification program that does this.	DOE 2010	x	x	x	x	x	Y
Enhance capacity for recovery	Upgrade control centers and communication equipment.	DOE 2016b, DOE 2010	x	x	x	x	x	N
	Install redundant communications.	DOE 2010	x	x	x	x	x	N
	Update emergency operations plan.	DOE 2016b	x	x	x	x	x	Y
	Conduct emergency preparedness planning and training.	DOE 2010	x	x	x	x	x	Y
	Arrange mutual aid agreements.	DOE 2016b	x	x	x	x	x	Y

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Conduct research on projected changes in climate.	Sempra RAMP Filing 2016	x	x	x	x	x	Y
	Identifying emergency replacement pipe and related equipment.	Sempra RAMP Filing 2016					x	Y
	Facilitate employee evacuation and reentry.	DOE 2010	x	x		x	x	N
	Coordinate priority restoration and waivers/permits.	DOE 2010	x	x	x	x	x	N
Enhance system planning	Integrate system changes to enhance resilience in long-range planning.	DOE 2016b	x	x	x	x	x	N
	When designing assets (including access roads), the utility could consider coastal flooding projections. Where flooding is inevitable, design sensitive assets (such as conduits and vaults) to be watertight. Creating a mapping system that illustrates projected sea level rise during average and storm conditions, and using this information in planning processes is recommended.	Seattle City Light 2016	x	x	x	x	x	N
	Institute a utility-wide policy requiring that future climate impacts be considered during the design of major proposed capital improvement projects.	Seattle City Light 2016	x	x	x	x	x	N
Reduce financial liability	Use indemnity-based insurance. Insurance tends to be for high-value assets, and/or high-cost events; thus may not cover lower-cost damages that occur frequently.	DOE 2016b, Adaptation workshop	x	x	x	x	x	N

Adaptation Measure Category	Adaptation Measure	Reference	Coastal	Wildfire	Heat	Inland Flooding	Landslide	Pursuing?
	Incorporate adaptation costs into general rate case.	Adaptation workshop	x	x	x	x	x	N

¹⁷ Many RCVs are hardened as they are pneumatically actuated as opposed to electrically actuated. Furthermore, actuators in vaults are resilient to moisture (though not submersible). Newer vaults are also hardened as SoCalGas uses sump pump cavities for draining, as opposed to using bottomless vaults.

¹⁸ While remotely controlled valves (RCVs) have been used to address geological threats, they have not yet used RCVs to address wildfire risks

¹⁹ This project, funded under the Fourth Assessment and conducted by the Nature Conservancy, investigates where natural infrastructure might be appropriate, and then completed engineering analyses on several different design options. This research was not conducted with energy infrastructure in mind, but rather with the general goal of protecting the shoreline.

²⁰ SoCalGas currently has a project to monitor and evaluate inland flooding areas, but does not monitor or evaluate the other hazards.

APPENDIX E. Example Existing Adaptation Efforts Relevant to SDG&E and SoCalGas

Many of the adaptation measures noted in the main body of the report build on or are facilitated by current adaptation-related activities at SDG&E and SoCalGas, as well as complementary efforts at the national, state, and local scale. These efforts are summarized below.

E.1 Existing Adaptation Efforts Within SDG&E and SoCalGas

There are several existing efforts underway at SDG&E and SoCalGas that are, directly or indirectly, addressing climate risk. Although some efforts are conducted by SDG&E rather than SoCalGas, relevant efforts by both SoCalGas and SDG&E are included due to the close relationship between the two companies in the SDG&E Service Area. These efforts are described in the following subsections:

RAMP Report

The California Public Utilities Commission (CPUC) requires IOUs to submit reports on their Risk Assessment and Mitigation (RAMP) Phase. The RAMP reports aim to provide insight into how the utilities identify and quantify risks and risk mitigation, particularly related to safety-related risks.

SDG&E and SoCalGas submitted their first, joint RAMP report in November 2016 (Sempra Energy 2016). This report covers risks posed by climate change and identifies near-term mitigation measures. In this report, SoCalGas proposes certain adaptation measures such as:

- **Geological Hazard Engineering Data Analysis and Flood Hazard Dashboard.** SoCalGas is developing a program to automate the assessment of land movement that might damage the system. The program will link satellite monitoring and flood hazard data to an eGIS system and create algorithms to identify problem areas. The dashboard will also overlay data on gas system areas susceptible to flash flooding and landslides.
- **Strain Gauge Installation Projects.** SoCalGas identified locations where strain gauges should be installed and maintained between 2016 and 2019. The team will continue to run this program, based on new information on land movement from the geological hazard and satellite monitoring programs.
- **Slope Stability & Erosion Control Projects.** SoCalGas will work with the internal operations group to identify areas where pipelines are prone to slope instability and erosion. SoCalGas will analyze adverse effects to assets in these areas, and initiate monitoring and/or mitigation as appropriate.

Santa Ana Wildfire Threat Index

SoCalGas/SDG&E, in partnership with the U.S. Department of Agriculture and the U.S. Forest Service, also developed a web-based tool that indicates fire threat potential based on Santa Ana

wind conditions (SDG&E 2015). The tool uses meteorological and fuel moisture inputs to create a 6-day forecast of wildfire index in the San Diego region (Rolinski et al. 2016). This forecast enables the utility and first responders to preemptively move firefighters and resources to high-risk areas, and alert the public to the fire risk (Casola and Zamuda 2017). The forecast also enables the utility to isolate major electricity transmission lines within high-risk areas (Casola and Zamuda 2017). These measures minimize the number of customers impacted by outages and reduce the likelihood of additional fires starting due to damage to electricity infrastructure (Casola and Zamuda 2017). This index could serve as a model for a similar threat index related to coastal hazards.

Blythe Compressor Station

In building the Blythe compressor station, SoCalGas modified design standards for operating temperatures to account for projected changes in temperatures, based on Cal-adapt.org projections (CEC 2017a).

Fiber Optic System

SoCalGas stakeholders reported the recent installation of the utility's first fiber optic pipeline monitoring system that will assist to detect and prevent leaks, as well as encroachments from third party dig-ins. Given the sensitivity of this monitoring system, there is scope to use this technology to monitor the impacts of climate hazards by, for example, detecting the sounds made by water flowing on the surface above a buried transmission pipeline. While the first such installations are outside the SDG&E Service Area, SoCalGas stakeholders reported that there are plans to install one of these systems soon in San Diego County.

Wildfire Emergency Response - Digging Coordination

SoCalGas stakeholders communicated that the utility has been active in coordinating with emergency responders during recent wildfire events to prevent any digging damage to pipelines. SoCalGas personnel actively work with firefighters during these events to ensure that any pipelines are not damaged during the removal of vegetation, particularly while constructing firebreaks.

E.2 National, State, and Local-Level Energy Adaptation Efforts Relevant to SDG&E/SoCalGas

U.S. Department of Energy (DOE) Partnership for Energy Sector Climate Resilience

As outlined in the previous section, SDG&E is an active member of the U.S. Department of Energy (DOE) Partnership for Energy Sector Climate Resilience. The program is a partnership between energy companies and DOE, and aims to enhance energy security by increasing the resilience of energy systems to extreme weather and climate impacts. Under the Partnership, energy companies commit to identifying priority climate vulnerabilities, developing and pursuing resilience strategies, and sharing lessons learned with fellow partners. Meanwhile, DOE provides technical assistance and develops tools to enable energy utilities to assess their vulnerabilities and evaluate the cost and benefits of resilience strategies. The Partnership has provided a forum for peer-to-peer discussion and mutual learning on climate change issues and the technical papers produced have proved valuable for this study.

As a part of the partnership, SDG&E has provided input into the DOE reports *Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning* (DOE 2016a) and *Climate Change and the U.S. Energy Sector: Regional Vulnerabilities and Resilience Solutions* (DOE 2015a). SDG&E also produced a high-level climate vulnerability assessment under the partnership.

CPUC Climate Adaptation in the Electricity Sector Vulnerability Assessments & Resiliency Plans

SDG&E has recognized the paper *Climate Adaptation in the Electricity Sector: Vulnerability Assessments & Resiliency Plans* produced by CPUC as helping to encourage IOUs to undertake climate change vulnerability assessments (CPUC 2016). The study recognized the thought leadership contained in the paper by inviting its lead author to attend TAC meetings.

California Adaptation Planning Guide

The first version of the Adaptation Planning Guide (APG) was released in 2012 and provides broad guidance on adaptation planning processes and measures (CNRA 2017). The APG is intended to be a generalized guidance and as such is not tailored to the specific needs of electricity utilities. It is understood that an update to the APG is planned for 2018 and SoCalGas could provide inputs into its development to enhance its usefulness for IOUs, should this be appropriate.

Safeguarding California: Implementation Action Plans: Energy Sector

The 2014 California climate change adaptation strategy, *Safeguarding California*, was accompanied by sectoral implementation action plans, including one for the energy sector (CNRA 2016). The Energy Sector Plan outlines potential vulnerabilities, progress in implementing the adaptation strategy, next steps to advance climate resilience, and indicators for monitoring and evaluating adaptation in the energy sector. The plan recommends next steps focused on collaboration and research. The plan proposes partnerships between the government agencies (i.e., CEC, CPUC, DOE) and energy utilities to develop plans to incorporate climate adaptation into utility operations, CPUC proceedings, and CEC research. The plan also suggests that energy sector government agencies and utilities collaborate to ensure that research produces actionable outcomes and results in adaptation investments.

This document highlights SDG&E/SoCalGas's efforts in advancing energy sector adaptation in California. The document calls attention to SDG&E's participation in the U.S. DOE Partnership for Energy Sector Climate Resilience, and points to SDG&E's South Bay Substation as a good example of infrastructure that has been upgraded to consider climate impacts and adaptation needs.

The recently released 2018 *Safeguarding California* update specifically cites as a next step that "[t]he Energy Commission will continue to explore, in collaboration with CPUC and other energy entities, best practices for incorporating climate change and adaptation into the investor- owned utilities' and publicly owned utilities' planning processes" (Next Step E-3.1.a) (CNRA, 2018).

CEC-supported Research Studies

Through its partnership role on the current study, SoCalGas is actively engaged in the Fourth Assessment process. The utility recognizes that this has the benefit of ensuring access to the latest thinking on adaptation assessment. SoCalGas could collaborate on future CEC-funded research

studies with a focus on those that improve base climate change scenarios to support adaptation decision making.

San Diego Regional Climate Change Collaborative

SDG&E is an active member of the San Diego Regional Climate Collaborative, including membership of the Steering Committee (San Diego Region Climate Collaborative 2017). One of the Collaborative's key roles is to support the region to prepare for local climate change impacts. The utility understands the benefit of regional coordinated adaptation planning and implementation to ensure the most cost-effective and equitable response. SDG&E remains committed to the Collaborative.

Additional Potential Local/Regional Climate Partnerships

Additional local and regional partnerships SoCalGas may wish to pursue include:

- The **Climate Science Alliance**, which is a regional group that aims to enhance climate resilience within the South Coast Eco-region, which stretches from Santa Barbara County down to San Diego County (South Coast Climate Science Alliance 2017). The alliance develops partnerships to increase awareness of climate change and climate impacts. Partnerships are focused on science, climate smart conservation, and community engagement; partners include government agencies, education and art organizations, conservation organizations, universities, and businesses and philanthropies. While SoCalGas is not currently a partner, SoCalGas could become a partner and engage the Alliance in the future should the utility decide to pursue activities that extend throughout the coastal Southern California region.
- **Climate Education Partners (CEP)**, a team of collaborators from California universities and the San Diego Foundation who work to share climate science with San Diego region leaders to help them make informed decisions (Climate Education Partners 2017). CEP focuses on educating leaders from the business, government, transportation, tribal, public health, and Latino communities. Should SoCalGas decide to pursue outreach efforts related to climate adaptation in the future, CEP could be a valuable partner.
- The University of California, San Diego's Scripps Institution of Oceanography recently established a **Center for Climate Change Impacts and Adaptation** (Scripps Institution of Oceanography 2017). The Center aims to advance understanding of climate change and climate impacts, as well as to enhance resilience to these impacts. To accomplish this mission, the Center performs research and outreach. In the future, SoCalGas could potentially collaborate with the Center to further investigate its climate vulnerabilities and develop adaptation solutions.
- Participation in updates to **LHMPs and Catastrophic Plans**. These plans not only discuss potential risks facing local communities, but also discuss potential impacts and necessary actions to manage the events. SoCalGas participation could ensure that potential impacts to the electric grid are fully understood, and that priority post-event actions are adequate.

Participation in local government **Local Coastal Program (LCP)** updates. LCPs aim to guide coastal zone development and protect coastal resources. Each LCP contains a land use plan as well

as measures to implement the plan (e.g., zoning ordinances). When local governments update their LCPs, SDG&E could collaborate with them to recommend guidance that would enhance the resilience of the electricity system.

APPENDIX F. References Reviewed During Literature Review

- Amir Aghakouchak Pers. Comm. (2016). Interview about A Multi-Hazard Investigation of Climate Vulnerability of the Natural Gas Energy System in Southern California. ICF International.
- Berg, N. and A. Hall (2015). Increased inter-annual precipitation extremes over California under climate change. *Journal of Climate* 28(16): 6324-6334.
- Bryant, B. and A. L. Westerling (2012). Scenarios to evaluate long-term wildfire risk in California: New methods for considering links between changing demography, land use, and climate, California Energy Commission.
- Bryant, B. and A. L. Westerling (2009). Potential effects of climate change on residential wildfire risk in California, California Climate Change Center.
- CA DWR (2013). California's flood future: recommendations for managing the State's flood risk, California Department of Water Resources (DWR) and Natural Resources Agency (NRA).
- Cal-adapt.org (2016). Temperature: Extreme Heat Tool. California Energy Commission.
- California Coastal Commission (2015). Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits. C. C. Commission. Sacramento, CA. California Coastal Commission Sea Level Rise Policy Guidance.
- California Climate Change Center (2012). Our Changing Climate 2012: Vulnerability & Adaptation to the Increasing Risks from Climate Change in California. A summary report on the Third Assessment from the California Climate Change Center. California's Third Climate Change Assessment.
- California Climate Change Center (2006). Our Changing Climate: Assessing Risks to California. A Summary Report from the California Climate Change Center. California Energy Commission. California Environmental Protection Agency.
- California Ocean Science Trust (2015). Sea-Level Rise and Floodplain Management in California.
- CAT (2009). Climate Action Team Biennial Report, California Energy Commission, Climate Action Team (CAT).
- Cayan, D. (2009). Climate Change - What Should Southern California Prepare for? Climate Change and the Future of Southern California, Southern California Association of Governments (SCAG).
- Cayan, D.R., Bromirski, P.D., Hayhoe, K., Tyree, M., Dettinger, M.D. & Flick, R.E. (2008) Climate change projections of sea level extremes along the California coast. *Climatic Change* 87, S57-S73.

- Cayan, D., Bromirski, P., Hayhoe, K., Tyree, M., Dettinger, M., & Flick, R. (2006). Projecting Future Sea Level. California Energy Commission (CEC).
- Cayan, D., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M., & Gershunov, A. (2010). Future dryness in the southwest US and the hydrology of the early 21st century drought. PNAS 107(50): 21271–21276.
- Cayan, D., Maurer, E. P., Dettinger, M. D., Tyree, M., & Hayhoe, K. (2008). Climate change scenarios for the California region. Climatic Change 87 (Suppl 1): S21-S42.
- Cayan, D., Tyree, M., Dettinger, M.D., León, H., Hugo, G., Das, T., Maurer, E.P., Bromirski, P., Graham, N. and Flick, R. (2009). Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment, California Energy Commission (CEC).
- Cayan, D., Tyree, M., Kunkel, K.E., Castro, C., Gershunov, A., Barsugli, J., Ray, A.J., Overpeck, J., Anderson, M., Russell, J. and Rajagopalan, B. (2013). Chapter 6: Future Climate: Projected Average. Assessment of climate change in the southwest United States. G. Garfin, A. Jardine, R. Merideth, M. Black and S. LeRoy. Washington, DC, Island Press.
- Cayan, D., Tyree, M., Pierce, D., & Das, T. (2012). Climate Change and Sea Level Rise Scenarios for California Vulnerability and Adaptation Assessment, California Energy Commission.
- Chadwick, B. (2014). A methodology for assessing the impact of sea level rise on representative military installations in the Southwestern United States (RC-1703). The Strategic Environmental Research and Development Program, SPAWAR Systems Center Pacific.
- Chandramowli, S. N. (2015). Impact of climate change on electricity systems and markets. Planning and Public Policy. New Brunswick, NJ, Rutgers. Doctor of Philosophy: 205.
- Chang Consultants (2010). Appendix B: Hydraulic and scour studies for proposed Interstate 5 bridge widening across three lagoons. San Diego Regional Lagoon Planning Studies Phase 2.
- Chester, M. V. (2016). Advancing Infrastructure and Institutional Resilience to Climate Change for Coupled Water-Energy Systems. From <http://urbansustainability.lab.asu.edu/azwen.php>.
- Chester, M. V. (2016). Prioritizing Cooling Infrastructure Investment for Vulnerable Southwest Populations. From <http://urbansustainability.lab.asu.edu/heat.php>.
- Christopher Benjamin and Scott Strenfel Pers. Comm. (2016). Interview about PG&E Climate Resilience. I. International.
- City of Chula Vista. (2010). Climate Adaptation Strategies.
- City of Del Mar. (2016). Community workshop and STAC meeting to discuss the preparation of an adaptation plan. Sea-level rise stakeholder technical advisory committee (STAC), Del Mar, CA.
- City of Del Mar. (2015). Del Mar Climate Action Plan.

- City of Encinitas. (2015). Encinitas-Solana Beach Coastal Storm Damage Reduction Project Integrated Feasibility Report & Environmental Impact Statement/Report (EIS/EIR).
- City of San Diego. (2015). Climate Action Plan. Krout Associates and Energy Policy Initiatives Center. https://www.sandiego.gov/sites/default/files/final_december_2015_cap.pdf.
- City of San Diego. (2011). What does Resilience look like? <https://www.sandiego.gov/sites/default/files/legacy/planning/community/pdf/cpc/agendas/CMAPpowerpoint.pdf>.
- City of San Diego. (2003). San Diego Region's 30-Yr Energy Infrastructure Study. <https://www.sandiego.gov/environmental-services/energy/news/30yrstudy>.
- Climate Education Partners. (2014). San Diego, 2050 is Calling. San Diego, University of San Diego.
- CNRA. (2016). Safeguarding California: Implementation Action Plans. California Natural Resources Agency (CNRA).
- CNRA. (2014). Energy Sector Plan. Safeguarding California: Implementation Action Plans. California Natural Resources Agency (CNRA).
- CNRA. (2014). Safeguarding California: Reducing Climate Risk. California Natural Resources Agency (CNRA).
- Con Edison. (2015). Appendix F. Storm Hardening and Resiliency Collaborative Phase Three Report, Consolidated Edison Company of New York Inc.
- Con Edison. (2013). Post Sandy Enhancement Plan. http://www.coned.com/publicissues/PDF/post_sandy_enhancement_plan.pdf, Consolidated Edison Company of New York (Con Edison).
- Dettinger, M. (2011). Climate change, atmospheric rivers, and floods in California - a multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association (JWRA)* 47(3): 514-523.
- DOE. (Unpublished). DOE's Partnership for Energy Sector Climate Resilience: Vulnerability Assessment Summary Report. DOE's Partnership for Energy Sector Climate Resilience, U.S. Department of Energy (DOE).
- DOE. (2013). U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. V. C. Tidwell, T. J. Wilbanks, M. Antes, G. Williams and C. W. Gillespie. Washington, D.C., U.S. Department of Energy (DOE).
- DOE. (2010) Hardening and Resiliency U.S. Energy Industry Response to Recent Hurricane Seasons. Washington, D.C., U.S. Department of Energy (DOE).
- Ebinger, J. and W. Vergara. (2011). Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation. World Bank Study. Washington, D.C., The World Bank: 178.

- ESA. (2016). DRAFT Coastal hazards, vulnerability, and risk assessment: Del Mar, CA. Environmental Science Associates (ESA).
- Everest International Consultants. (2004). Buena Vista lagoon restoration feasibility analysis. Carlsbad, CA, Buena Vista Lagoon Foundation.
- FEMA. (2016). FEMA Flood insurance Studies, Federal Emergency Management Agency (FEMA).
- FEMA. (2015). Coastal Frequently Asked Questions. Coastal Flood Risks. Accessed in 2016, from <http://www.fema.gov/coastal-frequently-asked-questions>.
- Flick, R. E., Chadwick, D. B., Briscoe, J., & Harper, K. C. (2012). 'Flooding' versus 'inundation'. *Eos, Transactions American Geophysical Union*, 93(38): 365-366.
- Gallien, T. (2016). Validated coastal flood modeling at Imperial Beach, California: Comparing total water level, empirical and numerical overtopping methodologies. *Coastal Engineering* 111: 95-104.
- GAO. (2014). Energy Infrastructure Risks and Adaptation Efforts. Climate Change, U.S. Government Accountability Office.
- Governor Edmund G. Brown Jr. (2015). Governor Brown declares state of emergency in California to bolster wildfire response. California Office of Governor Edmund G. Brown Jr.
- Governor Edmund G. Brown Jr. (2014). Governor Brown declares state of emergency in San Diego County, Cal OES Governor's Office of Emergency Services.
- He, M. and M. R. Gautam. (2016). Variability and trends in precipitation, temperature and drought indices in the state of California. *Hydrology* 3(2): 14.
- IPCC. (2014). WGII AR5 Annex II: Glossary. Retrieved from Cambridge, United Kingdom and New York, NY, USA: http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-AnnexII_FINAL.pdf
- IPCC. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation, Intergovernmental Panel on Climate Change (IPCC).
- IPCC. (2007). Appendix I Glossary. Contribution of Working Group II [Impacts, Adaptation, and Vulnerability] to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson. Cambridge, United Kingdom and New York, NY, USA, Intergovernmental Panel on Climate Change (IPCC): 976.
- Lenihan, J. M., et al. (2003). Climate change effects on vegetation distribution, carbon, and fire in California. *Ecological Applications* 13: 1667-1681.
- Moffatt & Nichol. (2015). Bridge hydraulics study for I-5 bridge over Batiquitos Lagoon. Final Hydraulics Report at 90% Design, SANDAG and Caltrans District 11.

- National Oceanic and Atmospheric Administration. (NOAA) Technical Report NOS CO-OPS 073 (2014). Sea Level Rise and Nuisance Flood Frequency Changes around the United States. Department of Commerce.
- New York City. (2013). A Stronger, More Resilient New York – Ch. 6 Utilities.
- OPC. (2016). Planning for Sea-Level Rise Database. California Natural Resources Agency (CNRA) and the Ocean Protection Council. <http://www.opc.ca.gov/climate-change/planning-for-sea-level-rise-database/>.
- Patsch, K. and G. Griggs (2007). Development of Sand Budgets for California's Major Littoral Cells, Institute of Marine Sciences.
- PG&E. (2015). Climate Change Vulnerability Assessment, Pacific Gas and Electric Company (PG&E).
- Ralff-Douglas, K. (2016). Climate Adaptation in the Electric Sector: Vulnerability Assessments & Resiliency Plans. C. P. U. Commission.
- Ren, D., et al. (2014). Trends in storm-triggered landslides over Southern California. *Journal of applied meteorology & climatology* 53(3): 217-233.
- Revell Coastal. (2016). City of Imperial Beach Sea Level Rise Study.
- SANDAG (2009). Coastal Regional Sediment Management Plan for the San Diego Regional. Coastal Regional Sediment Management Plan Workgroup, San Diego Association of Governments (SANDAG).
- San Diego County. (2010). Multi-Jurisdictional Hazard Mitigation Plan. San Diego, CA, San Diego County. <https://www.sandiegocounty.gov/content/dam/sdc/oes/docs/2010-HazMit-Final-August-2010.pdf>
- Savonis, M. J., Burkett, V., R., Potter, J. R. (2008). Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. Synthesis and Assessment Product 4.7. J. R. Potter, V. R. Burkett, M. J. Savonis and D. J. Dokken. Washington, D.C., U.S. Climate Change Science Program and the Subcommittee on Global Change Research.
- Schaeffer, R., Szklo, A.S., de Lucena, A.F.P., Borba, B.S.M.C., Nogueira, L.P.P., Fleming, F.P., Troccoli, A., Harrison, M. & Boulahya, M.S. (2012). Energy sector vulnerability to climate change: a review. *Energy* 38(1): 1-12.
- SDG&E. (2016). Partnership for Energy Sector Climate Resilience. Part I. Vulnerability Assessment, San Diego Gas and Electric (SDG&E).
- SDG&E. (2016). SDG&E Regional Energy Sector Vulnerabilities and Resilience Strategies, San Diego Gas and Electric (SDG&E).
- Solana Beach. (2014). Local Coastal Plan, Ch4 Hazards Shoreline Bluff Development.
- Sorensen, R. (1997). *Basic Coast Eng.*, 2nd Ed. New York.

- Stockdon, H. F., et al. (2006). Empirical parameterization of setup, swash, and run-up. *Coastal Engineering* 53: 573-588.
- U.S. Army Corps of Engineers. (1991). *State of the Coast Report, San Diego Region*. Los Angeles, CA, U.S. Army Corps of Engineers, Los Angeles District. Volume I.
- U.S. Army Corps of Engineers. (1991). *State of the Coast Report, San Diego Region*. Los Angeles, CA, U.S. Army Corps of Engineers, Los Angeles District. Volume II.
- USGCRP. (2016). Glossary. U. S. G. C. R. P. (USGCRP). <http://www.globalchange.gov/climate-change/glossary>.
- USGS. (2016-a). Coastal Storm Modeling System (CoSMoS) 3.0 Southern California. U. S. G. S. (USGS).
- USGS. (2016-b). Land Subsidence. USGS Water Science School. Accessed May 2016, from <http://water.usgs.gov/edu/earthgwlandsubside.html>.
- USGS. (2015). California aqueduct: evaluation of groundwater conditions and land subsidence along the California Aqueduct. *The California Aqueduct*. Accessed May 2016. <http://ca.water.usgs.gov/projects/central-valley/california-aqueduct-subsidence.html>
- USGS. (2013). Land Subsidence. Groundwater Information Pages. Accessed May 2016, from <http://water.usgs.gov/ogw/subsidence.html>.
- Yates, M. L., et al. (2009). Equilibrium shoreline response: observational modeling. *Journal of Geophysical Research* 114.
- Young, A. P. and S. A. Ashford (2006). Application of airborne LIDAR for seacliff volumetric change and beach-sediment contributions. *Journal of Coastal Research* 22(2): 307-331.