RISING SEAS AND ELECTRICITY INFRASTRUCTURE: POTENTIAL IMPACTS AND ADAPTATION OPTIONS FOR SAN DIEGO GAS AND ELECTRIC (SDG&E)

A Report for:

California's Fourth Climate Change Assessment

Prepared By:

Judsen Bruzgul[1], Robert Kay[1], Beth Rodehorst[1], Andy Petrow[1], Tommy Hendrickson[1], Maya Bruguera[1], Ken Collison[1], Dan Moreno[1], David Revell[2]

1 ICF
2 Revell Coastal

Edmund G. Brown, Jr., *Governor*

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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 multi-sector 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 clarifying sea level rise-related risks to San Diego Gas & Electric's (SDG&E) electricity system.

ABSTRACT

Rising sea levels pose a threat to California's energy infrastructure and the coastal communities that it serves. To better understand this threat, this study analyzed the exposure of San Diego Gas & Electric Company (SDG&E) electricity assets in San Diego County to climate change-driven coastal wave flooding, tidal inundation, and coastal erosion. The study found that the greatest potential direct impacts are damage to four substations in the Mission Bay and San Diego Bay areas. By modeling the potential costs to customers from unserved energy due to service disruptions driven by exposed substations, this study found economic impacts could—under an extreme sea level rise scenario in the late 21st century compounded by a 100 year storm-- range from $1.2 billion to $25 billion, assuming no adaptation actions are taken. Nearby communities could also experience indirect impacts if critical customers served by the substations—such as sewage pumping stations, hospitals, airports, and ports—are affected by outages. For other asset types, potential direct impacts are expected in the form of increased maintenance and repair costs.

The research team identified a range of potential adaptation measures to build resilience to potential impacts. The application of flexible adaptation pathways emerged through the study as the best approach to improve implementation of these measures in the face of future uncertainty. Rather than selecting adaptation measures based only on what is known today, flexible adaptation pathways help establish information that that should be tracked, termed signposts, to help navigate uncertainty, set thresholds that trigger adaptation actions, and determine if an adaptation plan is meeting its objectives. Using these pathways, four initial climate adaptation actions were identified for SDG&E: 1) enhance coastal storm prediction and response, 2) identify signposts and thresholds that indicate when the need for an adaptation decision is approaching, 3) conduct consultations with regional stakeholders to identify opportunities to improve community-wide resilience, and 4) improve and fine-tune cost-benefit analysis methods to increase accuracy and confidence in cost-benefit estimates that incorporate climate change.

Keywords: Climate change; direct and indirect impacts; coastal hazards; flexible adaptation pathways; electricity infrastructure and services

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HIGHLIGHTS

- Geospatial overlay analyses of SDG&E assets to climate-change-driven wave flooding, tidal inundation, and erosion found that thousands of electric substations, transformers, power lines, and other equipment are potentially exposed to damage under scenarios of sea level rise (SLR) of 0.5 and 2.0 m (1.6 and 6.6 ft.) for both annual and 100-year storm events. Most of the potentially exposed infrastructure is distribution infrastructure, rather than transmission infrastructure.
- The greatest potential direct physical impacts to assets are damage to substations in the Mission Bay and San Diego Bay areas. In these areas, four substations could be exposed to 100-year coastal wave flooding by mid-century, and 16 substations could be exposed to 100-year coastal wave flooding by the end of the century. If these substations were to be flooded with enough water to damage electrical equipment, substation service may be interrupted until flooding subsides and equipment is repaired. Substations are essential for providing service to customers, and temporary service loss of a substation could cause thousands of customers to lose electric service. For other asset types (e.g., underground duct banks, pole-mounted transformers, and others), potential impacts are more likely to take the form of increased maintenance and repair costs rather than widespread service disruptions.
- Because of the importance of substations to the distribution systems, the research team assessed potential economic impacts and general disruptions to other critical infrastructure in the community induced by loss of service from the potentially exposed substations. The assessment found that service disruptions could cost customers more than $300,000 under a 2 m (6.6 ft.) sea level rise scenario with periodic tidal inundation to approximately $25 billion for an extreme scenario of 2 m (6.6 ft.) of sea level rise coupled with a 1-in-100 year erosion and flood event. Furthermore, nearby communities could experience additional cascading adverse consequences if critical customers served by these substations—such as a sewage pumping station, a hospital, the airport and port, and a Navy yard—lose service.
- The "flexible adaptation pathways" approach, which refers to the implementation of adaptation over time to allow for the adjustment of actions based on new information or circumstances, emerged through the study as the appropriate framework for the utility to conceptualize adaptation actions, and to provide practical guidance to sequencing their implementation.
- Rather than predetermining a set of adaptation investments based only on what is known today, following flexible adaptation pathways will allow SDG&E to make and adjust adaptation decisions as technologies, customer needs, climate change information, the economic and policy landscape, and other factors change over time in order to maintain an acceptable level of risk. For example, under one pathway, the utility might first enhance its existing coastal storm prediction systems to better prepare for coastal wave flooding and also incorporate future climate change projections to model future impact zones, and then decide which adaptation measure is most appropriate to reduce the associated risks; doing so would allow more efficient and effective adaptation than if adaptation measures were implemented without first having

this more detailed impact modeling.

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1: Introduction

1.1 Purpose of the Study

This study aimed to further the state of knowledge on how climate change-driven coastal hazards could affect electricity infrastructure and services. The main influence of climate change on accelerating coastal hazards is sea level rise (SLR). SLR presents a critical threat to California's coastal areas and the energy infrastructure located there. The reliability and resilience of California's electricity service could be threatened by permanent periodic tidal inundation, temporary coastal flooding events that combine SLR with large infrequent storms, and accelerated coastal erosion driven by higher sea levels during large wave events.

Despite these risks, investor-owned utilities (IOUs) in California have lacked the key coastal hazard information, as well as clear guidance or best practices for methodology, necessary to inform proactive adaptation and resiliency investments in infrastructure that have been interpreted in decision-appropriate formats. San Diego Gas & Electric (SDG&E) recognized the risks posed by SLR and actively participated in this study to assess the potential direct and indirect impacts of coastal hazards on its infrastructure within San Diego County for the purposes of identifying adaptation measures.

The first objective of the study was to develop an in-depth understanding of the potential exposure of SDG&E's electrical system to SLR and its associated effects (e.g., coastal wave flooding during storms coupled with higher sea levels). The second objective was to investigate how SDG&E's electricity infrastructure could be affected by SLR (including both direct impacts, such as physical damage to infrastructure, and indirect impacts, such as economic losses to electricity customers and implications for the surrounding community and other critical infrastructure). A third objective was to identify potential near- and long-term adaptation measures and identify the potential implementation of those measures over time.

While this study focused on a single utility in California, other IOUs and regulators facing similar coastal hazards could apply these research methods and findings to inform their own adaptation and resiliency investments in California. While IOUs vary in service area and customer base, the utilities provide natural gas and electricity through similar physical transmission and distribution infrastructures.

1.2 Scope of the Study

The study conducted a detailed SLR exposure and impact assessment to determine vulnerabilities within most of the SDG&E service territory (Figure 1).[1] The results of the exposure assessment were used to analyze potential direct impacts on infrastructure and assets and indirect impacts deriving from service interruptions.

[1] The SDG&E service territory covers the majority of San Diego County and part of southern Orange County. While the USGS CoSMoS erosion data used in this project extends across the entire coast of the SDG&E service territory, the USGS CoSMoS coastal wave flooding and tidal inundation data only includes San Diego County, as data for Orange County was unavailable at the time of the analysis.

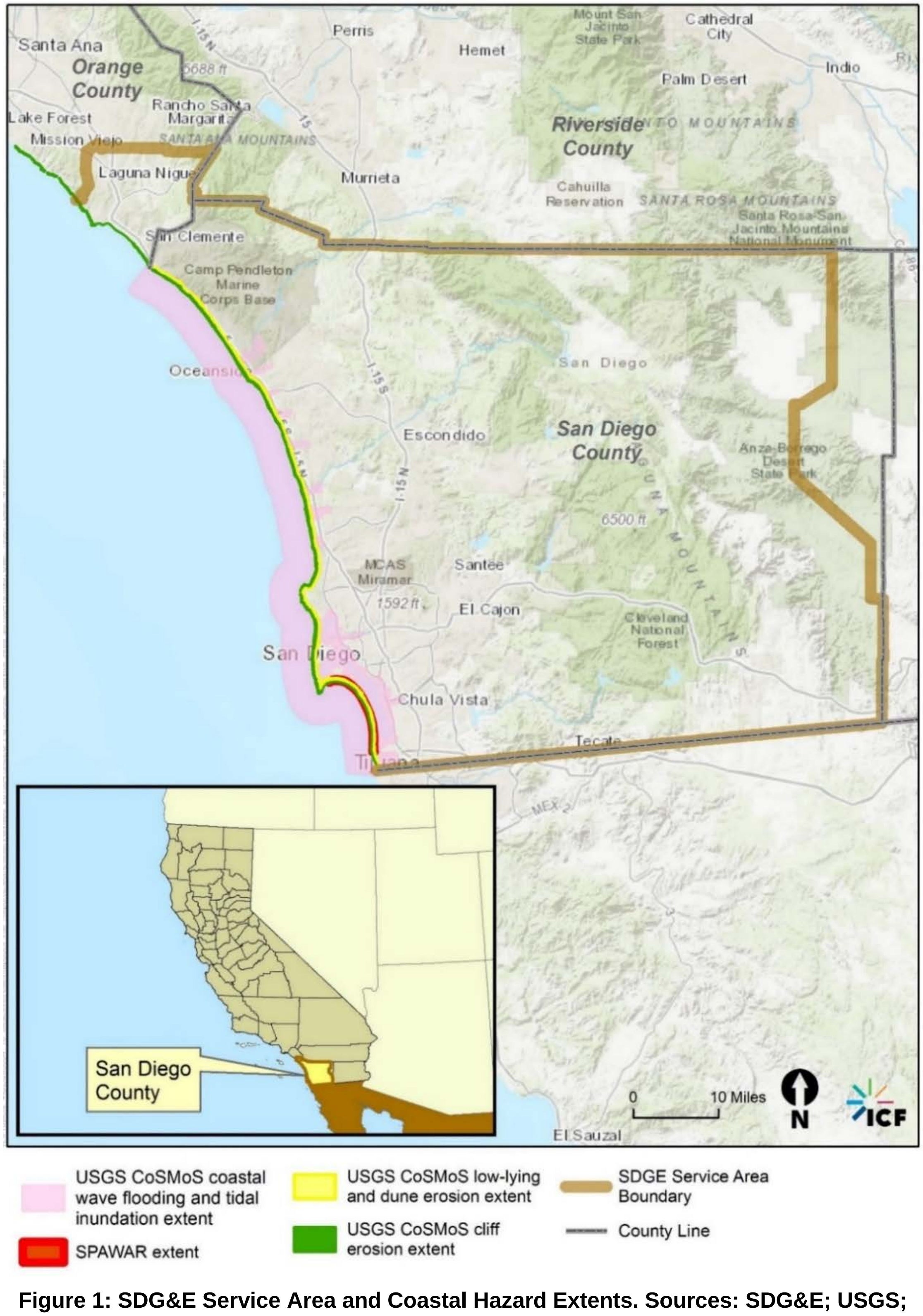

Figure 1: SDG&E Service Area and Coastal Hazard Extents. Sources: SDG&E; USGS; SPAWAREsri.

SDG&E provided the study team with data under a nondisclosure agreement on the type and location of key assets within its service territory, including available metadata for each asset. Assets were broadly divided into the categories shown in Table 1, below. Assets included both transmission assets (i.e., those that convey electricity from generators to the distribution network at high voltages, or voltages greater than about 12 kV) and distribution assets (i.e., those that convey electricity from the transmission system to customers at lower voltages, or voltages less than or equal to about 12 kV).

These asset data, totaling over 1.68 million "point assets" and 26,000 mi. (42,000 km) of "line assets' (Table 1), were vetted with the utility and internal ICF energy experts and categorized (by line and point assets, and by asset sub-types as described in the table below) to gain a better understanding of the key assets and possible dependencies and interdependencies between the assets for the study.

Table 1. SDG&E Key Electricity Assets

Asset Type	Brief Description	Potential Direct Impacts	# of Features	Length
Line				
Duct Bank	Contains the underground wiring and line assets in the underground transmission and distribution system.	Damage if conductive and corrosive saline water enters duct banks from tidal inundation and/or storm wave flooding. Failure if washed away by coastal erosion.	667,433	17,591 mi. (28,310 km)
Pole Line	Represents spans of overhead transmission, distribution or telecom conductor, or cabling between two structures.	Failure if integrity of overhead pole structures is compromised by tidal inundation and/or storm wave flooding or if washed away by coastal erosion.	223,677	8,458 mi. (13,612 km)
Point				
Transmission Overhead (OH) Structure	Represents the poles in the field used to support the overhead wires and equipment in the transmission system.	Damage if integrity of overhead pole structures is compromised by tidal inundation and/or storm wave flooding through salt water corrosion of guy wires or other surface stability control systems. Failure if washed away by coastal erosion.	24,367	
Distribution Overhead (OH) Structure	Represents the poles used to support the overhead wires and equipment in the distribution system.	See: Transmission Overhead (OH) Structure	238,290	
Surface Structure	Represents a ground level support base for the mounting of electric equipment.	Corrosion damage from tidal inundation and/or coastal wave flooding. Failure if washed away by coastal erosion.	118,737	
Underground Structure	Represents a preformed container placed below ground level or an enclosed area within a building structure for the placement of electric	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater.	201,765	

Asset Type	Brief Description	Potential Direct Impacts	# of Features	Length
	equipment	Failure if washed away by coastal erosion.		
Substation	Substations are central parts of the electrical power system where voltage is transformed from high to low or low-to-high for transmission, distribution, and switching.	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater. Failure if washed away by coastal erosion.	363	
Transformer Device	The Transformer Device feature, depending on the type, has the capability of increasing, decreasing, or converting primary voltage for other purposes.	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater. Failure if washed away by coastal erosion.	165,810	
Dynamic Protective Device	Dynamic Protective Devices are capable of sensing a flawed condition; they perform an automated operation to clear any faults, or to transfer the load to an alternate feeder if capable.	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater. Failure if washed away by coastal erosion.	2,949	
Fuses	Fuses react to excessive current by melting, thereby interrupting the flow of current. This operation helps to protect equipment from being damaged by faults.	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater. Failure if washed away by coastal erosion.	31,148	
Switch	A Switch feature is used to control and route the flow of primary voltage through primary conductors.	Corrosion damage from tidal inundation and/or coastal wave flooding together with potential long-term failure if permanently underwater. Failure if washed away by coastal erosion.	14,042	
Total			**1,688,581**	**26,050 mi. (41,922 km)**

The identification of potential impacts from coastal climate change hazards enabled a practical and decision-focused analysis of the various adaptation measures. A flexible adaptation pathways approach emerged during the project that identified a sequence of potential adaptation measures tailored to SDG&E's risk management and operational processes.

Several aspects of this project's scope were affected by concerns over security, confidentiality, and safety. These restrictions primarily affected the direct and indirect impacts analyses, as specific information about physical asset characteristics and related customer services could not be incorporated into the assessment.

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 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 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 investment (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 as a source for consistent peer-reviewed 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 support tools for 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. SDG&E and Southern California Gas Company (SoCalGas) submitted their first joint RAMP report in November 2016 (Sempra Energy 2016). In that report, SDG&E identifies SLR as one of the climate change hazards that poses a risk to the utility.

SDG&E notes that some of the potential risks driven by climate change (including SLR) are addressed through risk management processes unrelated to climate change. For example, the *Electric Infrastructure Integrity* chapter of the RAMP report discusses general risks and risk mitigation efforts that will improve the integrity of infrastructure to a number of different risks, including climate change. In addition, in the RAMP report, SDG&E outlines immediate-term actions intended to improve 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.

Also of relevance to this project is the CPUC paper *Climate Adaptation in the Electricity Sector: Vulnerability Assessments & Resiliency Plans*, produced to encourage IOUs to undertake climate change vulnerability assessments (CPUC 2016). Utilities already have active programs in place to mitigate risks to a number of natural- and human-related impacts. However, they are just beginning to consider and incorporate climate change into their risk management frameworks.

The State's coastal zone management system is required to consider potential sea level rise impacts 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 *Sea Level Rise Policy Guidance* in 2015 to guide the Commission's planning and regulatory actions; an update is currently being developed. The updated OPC Sea Level Rise Guidance was released in early 2018 (OPC 2018).

SDG&E is also 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 Local Hazard Mitigation Plans (LHMP) and Catastrophic Plans. 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. The 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 Definition of 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 within SDG&E's electric system and natural gas system, as categorized by the SDG&E asset management database. **Point assets** include assets such as substations and transformers. **Line assets** include duct banks and pole lines

- **Exposure** in this report refers to whether electricity assets are in geographic areas that are projected to experience the coastal hazards defined below. If a substation is in a location projected to experience coastal wave flooding, that substation would be exposed. However, just because something is exposed does not necessarily mean that there would be an impact.

- **Coastal Wave Flooding** refers to a temporary flooding 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.

    - **Coastal erosion of low-lying land** includes beach and dune systems that can potentially recover or be restored 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 customers and the surrounding community that could arise due to loss of electric service. In this report, the specific indirect impacts considered are the economic implications to customers of losing service (e.g., if a business or manufacturing plant needs to shut down temporarily and thus loses revenue) as well as the implications on the surrounding community if certain key customers lose service (e.g., sewage pumping plant or hospital).
- Climate Change **Adaptation** is the deliberate 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 adjust to new information and circumstances over time. This approach allows the decision maker to manage the uncertainty of the future, rather than getting locked into adaptation measures made in anticipation of potential impacts that may not occur or in ignorance of unforeseen impacts. The pathways include immediate adaptation actions that could be taken today, and other adaptation actions that could be taken as new information becomes available and certain thresholds are met.
- **Adaptation Measures** are the specific 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 to define the critical values of signpost variables beyond which additional actions should be implemented (adapted from Haasnoot, Kwakkel et al. 2013).
- **Unserved Energy** is

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

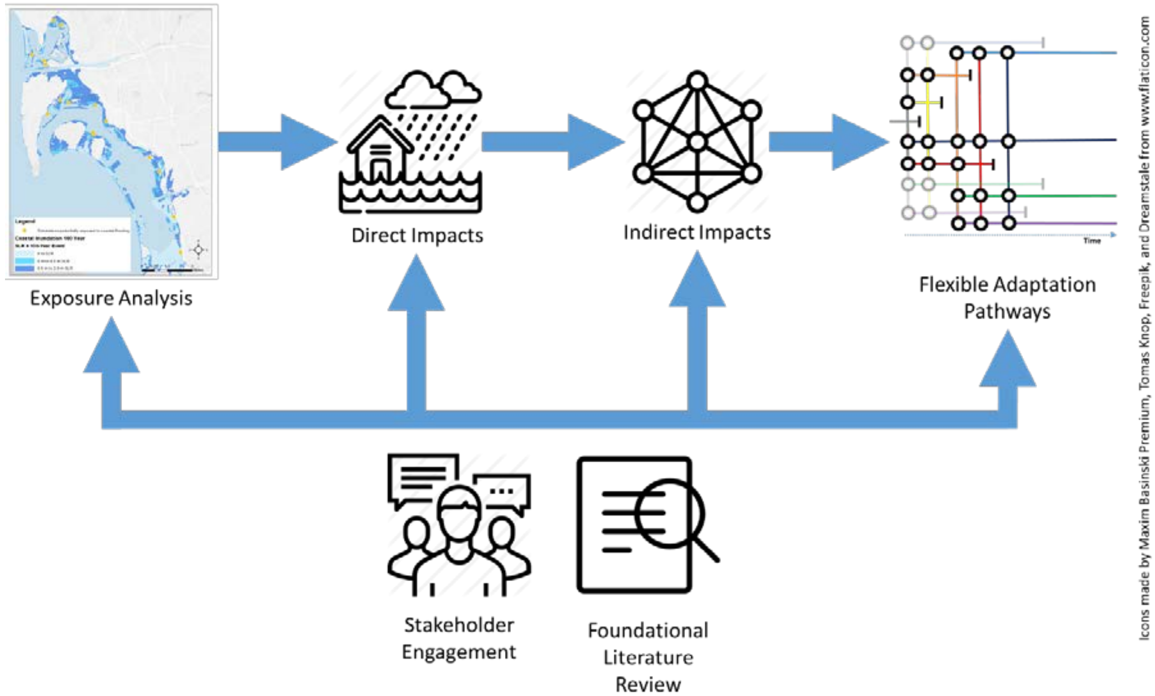

Figure 2: Visual Representation of Study Methodology

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 hazards in the region; vulnerabilities and adaptation in the electric sector with respect to climate change; and concurrent efforts at adaptation planning in the region and beyond.
- **Stakeholder engagement** that consisted of meetings of the Technical Advisory Committee and ongoing engagement throughout the project with internal stakeholders across SDG&E departments. Throughout the study, the research team coordinated closely with SDG&E experts who provided input through phone calls, workshops, and interviews, providing data and insights that would not otherwise be easily accessible and that allowed approaches to be customized to a California IOU. SDG&E 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 flooding, tidal inundation and cliff erosion hazards might intersect with SDG&E 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 from direct impacts, specifically due to disruptions at potentially exposed substations, including estimating the value of the lost service to customers and estimating community-wide impacts arising from service disruptions to critical customers.
- **Development of potential "flexible adaptation pathways" and priority adaptation measures for SDG&E**, with an emphasis on implementing measures that would facilitate access to key information, signposts, and thresholds to help SDG&E 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 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 allowed 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 interviews with select industry experts. Specifically, the research team conducted a literature search using the Elton B Stephens Company (EBSCO) Host Research Databases (EBSCO Industries 2018), the California Natural Resources Agency "*Planning for Sea Level Rise*" database (AB2516, Gordon), and general internet searches using Google and other search engines. This literature review was supplemented by coordinating with 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 those 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 of California's Fourth Climate Change Assessment (Fourth Assessment) efforts.

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

2.3 Exposure Analysis

The study incorporated SLR scenarios into the analysis of the following coastal hazards:

- **Coastal wave flooding** – A temporary flooding 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.

- **Coastal erosion –** The loss of land caused by both coastal wave processes and terrestrial mass wasting. 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.

The exposure analysis provided detailed spatial information about potential extents of coastal hazards and where these hazard areas intersect with electricity infrastructure. The research team and SDG&E implemented a three-phased approach to complete the exposure analysis:

- Phase 1 involved researching and collecting data on SLR projections, and selecting appropriate SLR scenarios.
- Phase 2 included identifying hazard exposure scenarios, including recurrence intervals (i.e., annual and 100-year events); identifying coastal hazard spatial models (i.e., USGS CoSMoS, FEMA, SPAWAR); and augmenting and/or adjusting the hazard information to better determine SDG&E asset exposure (e.g, filling in gaps in spatial coverage relevant to SDG&E territory). Appendix A gives fuller information on the models and scenarios that were used.
- Phase 3 applied Geographic Information Systems (GIS) software to overlay maps of electricity assets against each individual hazard to determine potential exposure.

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 in sections 3 and 4.

2.3.1 Phase 1—Research, Collection, and SLR Scenario Selection

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 the integration of expert elicitation. The Cayan et al. study identifies probabilities (50th, 95th, and 99.9th percentile) associated with different future SLR, by decade, for multiple emissions scenarios (RCP 8.5 and RCP 4.5). The Climate Action Team Research Working Group provided Fourth Assessment research projects with recommendations for interpreting the Cayan et al. (2016) SLR scenarios (Franco et al. 2017). These recommendations include using the RCP 8.5 50th, 95th, and 99.9th percentile SLR projections for planning horizons before 2060, and RCP 4.5 and 8.5 (50th, 95th, and 99.9th percentile) beyond 2060.

As this project aimed to consider a worst-case scenario, SDG&E requested simplicity, and the project time horizon is 2050, the research team selected the RCP 8.5 (99.9th percentile SLR value), or 0.52 m (1.7 ft.). To consider extreme impacts toward the end of the century, the project team selected an additional SLR scenario of 2.0 m (6.6 ft.). This scenario was selected because it is the maximum SLR scenario modeled by the SLR and erosion spatial model used in this project, USGS CoSMoS, as described further in the following section; this value approximates the RCP 8.5 2090 99th percentile projection (Cayan et al. 2016) and is very close to the 99.5th percentile projection indicated by the Ocean Protection Council's 2018 update to the State of California Sea Level Rise Guidance Document. However, it is important to note that the end-of-century (2100) probabilistic projection developed for RCP8.5 suggest a 99.9th percentile value of 2.9 m (9.4 ft). Additionally, the Ocean Protection Council's 2018 guidance suggests consideration of a worst-case scenario of 3 m (10 ft).

2.3.2 Phase 2—Hazard Scenario and Spatial Model Selection and Changes/Adjustments

The research team consulted with SDG&E on how best to develop 'project scenarios' that would be based on the best available science—as per Fourth Assessment recommendations—while also being of practical application in the study including during engagement with SDG&E stakeholders. The outcome of these deliberations was to use several SLR scenarios for the coastal hazard exposure analysis, combined with an annual event (i.e., 1-year return interval) that SDG&E considered as potential nuisance flooding events, and larger storms with 1% annual chance event (i.e., 100-year return interval):

- Baseline exposure scenario: 0.0 m (0.0 ft.) SLR (annual and 100-year events)
- Exposure scenario 1: 0.5 m (1.6 ft.) SLR (annual and 100-year events) – selected to represent mid-century timeframe
- Exposure scenario 2: 2.0 m (6.6 ft.) SLR (annual and 100-year events) – selected to represent an end-of-century time frame

These exposure 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 in use —including supply, demand, and infrastructure (for example, the extent of future distributed energy generation)—are likely to change significantly by the end of the 21st Century. However, end-of-century exposure assessment (exposure scenario 2 using 2.0 m or 6.6 ft. SLR) is also described to help illustrate potential extent of exposure that SDG&E could face within this century. It is important to note that while the using the 2.0 m (6.6 ft.) SLR (exposure scenario 2) for the late 21st century exposure assessment, this does not encompass the highest possible SLR projections of 2.4 m and 2.9 m (7.9 ft. and 9.5 ft.) of RCP 8.5 95th and 99.9th percentiles for 2100 (Cayan et al., 2016) that factor in the potential for large Antarctic ice loss contributions to SLR in the second half of the 21st century.

A key challenge with directly implementing the SLR recommendations for Fourth Assessment research was interpreting how selected SLR scenarios translate to available coastal hazard spatial model data. Based on the needs of the study, the above model assessment, and the suggested combination of SLR and flood event recurrence periods, and Fourth Assessment Recommendations on harmonizing SLR scenarios with coastal hazard spatial models, 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 Appendix A for detailed information about these models and why they were selected:

- Coastal Wave Flooding (episodic storm impacts)
    - USGS CoSMoS 3.0[2]
- 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 interpretation[3]) and SPAWAR (see Section 2.3.2.1 Data Gap Filling, below) Erosion of dune and low-lying inlets from USGS CoSMoS 3.0 COAST module (plus geomorphic interpretation[3]) and SPAWAR (see Section 2.3.2.1 Data Gap Filling, below)
    - Cliff erosion of higher-elevation coasts from USGS CoSMoS 3.0[2]

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)

Prior to analyzing electricity asset exposure to these layers, the research team conducted gap filling, as described below.

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[2] Note: CoSMoS cliff erosion data does not include a 'baseline' for existing erosion hazard conditions

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

2.3.2.1 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.
2. No Hold the Line.
3. Continuing Nourishment.
4. No Further Nourishment.

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 as a shoreline position does not account for the full extent of wave runup process and, as a result, is likely be conservative in its depiction of the potential extent of coastal erosion and wave run up hazards. Wave runup can produce water levels upwards of 3 to 5 m (10 to 15 ft.) 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 vulnerability 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.

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 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.

2.3.3 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.

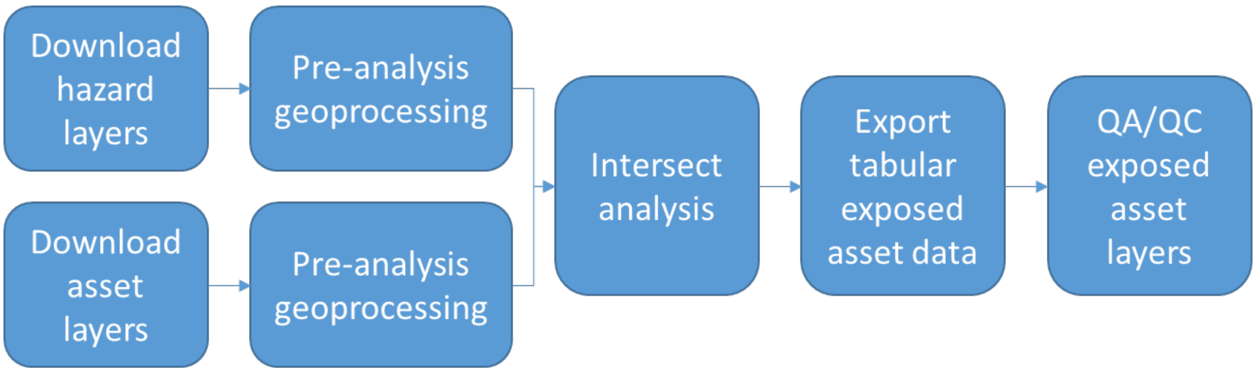

Figure 3. GIS Exposure Analysis Process

2.4 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 SDG&E expertise and modeling of economic impacts from loss of power to customers. Direct impacts refer to damage to infrastructure and the interruptions in service that would result from the projected exposure. Indirect impacts refer to how the customers and surrounding community could be affected by loss of electric service. 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 SDG&E electricity assets to identify which assets would be exposed. Then the research team held a workshop with 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 quantifying the economic impact on customers if electric service was lost from exposed substations, then evaluating how disruptions of electricity service to key customers (such as the sewage pumping station, the airport, the hospital, and others) could affect the surrounding community. The methods are discussed below.

2.4.1 Stakeholder-Driven Approach to Understanding Direct Impacts

The research team worked closely with SDG&E experts to build upon the background research and to ground-truth and further characterize the specific potential direct impacts to SDG&E assets based on the exposure analysis results. For this, the research team employed an approach that was primarily stakeholder based. Information on the direct impacts of hazards to the electricity system was obtained primarily through a workshop, *Electricity System Climate Change Exposure and Impacts*, held on May 24th, 2017 for five and a half hours.

Workshop participants were recruited by the SDG&E Project Focal Point for the study (the 'Focal Point'). The Focal Point's recruitment strategy was to invite pre-existing members of an interdepartmental climate advisory group. In addition, the Focal Point reviewed the SDG&E Enterprise Risk Registry to send targeted invitations to the leaders of specific teams with responsibilities for systems engineering, risk management, emergency management and maintenance. The Focal Point tracked respondents through the internal SDG&E computer calendar system. The Project Team and eleven representatives from across SDG&E attended the workshop. Their positions within the company included directors, program managers, team leaders and technical specialists representing electricity transmission and distribution engineering, construction engineering, grid modernization, emergency management, and insurance 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 SDG&E 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.

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.[4] 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.

2.4.2 Analysis of Potential Economic and Community-Wide (Indirect) Impacts

Substations were identified by the research and SDG&E teams to be critical infrastructure. The exposure analysis and assessment of impacts indicated potential impacts to substations and, as a result, the research team investigated indirect impacts from potential substation exposure, namely the extended impact of outages that could occur from loss of service to potentially exposed substations.

Using the exposure analysis results, the research team developed three specific asset loss scenarios to analyze, based on the climate-driven coastal hazard scenarios. The scenarios span a range of plausible conditions, namely:

Impact Scenario 1: Future Periodic Tidal Inundation

This scenario relates to future tidal inundation of substations from 2.0 m (6.6 ft.) of SLR, projected for the end of the century. This reflects exposure scenario 2's SLR with no 1-in-100 year (100-year) storm. Under this scenario, there would be a simultaneous loss of 12 substations with the outage anticipated from this tidal event lasting 12 hours due to flooding around the high tide and subsequent time for restoration crews to complete their work.

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[4] 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.

Impact Scenario 2: Future Storm Coastal Wave Flooding

This scenario represents flooding from a future coastal wave event associated with a 100 year storm[5] in addition to 0.5 m (1.6 ft.) of SLR projected for 2050. This reflects exposure scenario 1. Under this scenario, there would be simultaneous loss of 4 substations; the outage is considered severe given the potential low-probability but high-impact nature of a 100-year storm, and the outage duration under this scenario is 2 weeks.

Impact Scenario 3: Extreme Future Storm Coastal Wave Flooding

This scenario represents flooding from a future coastal wave event associated with a 100-year storm in addition to 2.0 m (6.6 ft.) of SLR projected for the end of the century; it represents a plausible extreme event. This reflects exposure scenario 2. Under this scenario, there would be simultaneous loss of 13 substations; like Impact Scenario 2, the outage is considered severe, and the outage duration under this scenario is 2 weeks.

For each of the three scenarios, the research team analyzed the potential indirect economic impacts to customers served by the affected assets. The analysis considered the distribution system design and customer types to estimate potential impacts. The research team calculated the economic impact of the service disruptions by applying the estimate of the costs to consumers of interruption of service, referred to as the Value of Lost Load (VOLL), to the estimate of unserved load derived from the modeling. VOLL is a measure of customers' willingness to pay for electricity service (London Economics 2013). VOLL is usually measured in dollars per megawatt hour (MWh) or similar. VOLLs vary depending on the duration and type of outage, customer class, regional economic conditions, and other factors (London Economics 2013; DOE 2016b). VOLL values are generally estimated through value of service reliability and interruption cost surveys, normally conducted by major electric utilities (Sullivan et al. 2015). The result is an estimate of costs that customers incur, including loss of revenue, due to losing power.

Cost of unserved energy is calculated using the following equation:

$$\text{Cost of Unserved Energy (\$)} = \text{VOLL (\$/kWh)} \times \text{Unserved Energy (MWh)} \times 1000$$

To better understand opportunities for adaptation to future low-probability, long-duration outages from coastal hazards, the research team also developed estimates for interruption costs to customers over a two-week outage. A two-week period was chosen in consultation with SDG&E to represent an outage under a low-probability but high-impact 100-year storm event. Two weeks reflects the duration of the potential flood event, which could span multiple days, as well as time to repair significant impacts to damaged substations. Table 3 shows VOLL estimates used for each scenario; these are based on values found in Sullivan et al. (2009, 2015). An overall VOLL value for each scenario was calculated from the Medium/Large Commercial & Industrial (C&I), Small Commercial & Industrial, and Residential VOLL estimates based on customer class breakdown for each substation and feeder (i.e., conductor carrying power to customers), where possible; see Appendix C for more details.

[5] This refers to a coastal storm event that could occur with a 1 percent chance in a given year. The terms 1-in-100 year, 100-year, and 1% annual probability of occurrence all have the same meaning.

Table 3. Value of Lost Load estimates used in the analysis by customer type for each scenario

Impact Scenario	VOLL Estimates ($/unserved kWh)								
	Low			Medium			High		
	Medium/ Large C&I*	Small C&I	Resi-dential	Medium/ Large C&I	Small C&I	Resi-dential	Medium/ Large C&I	Small C&I	Resi-dential
1	$12	$240	$1				$12	$241	$1
2	$3	$258	$1	$136	$2,756	$14	$269	$5,4653	$27
3	$13	$258	$1	$136	$2,756	$14	$269	$5,4653	$27

*Commercial & Industrial

Source: Based on values from Sullivan et al. (2009, 2015).

The research team also undertook a qualitative review of the potential cascading impacts due to a major power disruption. For example, if certain critical customers (such as a sewage pumping station or a hospital) lost electricity, what would be the impact on the community? Many community systems rely on other systems to operate (e.g., electricity is needed to move water and water is needed to generate electricity). Understanding these system relationships before events occur allows SDG&E, and communities served by it, to better prepare, understand risks and liabilities and ultimately be more resilient to climate change events.

The review effort relied on readily available public information identified through internet searches and knowledge and expertise within the research team, as a comprehensive literature review was beyond the scope of the present study (additional research into potential cascading impacts may be important to pursue in the future, as described in Section 4.3).

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 grid may change.

To help guide SDG&E 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, Fazey et al. 2014; Haasnoot, Kwakkel et al. 2013; Wilby and Dessai 2010). Engagements with SDG&E 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 a parallel project that focused on the natural gas sector; the second one was held under this project. 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 3.2.

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 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, setting thresholds that establish limits on the pre-determined levels of risks that would lead to severe impacts and potentially irreversible consequences. Signposts are also established that help to assess what information should be collected to determine if an adaptation plan is proving adequate and if alternative adaptation pathways should be taken if thresholds are being neared (Haasnoot, Kwakkel, et al. 2013).

Low- and no-regrets adaptation actions 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 is 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, SDG&E is ideally placed to test this approach.

2.5.3 Methodology for Adaptation Workshops

Two adaptation planning workshops were undertaken. The first, held under a parallel Energy Commission research project (Agreement Number PIR-15-004), 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 this project that used a 'bottom-up' approached that drew from the skills and expertise of SDG&E staff[6].

The research projects that encompassed Workshop 1 and Workshop 2 were conducted in parallel throughout, so that each project could build upon methods and results of the other.

2.5.3.1 Workshop 1

The first workshop was held for five and a half hours on October 16th, 2017. Recruitment for the workshop was undertaken using the same process as for the exposure and impacts workshop held earlier in the project, as outlined in Section 3.2.1. Attendees included the Project Team and seven SDG&E/SoCalGas representatives from the engineering and enterprise risk management departments. This 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 pre-determined set of criteria. Although this workshop focused on natural gas assets rather than electricity, the approach tested could also have been applied to electricity assets. 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 a testing 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 study 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 of action. 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 assessment matrix allows 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 SDG&E'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

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[6] Although Workshop 1 was held under a different research project, it is described in this report as it was the combination of Workshops 1 and 2 that allowed the testing of different approaches for evaluating adaptation measures. Workshop 1 focused on the natural gas sector, but the methods could be applied to either natural gas or electricity.

Integrating the lessons learned from the first workshop, and working in consultation with SDG&E, Workshop 2 was held for five and a half hours on November 7th, 2017. Participants were recruited using the same process adopted for the previous project workshop held on May 24th 2017 outlined in Section 3.2.1. The Project Team and seven representatives from across SDG&E attended the workshop. Their positions within the company were program managers, team leaders, and technical specialists representing electricity transmission and distribution engineering and emergency management.

The Workshop took a different approach for working through adaptation measures and approaches that were drawn from the expertise of workshop participants. This approach drew from the knowledge and experience of SDG&E utility engineers, risk managers, and meteorologists on measures and approaches that are currently in place to manage climate-driven hazards, how these could be adjusted to integrate climate change factors, and outlined new adaptation options.

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 provided a structure for their subsequent analysis in small-group and plenary sessions.

3: Findings

This section discusses both the exposure results and the corresponding potential impacts to electricity infrastructure, organized by the following infrastructure types: substations, transformers, duct banks, poles and lines, and meters, relays, and switches. This section also discusses the potential indirect impacts the modeled exposure could have due to damage to substations; the indirect impacts discussed include potential economic impacts to customers and potential impacts to interdependent critical systems and customers. Finally, this section discusses potential flexible adaptation pathways that SDG&E 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's recommendation.

3.1 Exposure and Impacts

3.1.1 Overview

By mid-century, a large number of both point and line assets[7] are projected to be in the exposure

[7]. See Table 1 for a full list of point and line assets, and definitions of each asset type.

zones; see Appendix B for detailed results. Most of these assets are distribution assets to residences and businesses in coastal communities. Coastal wave flooding is of particular concern along the shores of Mission Bay and San Diego Bay, as well as the borders of inlets along the coast, as illustrated in Figure 4, below. On a percentage basis, the exposed assets represent less than 1% of SDG&E's total assets, as coastal flooding and erosion only affect areas very near the coastline. However, this small percentage should not belie the fact that ocean front development in coastal communities could result in a disproportionate impact on the local economy as well as the tremendous regional economic reliance on coastal tourism.

A similar magnitude of assets could also be exposed to low-lying erosion by 2050. The projected exposure assumes that no adaptive measures are taken by organizations with coastal management responsibilities, for example, city governments. Such adaptive measures could include implementing enhanced beach nourishment or upgrading protection measures. The research team assumed no such third-party adaptive measures are implemented, to ensure that a full picture of potential exposure is provided. Clusters of assets are exposed to low-lying erosion in Oceanside, Carlsbad, Del Mar, Mission Beach, and Coronado, as shown in Figure 4, below.

Coastal cliff erosion is projected to affect a very small number of point and line assets, but indicates potential problems for specific neighborhoods along the coast. Assets are primarily exposed to coastal cliff erosion along the coasts of Dana Point, San Clemente, Encinitas, Solana Beach, and La Jolla, as shown in Figure 4.

Notably, many of the highly exposed areas are also denser population centers, such as around San Diego Bay where indirect impacts may have a much broader impact. Due to security, confidentiality, and safety concerns, specific information about physical asset characteristics and related customer services could not be incorporated into the assessment. Therefore, the following section discusses impacts more generally.

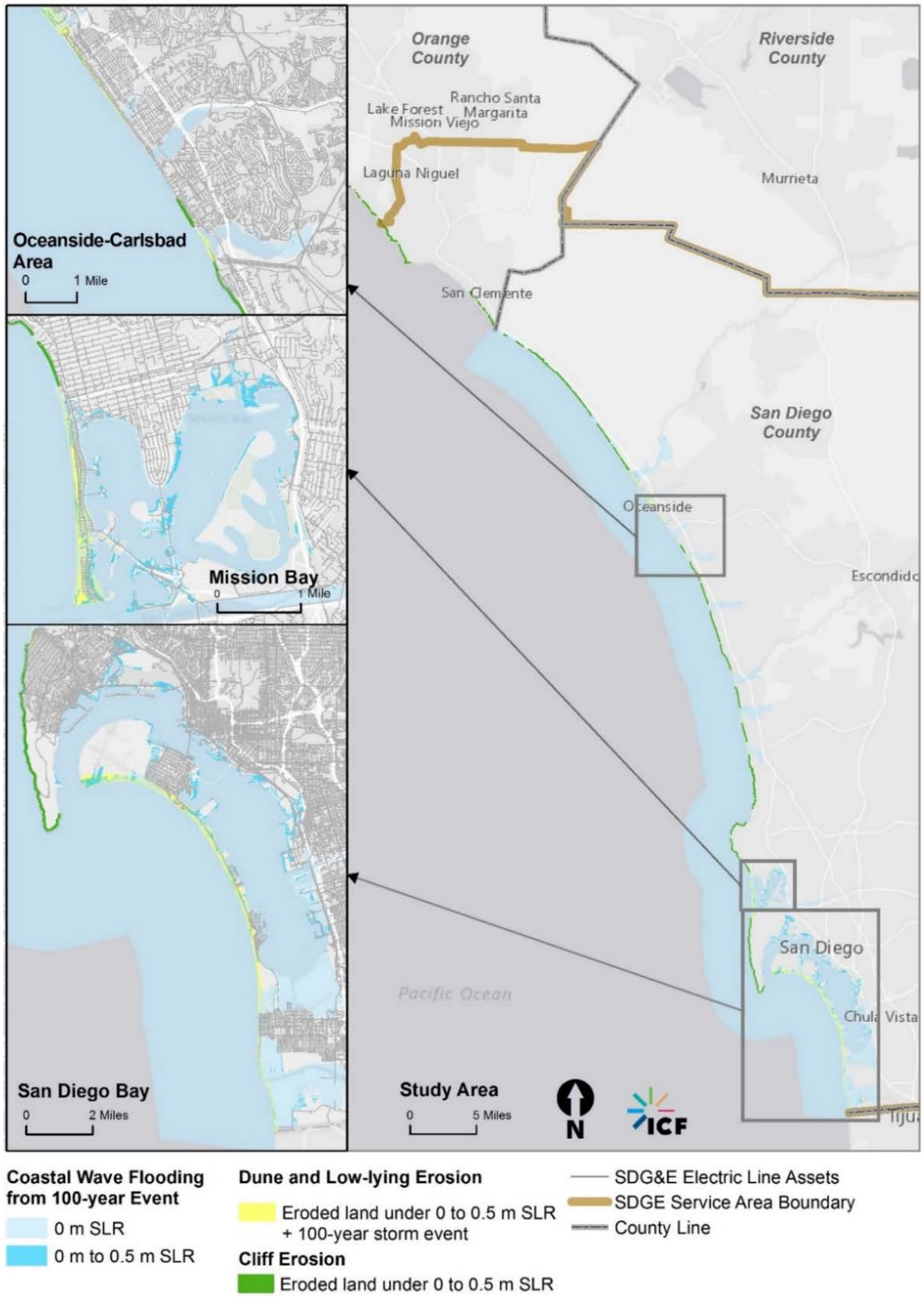

Figure 4. Potential mid-century coastal hazard exposure in the SDG&E Service Area. Hazards include coastal wave flooding under a 100-year event plus 0 and 0.5 m of SLR, dune and low-lying erosion under 0.5 m SLR, and cliff erosion under 0.5 m SLR and no coastal armoring. Focus area maps show the Oceanside-Carlsbad area, Mission Bay, and San Diego Bay. Sources: SDG&E; USGS; SPAWAR; Esri

Most of the potentially exposed infrastructure is distribution infrastructure (i.e., lower voltage infrastructure that brings power from substations to the end user), rather than transmission infrastructure (i.e., higher voltage infrastructure that moves large quantities of electricity from power generation facilities to substations). Although population tends to be concentrated along the coast rather than inland, most of the transmission infrastructure is situated just far enough away from the coast that only a small number of transmission assets are exposed to coastal hazards. Less than 7% of assets potentially exposed to annual tidal inundation or coastal wave flooding mid-century are part of the transmission system. Specifically, 5 mi. (8 km) of transmission duct banks and 140 point assets are potentially exposed during mid-century (0.5 m or 1.6 ft. SLR) annual tidal inundation and 8 mi. (13 km) of transmission duct banks and 190 point assets are potentially exposed to coastal wave flooding during mid-century 100-year storm events (0.5 m or 1.6 ft. SLR). The potentially exposed transmission line assets are buried lines that are primarily sensitive to slow-acting damage from water submersion, such as from corrosion. Of the exposed point assets, most (90%) are overhead structures, which due to their raised nature have limited sensitivity to inundation. Therefore, the discussion in this report focuses primarily on distribution assets.

The greatest potential direct impacts from coastal hazards to service delivery are damage to substations, including the four substations around San Diego Bay that would be exposed to coastal wave flooding during a 100-year storm by mid-century. Depending on the characteristics of a particular event, a single event could conceivably damage all four of these substations, potentially disrupting service to tens of thousands of customers. The threat increases toward the end of the century, when an additional 16 substations could be exposed. Damage to these substations could in turn cause indirect impacts in the form of economic impacts to customers and impacts to interdependent critical systems and customers. Costs to customers could range from more than $300,000 under a 2 m (6.6 ft.) sea level rise scenario with periodic tidal inundation (Impact Scenario A) to approximately $25 billion for an extreme scenario of 2 m (6.6 ft.) of sea level rise coupled with a 1-in-100 year event (Impact Scenario C), as discussed below. Furthermore, the community could experience additional adverse consequences if critical customers served by these substations—such as a naval yard, hospital, port, and sewage pumping station—lost service due to impacts of coastal flooding on substations. The current study did not include an analysis of the existing resilience of these critical customers, which would affect the consequence of lost service. In addition, such impacts could pose liability risks to SDG&E; however, the analysis of the liability risks is beyond the scope of the current study.

Direct impacts to other equipment would likely come in the form of corrosion or longer-term damage to equipment. Because this damage happens over time, and because there are equipment monitoring systems in place, it is unlikely that widespread service disruptions would occur very often due to damage to these assets. The impacts experienced would be in the form of increased maintenance, repair, and replacement costs. Given the large number of assets, these additional costs could be significant over time.

The subsections that follow detail the potential exposure results and associated impacts for different asset types based on findings from the literature, workshops, and follow-up interviews.

3.1.2 Substations

Substations are considered to be among the most critical of SDG&E's exposed assets. Substations and the assets they house are critical for the delivery of power to customers, as they are the connection point for feeders that serve customer demand. Damage to substations and substation equipment could result in significant service disruptions as well as significant cost impacts. Due to security concerns and non-disclosure agreements with SDG&E, the substations will be referenced only as Substation A, Substation B, etc. in this report.

3.1.2.1 Exposure and Direct Impacts

Four substations are projected to experience flooding by mid-century. Specifically, two substations are potentially susceptible to 100-year storm coastal wave flooding even under present-day sea level and a 100-year event (Substations G and E; two additional substations are potentially susceptible to inundation under 0.5 m (1.6 ft.) SLR and a 100-year event (Substations F and A). By late in the 21st Century, an additional 12 substations would be exposed to 100-year event flooding. These substations are shown in Figure 5, below, along with substations potentially exposed by late in the 21st Century. A single event could (but not necessarily would) simultaneously expose multiple substations.

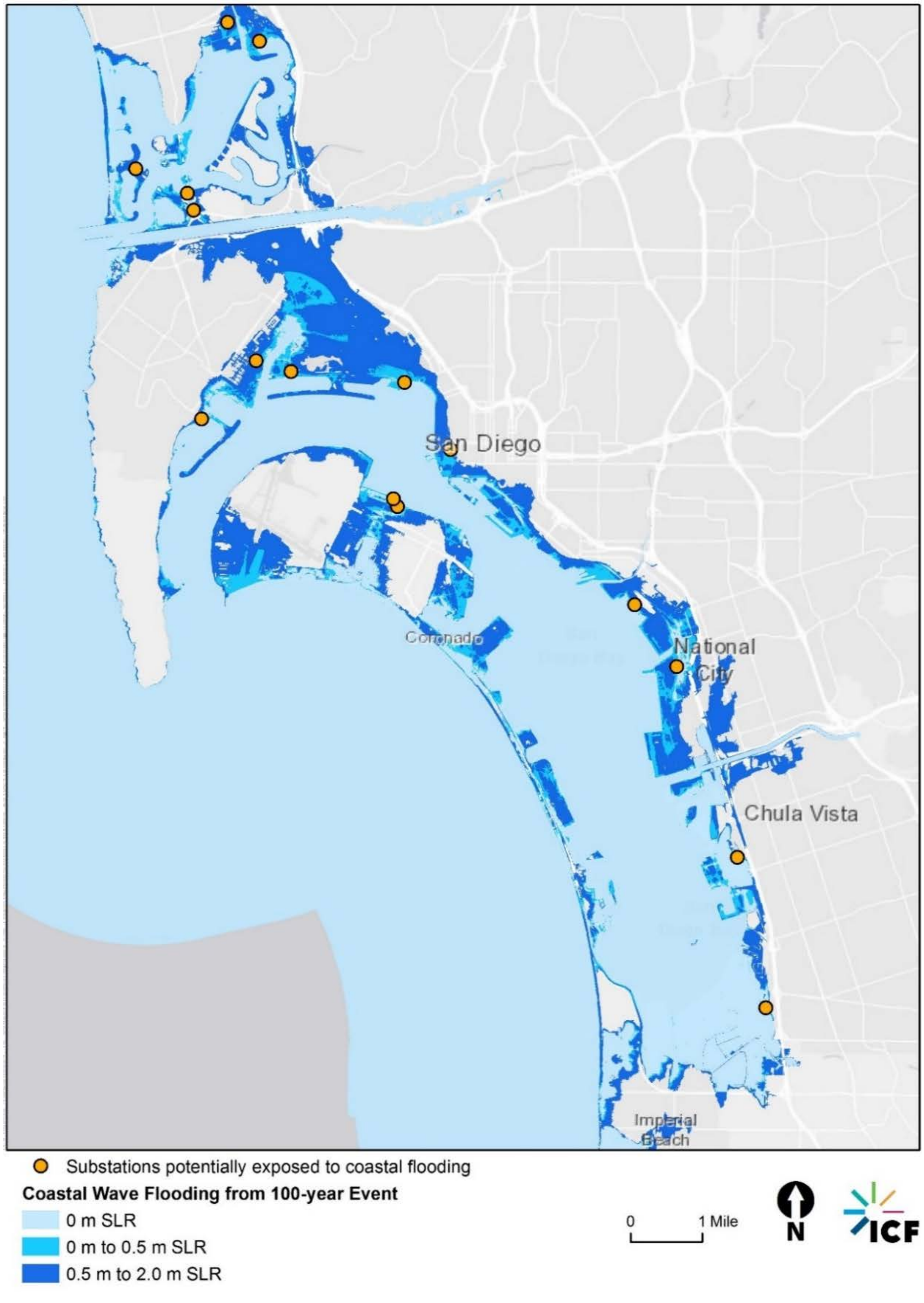

Figure 5. Potential substation exposure to coastal wave flooding under a 100-year event and SLR of 0 m, 0.5 m, or 2.0 m. Sources: SDG&E; USGS; SPAWAR; Esri

Because of the importance of substations, additional analysis was conducted to characterize the depth of inundation. These results are shown in Table 4 and Table 5.[8] As these tables indicate, Substation G could be particularly exposed, experiencing inundation depths of about 0.6 to 1.0 m (2.0 to 3.4 ft.) by mid-century under a 1-year event.

Table 4. Summary of Inundation Depths (m and ft.) at Substations Exposed by Mid-Century, 0.5 m (1.6 ft.) SLR, 1-yr Event

Substation	Minimum Depth	Maximum Depth	Max Depth + Uncertainty
Substation G	0.61 m (2.00 ft.)	1.04 m (3.41 ft.)	1.72 m (5.64 ft.)
Substation E	0.00 m (0.00 ft.)	0.04 m (0.13 ft.)	0.72 m (2.36 ft.)

Note: Minimum depth and maximum depths indicate the shallowest and deepest inundation levels within the polygon defining the boundary of the substation. In some cases, the uncertainty surrounding these values is significant, so the maximum depth plus the uncertainty value is also presented in the table to represent a more extreme, but plausible, depth value.

Table 5. Summary of Inundation Depths (m and ft.) at Substations Exposed by Mid-Century, 0.5 m (1.6 ft.) SLR, 100-yr Event

Substation	Minimum Depth	Maximum Depth	Max Depth + Uncertainty
Substation G	0.70 m (2.30 ft.)	1.13 m (3.71 ft.)	1.81 m (5.94 ft.)
Substation E	0.00 m (0.00 ft.)	0.85 m (2.79 ft.)	1.53 m (5.02 ft.)
Substation F	0.00 m (0.00 ft.)	0.27 m (0.89 ft.)	0.95 m (3.12 ft.)
Substation A	0.14 m (0.46 ft.)	0.25 m (0.82 ft.)	0.93 m (3.05 ft.)

Note: Minimum depth and maximum depths indicate the shallowest and deepest inundation levels within the polygon defining the boundary of the substation. In some cases, the uncertainty surrounding these values is significant, so the maximum depth plus the uncertainty value is also presented in the table to represent a more extreme, but plausible, depth value.

Exposure to saltwater can be very damaging given the electrical (not mechanical) nature of the equipment. Furthermore, submersion of electrical equipment can create a significant safety hazard and a liability as people (SDG&E staff or the public) could be electrocuted. Substations may not be able to operate during the inundation, and equipment could be damaged and corroded from the saltwater, requiring repair and replacement after waters recede.

Furthermore, debris in the water and the force of wave runup can also damage equipment. In short, where equipment is not raised above inundation levels, substations are very vulnerable to inundation. Workshop participants indicated that equipment within substations can be as low as 2 to 3 ft. (0.6 to 0.9 m) above ground level, indicating that equipment within the substations analyzed could become exposed to seawater. However, with some depths approaching or exceeding 3 ft. (0.9 m), it is likely that some electrical equipment would be inundated.

Coastal flooding can also delay repairs by inhibiting access to the substation and preventing water

[8] Results provided focus on mid-century exposure due to request by SDG&E,which noted the large uncertainty not only in sea level rise projections at end of century, but also large uncertainty regarding demographics, grid infrastructure, and technology that far into the future.

drainage, depending on the sloping of the site, whether the access road is raised or destroyed, and whether there are walls that prevent water drainage (CIGRE 2015).

The substations in the modeled exposure zones are all distribution substations, which in the SDG&E Service Area rely on circuits that are radial (or linear), as opposed to the mesh circuits of transmission substations.[9] Radial circuits send electricity in one direction and do not have closed loops, and if one line loses power, all downstream lines also lose power (Santos 2013). Mesh circuits, on the other hand, can have closed loops and can deliver power through multiple lines (Santos 2013). Because of the radial substation design, the failure of a single distribution substation would cause service outages for all customers downstream of that substation. It is possible that these impacted radial networks could be switched to an alternative electricity source, but this is only possible for a few potentially exposed substations.

3.1.2.2 Indirect Impacts

As noted in the Methodology section, due to the importance of substations, additional modeling work was undertaken to estimate the potential indirect impacts to customers and the broader community due to loss of substation service. This analysis found potential for significant economic consequences for the local community and cascading impacts to critical infrastructure and regional systems. The scenarios analyzed provide a plausible range of potential impacts from coastal hazards, with potential costs of unserved energy to customers of more than $25 billion under an extreme scenario. In addition to the impacts that are accounted for in the VOLL framework, cascading impacts would be expected due to loss of key services and facilities that depend on electricity from the substations in question depending on their own resilience, e.g., the communities around the substations could experience adverse consequences from loss of electric service to the sewage pump stations, hospital(s), San Diego International Airport and Port of San Diego, Tijuana Airport, and a naval yard.

Potential Economic Impacts to Customers

Table 6 provides a summary of average demand (MW) and customer counts for each substation included in the analysis. Customer totals are broken out by type (commercial or residential) where information was provided.

Table 6. SDG&E substation average demand and customer counts

		Customers		
Substation	Average Demand (MW)	Total	Commercial	Residential
A*	2.1	643	79	564
B	1.1	52	Not Available	Not Available

[9] Had transmission substations been exposed, or if distribution substations had been designed as mesh networks, the mesh nature of the circuits could avoid service disruptions as other transmission substations could fulfill the service needs. However, mesh networks can also experience service disruptions due to substation failures. For example, if multiple transmission substations in the mesh network were affected, or if the other substations could not adequately fulfill service needs, then significantly larger portions of the grid could experience impacts, meaning more customers would be potentially at risk.

C	0.2	9	9	0
D**	401.6	12,226	Not Available	Not Available
E	Not Available	1	1	0
H	0.6	8	8	0
I	Not Available	4	4	0
J	Not Available	1	1	0
F, G, K-P	Not Available	Not Available	Not Available	Not Available
Total	**405.6**	**12,944**	**102**	**564**

*Substation A has 3 feeders, each with a different average demand.
**Substation D has 23 feeders, each with a different average demand.

The estimates of unserved energy costs vary widely by Impact Scenario. Estimates of unserved energy costs for Impact Scenario 1 (future periodic tidal inundation under 2.0 m or 6.6 ft. SLR) range from $317,000 to $332,000; estimates for Impact Scenario 2 (future storm coastal wave flooding under 100- year storm and 0.5 m SLR) range from $5,358,000 to $113,546,000; and estimates for scenario 3 (extreme future storm coastal wave flooding under 100-year-year storm and 2.0 m or 6.6 ft. SLR) range from $1,180,815,000 to $25,021,734,000. Table 7 provides a summary of the cost of unserved energy estimates by scenario.

Table 7. Estimates of total cost of unserved energy by scenario

	Cost of Unserved Energy Estimates ($Millions)		
Impact Scenario	**Low**	**Medium**	**High**
1: Future Periodic Tidal Inundation	$0.3		$0.3
2: Future Storm Coastal Wave Flooding	$5.4	$57.3	$113.5
3: Extreme Future Storm Coastal Wave Flooding	$1,180.8	$12,622.0	$25,021.7

Cells shaded gray are not included in the corresponding scenario; see Appendix C for more details.

Because Impact Scenario 1 is a shorter-duration outage (12 hours), the estimates for cost of unserved energy are much lower than for Impact Scenarios 2 and 3. Both Impact Scenarios 2 and 3 are 2-week duration outages, and Impact Scenario 3 represents an outage affecting more substations than Impact Scenario 2.

Table 8 provides a breakdown of costs of unserved load by substation for each scenario. Substations with cells shaded gray are not included in the scenario analysis.

Table 8. Costs of unserved energy by substation for each scenario ($Millions)*

	Impact Scenario 1: Future Periodic Tidal Inundation		**Impact Scenario 2**: Future Storm Coastal Wave Flooding			**Impact Scenario 3**: Extreme Future Storm Coastal Wave Flooding		
Sub-station	**Low**	**High**	**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
A	$0.2	$0.2	$5.4	$57.3	$113.5	$5.4	$57,284.8	$113.5

B	$0.1	$0.1				$3.3	$35.6	$70.6
C	<$0.1	<$0.1				$1.0	$10.4	$20.7
D						$1,171.1	$12,518.7	$24,816.9
E-G	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available	Not Available
H-P	Not Available	Not Available				Not Available	Not Available	Not Available
Total	**$0.3**	**$0.3**	**$5.4**	**$57.3**	**$113.5**	**$1,180.8**	**$12,622.0**	**$25,021.7**

*The estimates include low and high ranges (Impact Scenario 1) or low, medium, and high ranges (Impact Scenarios 2 and 3) based on VOLL values used for each calculation. Substations with cells shaded gray are not exposed in the corresponding scenario. Substations with values listed as Not Available are missing data; total costs of unserved energy for each scenario would likely be greater than those provided with inclusion of missing data, however the research team is unable to estimate by how much.

Potential Impacts to Interdependent Critical Systems and Customers

A review of potential key interdependencies between the electric system and other critical infrastructure was undertaken using publicly available information, identified through internet searches and knowledge and expertise within the research team (see Section 2.4.2). As a result, the research team found the potential for significant indirect impacts throughout the community from a major adverse event. Although some of the work reviewed was undertaken to understand the potential cascading impacts from hazards unrelated to the climate, there is no reason to believe the systems would respond differently to a climate-related hazard event.

The 16 substations exposed under Impact Scenario 3 serve over 12,900 customers, 517 of which have a critical designation by SDG&E, and 112 designated by SDG&E as medical. It is also important to note that one of the substations serves the Navy base and the exact number of customer and critical operations served by this substation is unknown. However, the U.S. Department of Defense (DoD) has been actively assessing the risk of losing power at all bases and has been taking actions to reduce the demand on bases and increasing assurance of access to power. The DoD's Office of the Deputy Assistant Secretary of Defense for Installation Energy (ODASD IE) oversees programs related to installation energy, water use management, and the cybersecurity of facility related control systems (ODASD 2017).

Substation outages due to coastal flooding would create consequences for both commercial and residential customers based on the anticipated substations impacted and the customers serviced by those substations. In addition to loss of power to thousands of customers, it could disrupt the operations of the naval yard, a hospital, ports (airport and sea port), and several sewage pumping stations. Below is an overview of some of the more significant potential impacts:

Sewage Pump Stations—One of the most significant concerns under this scenario is the possible loss of functionality of the sewage pump stations. The loss of functionality could lead to release of biohazard material, creating a public health issue. These kinds of situations present unique challenges for local governments as they usually other life-safety issues without anticipating having to address this too. In many cases, because the pump stations are in low-lying areas the release could be continuous, leading to the need to evacuate people.

Hospital—The impacts to the hospital could be significant. While many patients could be moved to other facilities, some patients who are less mobile, rely on equipment to survive, and require more intense care would be more difficult to move. The impact could be increased due to obstructed roadways to evacuate patients.

Airport—Impacts at the airport could include an increase in the number of people exposed to structural damage and damage to operations that could have significant economic consequences to the region. The loss of the airport for commercial use would create significant disruption. The San Diego International airport (Lindbergh Field) is the only major commercial airport in the county, with the closet airport in the U.S. being 90 mi. (145 km) away in Orange County (John Wayne International Airport). Some of the cargo and commercial business may be able to be move to smaller local airports but many are not designed for large commercial airplanes. It should be noted that there are several military airports that would be used to transport logistics in the area if necessary.

Port—The Port of San Diego controls four maritime and cruise ship terminals, over 20 public parks, and hundreds of tenant business leases (Port of San Diego 2018). The Port could experience disruptions impacting these commercial and recreational services. While the economic loss from tourism would be substantial, the loss from commercial operations will also be of concern through its impact to the regional economy. The loss of power could hinder the port's ability to load and unload cargo from vessels. Additionally, stored shipments could be lost from inundation.

Naval Yard- The impact on the naval yard is unknown but as previously mentioned the U.S. DoD has been taking steps to mitigate against potential loss of power. The unknown factor could become a problem if the Navy is unable to sustain normal operations.

3.1.3 Other Electricity Infrastructure

In addition to substations, several other types of assets may be exposed to the climate-driven coastal hazards. The sections that follow provide results of the exposure analysis for these other asset types, as well as a general discussion of potential impacts; detailed modeling of these impacts was beyond the scope of this study.

3.1.3.1 Transformers

Over 1,200 transformers are projected to be in the exposure zones of one or more coastal hazards at mid-century (exposure scenario 2 with or without the 100-year storm), out of a total of 165,810 transformers in the study area.[10] A small number of these transformers are critical transformers located in substations. Most of the rest are transformers located on poles throughout the distribution network and are generally located above flood depth levels (generally, located about 9 m. or 30 ft. off the ground); thus, the numbers reported in this section do not mean that all of the actual transformers will be exposed (a limitation of this study), but that they are located in areas that could be exposed.

As shown in Table 9, below, most (977) are potentially exposed only to flooding, and low-lying

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[10] Given 2.0 m (6.6 ft.) of SLR (exposure scenario 2 without the 100-year storm), 2,842 transformers are exposed to one or more coastal hazard. Between 2050 and end of century, an additional 1,510 transformers become exposed to 100-year event coastal wave flooding, of which about three quarters (1,118) are exposed to annual tidal flooding. Exposure to erosion also increases, with 94 more transformers exposed to cliff erosion, and 143 more transformers exposed to 100-year event low-lying erosion, of which over one third (50) are exposed to annual low-lying erosion.

erosion potentially affects another 213. A small number (18) are potentially exposed to cliff erosion. Most transformers that are potentially exposed to some combination of coastal hazard lie near inlets or are clustered around Mission Bay or San Diego Bay. In theory, transformers may undergo damage if electrical components are exposed to water or if the transformer is hit by debris carried by water from SLR or wave runup. Older transformers are particularly sensitive, as some are made of alloys that are highly susceptible to corrosion. However, flood depths would need to be significant in order to reach the transformers.

Figure 6, Figure 7, and Figure 8, below, illustrate transformers potentially in flooding, low-lying erosion, and cliff erosion exposure zones. The first two rows indicate that over 300 transformers could potentially be exposed to a flood event today, but transformer outages due to flooding are rare. This makes sense because transformers tend to be located high up on poles (around 9 m or 30 ft. off the ground), meaning a flood could occur without actually touching the transformer itself. Thus, although the modeling indicates a few hundred transformers may be in flood zones, it is unlikely that many would actually be in contact with the flood waters. The flooding could still introduce additional saltwater related corrosion, although it is difficult to project the extent to which that would occur.

Transformers in the erosion zones could still be affected, despite being elevated, since erosion would affect the poles to which they are attached. Therefore, the damage experienced by transformers to coastal hazards would likely come from impacts to their poles from erosion events, as well as possibly increased maintenance or shortened lifetimes from corrosive effects. Section 3.1.3.3 discusses some of the potential impacts to poles.

Table 9. Potential incremental transformer exposure to coastal hazards

Exposure Category	Description of Earliest Exposure (event frequency + amount of SLR)	Incremental # of Transformers Exposed*
Flood exposure only	Annual tidal flooding at 0 m (0 ft.) SLR	301
	100-year event coastal wave flooding at 0 m (0 ft.) SLR	351
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR	37
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR	288
	Total exposed to only flooding	**977**
Low-lying erosion only	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	107
	Total exposed to only low-lying erosion	**107**
Cliff erosion only	Cliff erosion at 0.5 m (1.6 ft.) SLR	17
	Total exposed to only cliff erosion	**17**
Low-lying erosion & flood exposure	ow-lying erosion at 0.5 m (1.6 ft.) SLR, Annual tidal flooding at 0 m (0 ft.) SLR	56
	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR, 100-year event coastal wave flooding at 0 m (0 ft.) SLR	34
	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR, Annual tidal flooding at 0.5 m (1.6 ft.) SLR	1
	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR, 100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR	15
	Total exposed to low-lying erosion & flooding	**106**
Cliff erosion & flood exposure	Cliff erosion at 0.5 m (1.6 ft.) SLR, 100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR	1
	Total exposed to cliff erosion & flooding	**1**
	Total Transformers Exposed	**1,208**
	Total Transformers in System	**165,810**

* The numbers in this column represent the number of transformers potentially exposed *for the first time* during the scenario described, not the *total* number potentially exposed for that scenario.

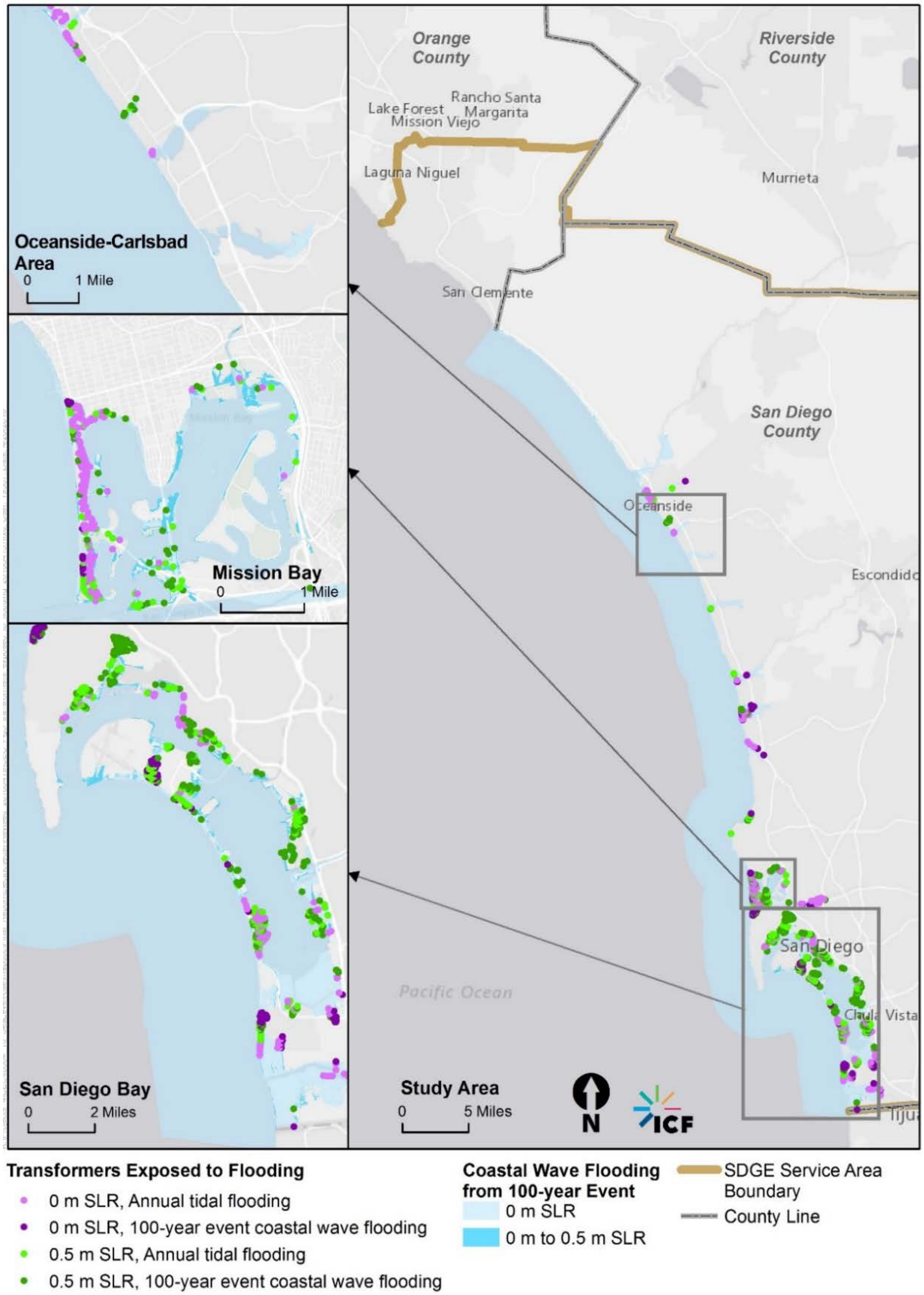

Figure 6. Potential transformer exposure to coastal flooding by mid-century. Transformers are categorized by earliest potential exposure, from present day annual events (0 m SLR, annual tidal flooding) to mid-century 100-year events (0.5 m SLR, 100-year event coastal wave flooding). Sources: SDG&E; USGS; SPAWAEsri

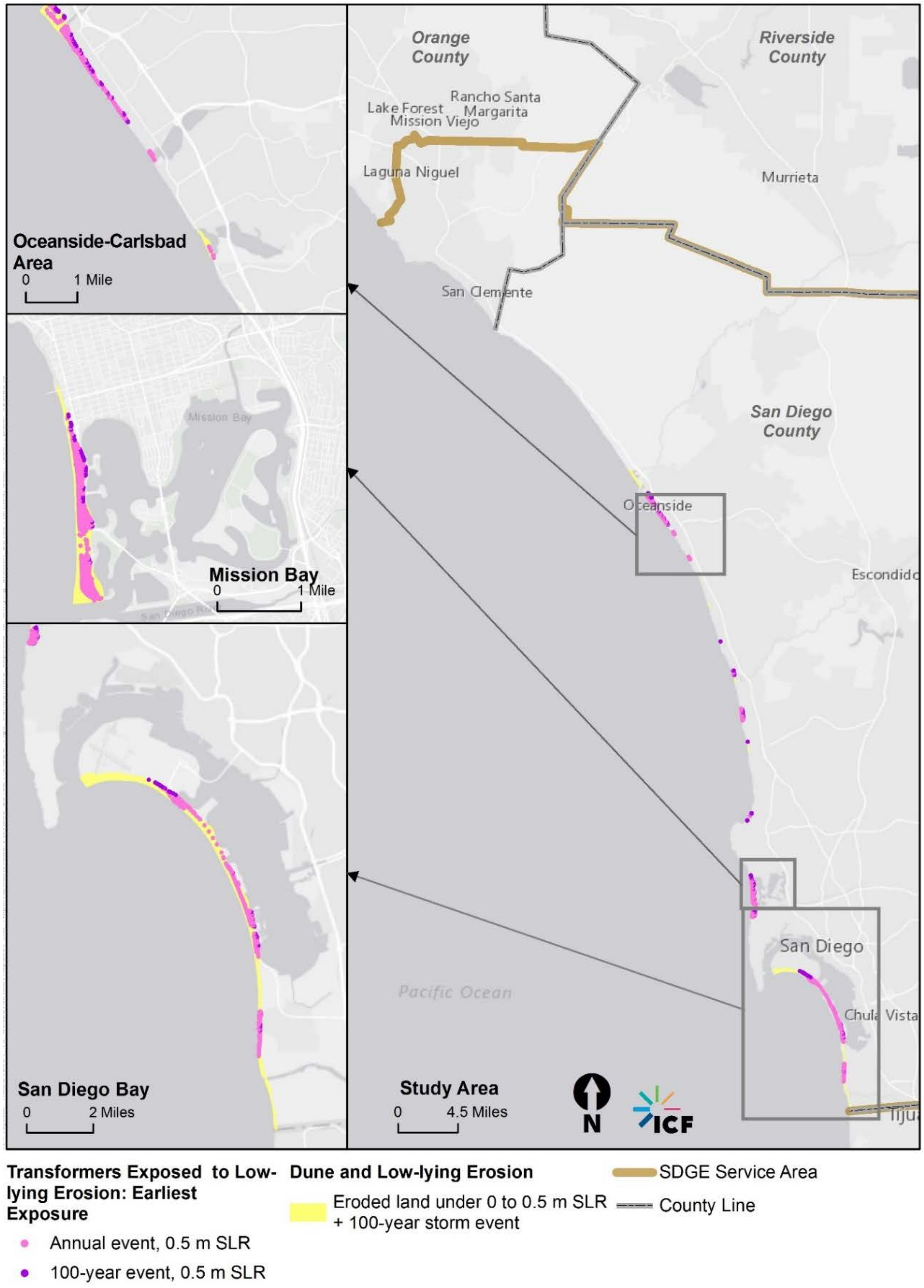

Figure 7. Potential transformer exposure to low-lying erosion by mid-century. Transformers are categorized by first earliest potential exposure. Sources: SDG&E; USGS; SPAWAR; Esri

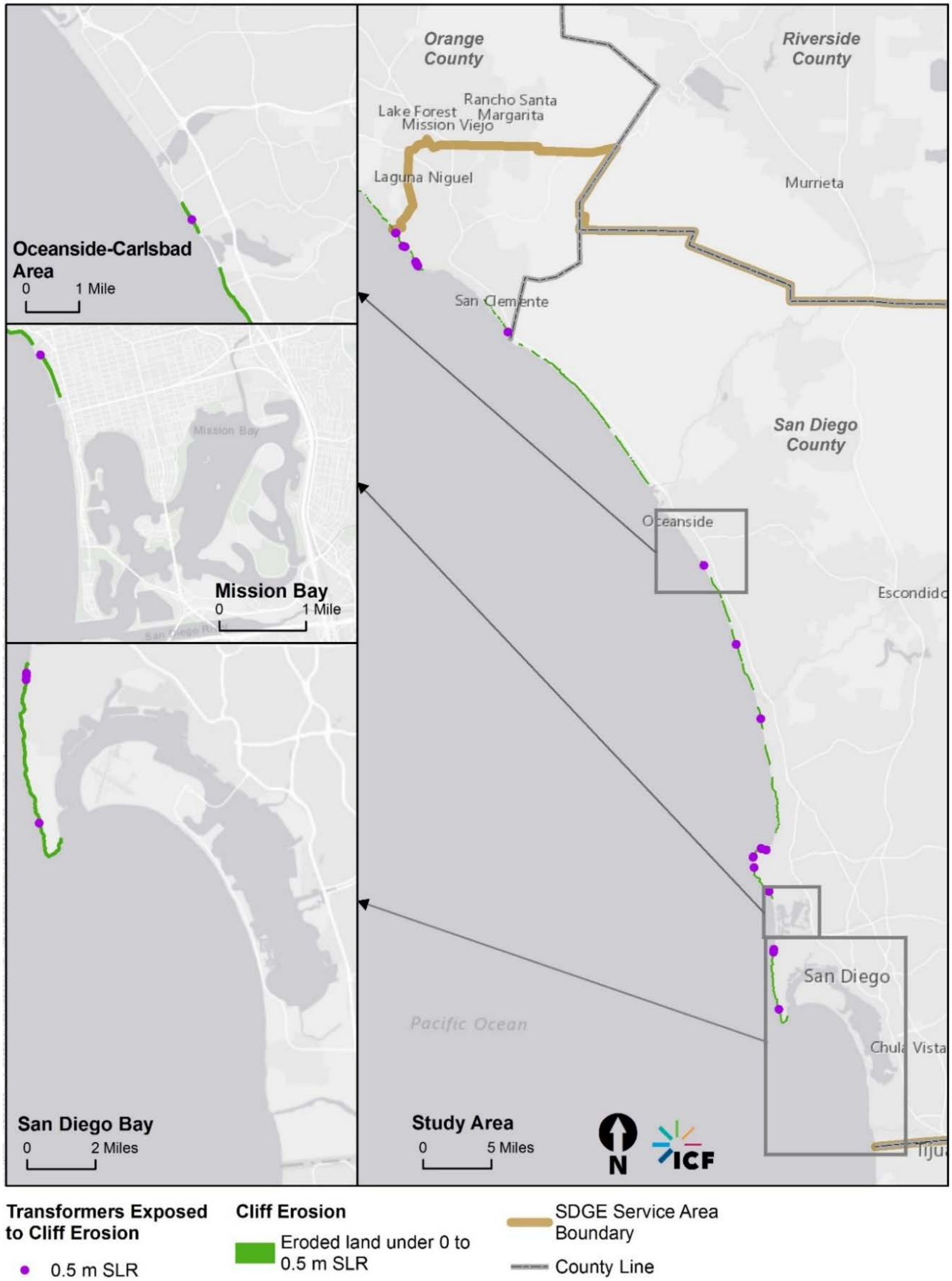

Figure 8. Potential transformer exposure to cliff erosion. Sources: SDG&E; USGS; SPAWAR; Esri

Duct Banks

Duct banks, which are conduits installed underground, are not fully protected from seepage from aboveground flooding or from a rising water table. Exposure to saltwater can cause corrosion of the equipment in the duct banks. The connectors within the duct banks are particularly susceptible to damage from saltwater. Meanwhile, the cables within duct banks are insulated, protecting them against exposure to water.

As shown in Table 10, below, nearly one percent of duct bank length within the SDG&E electricity system (151.7 mi., 248.9 km) will be potentially exposed to a coastal hazard by mid-century. Of these, most (65% or 98.6 mi., 158.8 km) are potentially exposed only to flooding. Nearly one fifth (32.3 mi., 52.0 km) are potentially exposed to flooding and dune and low-lying erosion. Thirteen percent (19.5 mi., 36.2 km) are potentially exposed to only dune and low-lying erosion. Less than one percent (1.2 mi., 1.9 km) are potentially exposed to cliff erosion.

As illustrated in Figure 9 and Figure 10, below, several duct banks are projected to be exposed to coastal flooding within Mission Bay and San Diego Bay. Notably, about 5% of these duct banks are transmission duct banks. Of the coastal hazards, duct banks could experience the greatest exposure to coastal flooding. Currently, 86 mi. (138 km) of duct banks are in the modeled 100- year event coastal wave flooding zone (out of about 17,500 mi. or 28,000 km total in the study area), about half of which are in the annual tidal flooding zones. By mid-century, exposure could increase considerably (by over 50%), and 130 mi. (209 km) could be exposed to 100-year event coastal flooding, about 60% of which could also be exposed to annual tidal flooding. The vast majority (94%) of these duct banks are part of the distribution system, while the rest are part of the transmission system. Distribution system (but not transmission system) duct banks are also exposed to erosion at mid-century. Specifically, 1 mi. (1.6 km) is exposed to cliff erosion, 51 mi. (82 km) are exposed to low-lying erosion under a 100-year event, of which over 90% are also exposed to annual low-lying erosion.[11]

Older 4 kV circuits are more susceptible to damage from storm conditions. However, SDG&E is currently in the process of adapting and upgrading these to newer 12 kV circuits. About 22% of customers are currently on the old, 4 kV circuits.

As with transformer and substation exposure, projected duct bank exposure to coastal hazards is generally concentrated around inlets and around Mission Bay and San Diego Bay, as depicted in Figure 9 and the more close-up Figure 10, below.

[11] By late in the 21st Century, an additional 127 mi. (204 km) will be exposed to annual tidal flooding, and another 37 mi. (60 km) will be exposed to 100-year event coastal-wave flooding. Low-lying erosion exposure also increases by late in the 21st Century, with an additional 8 mi. (13 km) exposed to low-lying erosion during an annual tidal event, and another 8 mi. (13 km) exposed to low-lying erosion during a 100-year wave event. An additional 6 mi. (10 km) of duct bank are also exposed to cliff erosion by late in the 21st Century. These numbers assume 2.0 m. (6.6 ft.) of sea level rise by the end of the century.

Table 10. Potential incremental duct bank exposure to coastal hazards

Exposure Category	Description of Earliest Exposure (event frequency + amount of SLR)	Incremental Length of Duct Banks Exposed	
		mi.	**km**
Flood exposure only	Annual tidal flooding at 0 m (0 ft.) SLR	26.6	42.9
	100-year event coastal wave flooding at 0 m (0 ft.) SLR	31.4	50.6
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR	3.8	6.2
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR	36.8	59.2
	Total exposed to only flooding	**98.7**	**158.8**
Dune & low-lying erosion exposure only	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	16.6	4.7
	100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	2.9	31.4
	Total exposed to only low-lying erosion	**19.5**	**36.2**
Cliff erosion only	Cliff erosion at 0.5 m (1.6 ft.) SLR	1.2	1.9
	Total exposed to only cliff erosion	**1.2**	**1.9**
Flood and dune & low-lying erosion exposure only	Annual tidal flooding at 0 m (0 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	16.3	26.3
	100-year event coastal wave flooding at 0 m (0 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	0.7	1.1
	Annual tidal flooding at 0 m (0 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	9.1	14.7
	100-year event coastal wave flooding at 0 m (0 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	1.3	2.2
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	1.0	1.6
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	0.1	0.1
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	3.4	5.5
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	0.3	0.4
	Total exposed to low-lying erosion & flooding	**32.3**	**52.0**
Total length of duct banks exposed		**151.7**	**248.9**

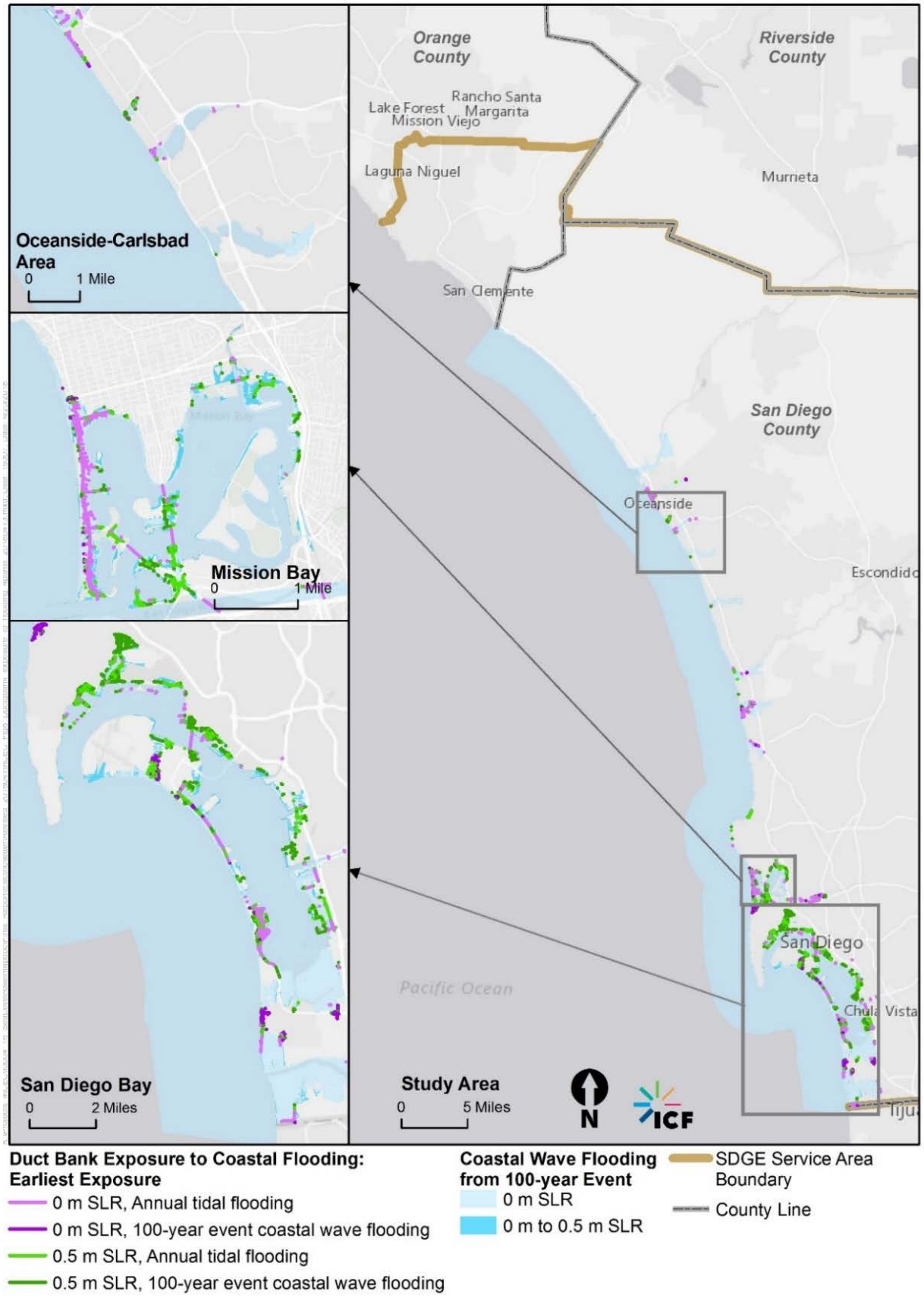

Figure 9. Potential duct bank exposure to coastal flooding under present-day and mid-century levels. Duct banks are categorized by earliest potential exposure, ranging from current annual events (0 m SLR, annual tidal flooding) to mid-century 100-year events (0.5 m SLR, 100-year event coastal wave flooding). Sources: SDG&E; USGS; SPAWAR; Esri

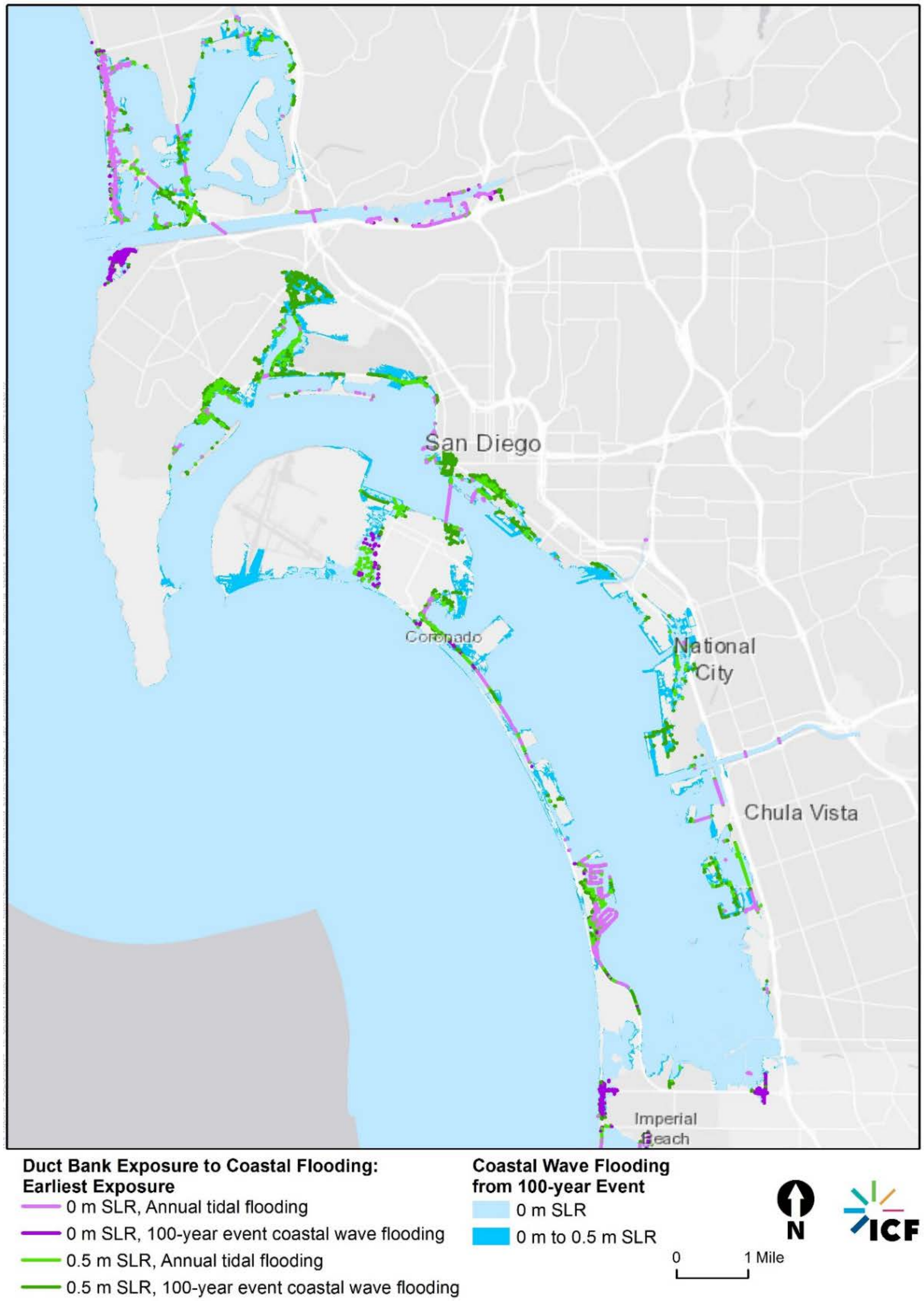

Figure 10. Potential duct bank exposure to SLR in San Diego Bay and Mission Bay. Duct banks are categorized by earliest potential exposure, ranging from current annual events (0 m SLR, annual tidal flooding) to mid-century 100-year events (0.5 m SLR, 100-year event coastal wave flooding). Sources: SDG&E; USGS; SPAWAR; Esri

3.1.3.2 Poles and Lines

Transmission lines generally are not located along the coast and therefore have limited exposure to coastal hazards. There is a larger number of *distribution* poles and lines, on the other hand, in the hazard zone. Coastal wave flooding is the primary hazard of concern.

As shown in Table 11 below, approximately 52.5 mi of pole and line length within the SDG&E electricity system (84.5 km, 0.6 percent of total length) will be potentially exposed to a coastal hazard by mid-century. Of these, most (40.9 mi., 65.8 km, 78 percent) are potentially exposed only to flooding. 7.7 mi. (12.5 km, fifteen percent) are potentially exposed to flooding and dune and low-lying erosion. 3.8 mi. (6.1 km, less than ten percent) are potentially exposed to only dune and low-lying erosion. 0.1 mi. (0.1 km, less than one percent) are potentially exposed to cliff erosion.

According to the exposure modeling, there are 39 mi. (63 km) of poles and lines currently within the modeled 100-year event coastal flood zones. By mid-century, flood exposure could increase by nearly 25%. By mid-century, a small number of poles and lines are projected to be exposed to erosion, with 1 mi. (1.6 km) exposed to cliff erosion, and 21 mi. (34 km) exposed to 100-year event low-lying erosion, half of which are exposed to annual low-lying erosion.[12] SDG&E has approximately 8,500 mi. (13,600 km) of poles and lines in the study area, meaning the exposure of poles and lines is small overall.

The lines themselves are mostly protected from flooding since they are raised high (by at least 3 m or 10 ft.) above ground (SDG&E 2017b). However, their supporting infrastructure—the poles and associated equipment—are built into the ground and thus would be in contact with saltwater during flooding. The force of the water can cause erosion of soil and scour around stationary objects, such as poles and pole anchors. Furthermore, the force of breaking waves and floating debris is known to damage infrastructure in the flood path (FEMA 1999). Exposure to saltwater can also corrode equipment (Seattle City Light 2016), including equipment associated with the poles.

Steel distribution poles and wood distribution pole guy anchors in the SDG&E territory have historically been susceptible to corrosion from humidity and precipitation. However, SDG&E's efforts to upgrade the system from 4 kV lines to 12 kV lines will help reduce the likelihood of a pole downing since they will be reinforced with steel, which is less corrosive.

The impacts to SDG&E will likely come in the form of increased maintenance costs. Service disruptions could occur as well, although the number of customers affected by loss of a single pole is relatively low; customers along a single circuit would be affected, but larger downstream impacts would not occur. Furthermore, inspection and maintenance programs are designed to identify and correct problems before they occur, since scour and corrosion tend to exert their impacts over time rather than coincide with a single event. Thus, a downed line from a flood event is possible, but not likely to be a widespread or frequent problem. Rather, the primary impact to SDG&E from damage to poles and lines are likely to manifest in the form of increased costs to monitor, upgrade, maintain and repair this infrastructure due to increased corrosion and

[12] By late in the 21st Century, 53 more mi. (85 km) of poles and lines are exposed to 100-year event coastal flooding, nearly 70% of which (36 mi. or 58 km) are also exposed to annual flooding. An additional 1 mi. are exposed to coastal cliff erosion, and an additional 6 mi. (10 km) are exposed to 100-year event low-lying erosion, half of which are also exposed to annual low-lying erosion.

scour impacts.

It is important to note that the 100-year flooding events are likely to occur in conjunction with a storm; storms bring not only flooding but also high winds. Although wind is outside the scope of this study, it is worth mentioning this hazard as SDG&E stakeholders noted that winds tend to be more damaging to their system than coastal floods. At a national level, climate change is projected to increase wind damage to electricity infrastructure. However, these projections vary regionally, and may not be linked to coastal storms in the Southwest (DoE, 2015). Climate model wind projections were incorporated into California's Third Climate Change Assessment, but only for coastal flooding hazards (i.e., wave height and direction). The Third Assessment found that increased coastal flooding from storms was driven relative sea level changes in the San Diego area, but wave height remained relatively unchanged, suggesting that wind did not significantly impact flooding (Bromirski et al. 2012). Consequently, it is unclear how wind-related impacts outside of coastal flooding may increase in the future in the San Diego area. Since wind is outside the scope of this study, this topic was not explored in detail; however, it may be a good focus for future research projects given the potential for damage from wind.

As is the case for the other assets, projected exposure is generally concentrated around inlets and Mission Bay and San Diego Bay, as depicted by Figure 11 and Figure 12, below.

Table 11. Potential incremental pole and line exposure to coastal hazards

Exposure Category	Description of Earliest Exposure (event frequency + amount of SLR)	Incremental Length of Poles and Lines Exposed	
		mi.	km
Flood exposure only	Annual tidal flooding at 0 m (0 ft.) SLR	18.9	30.4
	100-year event coastal wave flooding at 0 m (0 ft.) SLR	13.6	21.9
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR	0.6	1.0
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR	7.8	12.5
	Total exposed to only flooding	**40.9**	**65.8**
Dune & low-lying erosion exposure only	Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	3.3	5.3
	100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	0.5	0.7
	Total exposed to only low-lying erosion	**3.8**	**6.1**
Cliff erosion only	Cliff erosion at 0.5 m (1.6 ft.) SLR	0.1	0.1
	Total exposed to only cliff erosion	**0.1**	**0.1**
Flood and dune & low-lying erosion exposure only	Annual tidal flooding at 0 m (0 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	3.1	5.0
	100-year event coastal wave flooding at 0 m (0 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	1.1	1.7
	Annual tidal flooding at 0 m (0 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	1.8	3.0

	100-year event coastal wave flooding at 0 m (0 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	0.2	0.3
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	0.3	0.5
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR, Annual low-lying erosion at 0.5 m (1.6 ft.) SLR	0.0	0.0
	Annual tidal flooding at 0.5 m (1.6 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	1.1	1.8
	100-year event coastal wave flooding at 0.5 m (1.6 ft.) SLR, 100-year event low-lying erosion at 0.5 m (1.6 ft.) SLR	0.1	0.1
	Total exposed to low-lying erosion & flooding	**7.7**	**12.5**
Total length of poles and lines exposed		**52.5**	**84.5**

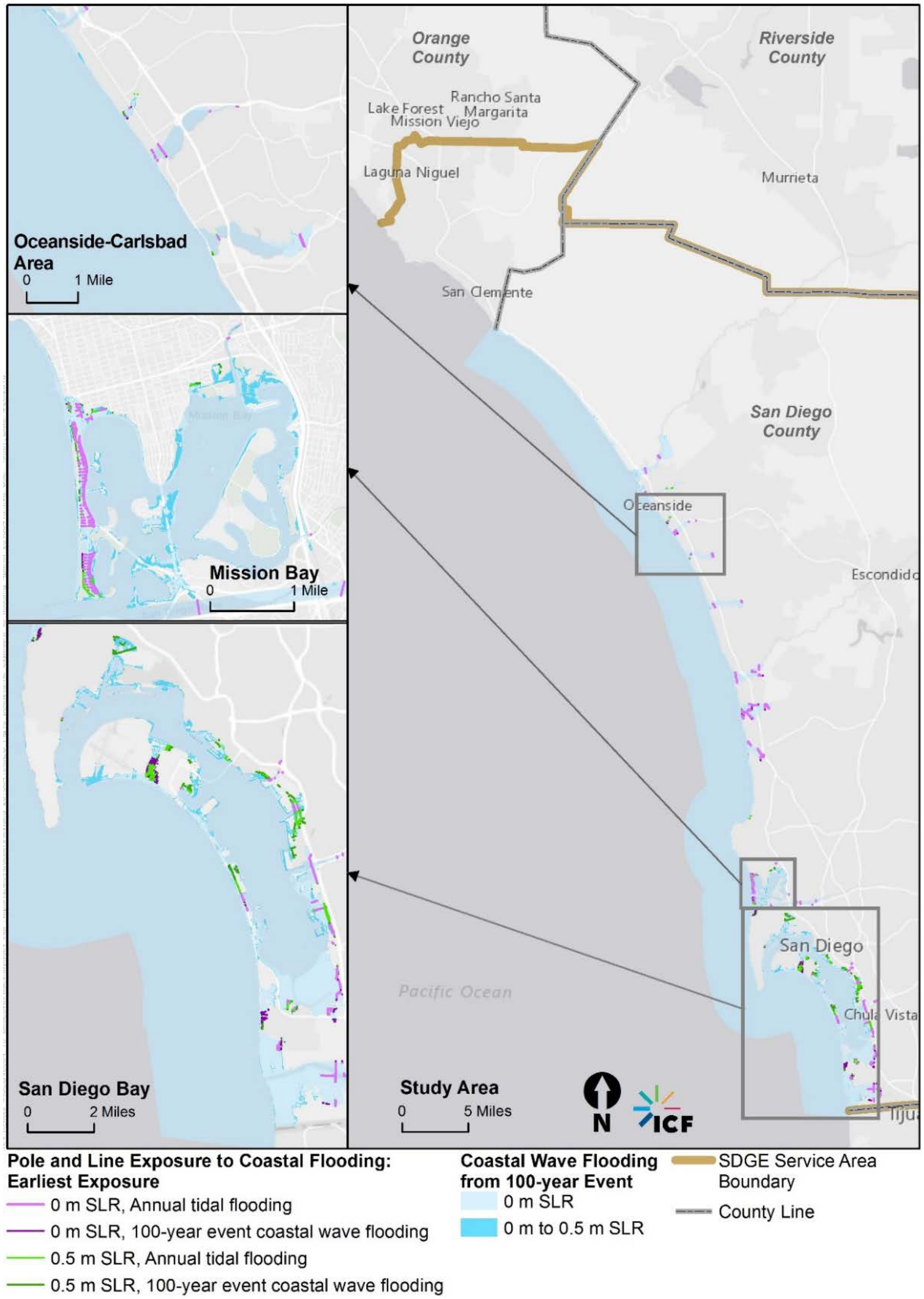

Figure 11. Potential pole and line exposure to coastal flooding under present-day and mid-century sea levels. Poles and lines are categorized by earliest potential exposure, ranging from current annual events (0 m SLR, annual tidal flooding) to mid-century 100-year events (0.5 m SLR, 100-year event coastal wave flooding). Sources: SDG&E; USGS; SPAWAR; Esri

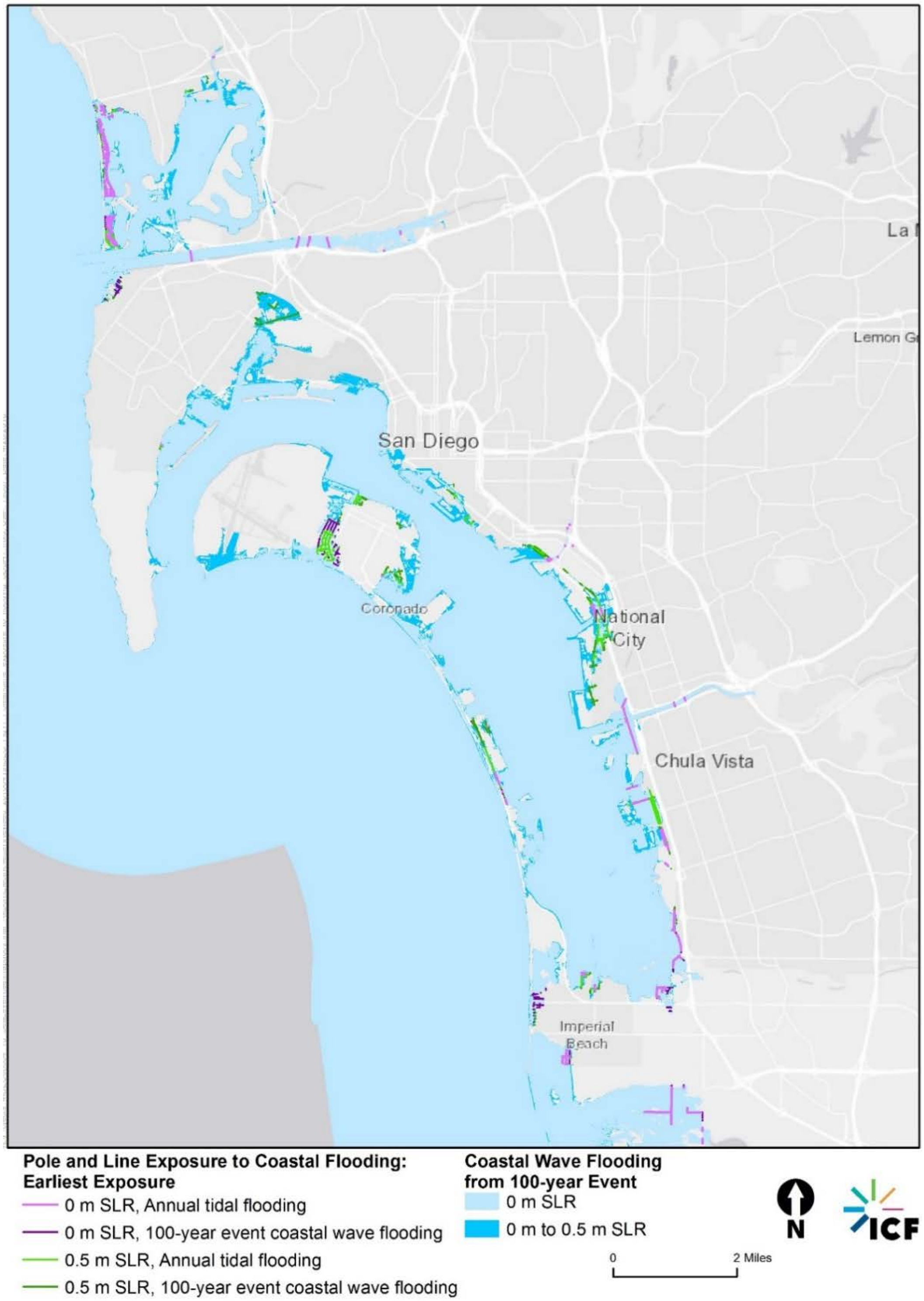

Figure 12. Potential pole and line exposure to SLR in San Diego Bay. Poles and lines are categorized by earliest potential exposure, ranging from current annual events (0 m SLR, annual tidal flooding) to mid-century 100-year events (0.5 m SLR, 100-year event coastal wave flooding). Sources: SDG&E; USGS; SPAWAR; Esri.

3.1.3.3 Meters, Relays, Switches

Saltwater can damage electrical components of customer meters and relays.[13] Meters are typically around 1.5 m (5.0 ft.) above ground but can be as low as 0.9 m (3.0 ft.). Relays, which are in aboveground duct bank control boxes, are typically lower, ranging between 0.9 and 1.2 m (3 and 4 ft.) high. Low height meters and relays are susceptible to water infiltration, which could damage the electrical equipment. Relay boxes are not waterproof, so any tidal inundation or wave flooding reaching the height of the box could allow water to seep into the relay itself.

Debris carried by water from SLR or wave runup can also damage meters and relays.

In some ways, temporary inundation could be more troublesome for customer connections than permanent inundation because the utility will need to repair and maintain these customer connections. Restoring service after a temporary inundation event faces an additional hurdle if residents evacuate coastal areas during a storm, so even if the utility is able to restore power, the customer load (or energy demand) may not be high enough to restore service. SDG&E cannot opt to stop providing service to an existing customer, even if that customer's connection requires frequent repair.[14]

In the case of permanent inundation, on the other hand, the customers may relocate so SDG&E would not need to provide service. However, the utility would still incur costs to terminate and remove abandoned connections, and there may be increased costs in the interim as the location in question moves from more frequent temporary inundation to permanent inundation.

Switches, in general, are sensitive to corrosion. SDG&E has a corrective maintenance program in place to identify and reinforce corroded switches, and upgrade switch alloys to increase salinity tolerance, helping to minimize the risk.

3.2 Flexible Adaptation Pathways

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

3.2.1 Key Findings from Workshops

Workshop Key Finding #1: Climate change exposure and impacts information is often lacking, but necessary to effectively use existing SDG&E processes to manage climate-related risks.

A key finding of Workshop 1 was that a system-wide, 'top down' multi-criteria approach for selecting and 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 few site- and context-specific conditions may determine the appropriate adaptation measures, and alternative adaptation measures quickly drop out of consideration based on those conditions. Therefore, evaluating each possible adaptation measure against a pre-determined set of criteria with the intention of then comparing and selecting adaptation measures was not necessary.

Overall, introducing a scoring system to rank the prioritization of adaptation measures was not

[13] The GIS asset datasets do not contain these asset types; therefore, exposure statistics could not be generated.

[14] The CPUC has often stated that the utilities obligation to serve must be met, as evidenced by the CPUC's General Order planning and construction rules (CPUC 1995; Hanschen and Gordon 2004).

helpful, as the utility seems well aware of appropriate adaptation measures for a given hazard and location, based on experience in managing impacts from the familiar climate-driven hazards, such as wildfire and river flooding. Consequently, additional adaptation to climate change can be evaluated using current systems, but the systems will require those undertaking the analyses to have ready access to credible and up-to-date climate change impact information.

Rather than introducing a new scoring system or new risk-management systems, therefore, it may be better to ensure that appropriate information and decision-making frameworks are in place that would allow existing risk-management systems to include climate change considerations.

Workshop Key Finding #2: Integrating climate adaptation considerations into existing decision-making processes is an opportunity to support implementation.

SDG&E's internal engineering design, risk management and disaster preparedness systems generally function well to address current familiar climate-related risks, with several examples from the management of wildfire risk. Importantly, enhancements to the forecasting of coastal climate hazards—storm flooding and coastal erosion events—were stressed as being valuable for both managing current levels of coastal risks and also as an important pre-requisite to systematic long-term adaptation investments. The research team found, based on workshop discussions, that SDG&E has the ability to evaluate risk mitigation measures based on situation-specific factors, but requires robust climate hazard information to support adaptation decision making, guided by its enterprise risk management system through programmatic investment, such as increasing the resilience of specific hazard-exposed infrastructure.

Workshop Key Finding #3: Investment in adaptation can occur gradually and opportunistically, but a long-term programmatic approach to adaptation planning is still needed to ensure continuity of investment and allow evaluation over time.

The research team found that SDG&E 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 over a programmatic/decadal timeframe. This could allow SDG&E to track asset performance related to climate hazards over time, improving insights into how climate hazards are impacting the system, and if adaptation actions are meeting expectations. Importantly, however, the development of a detailed adaptation investment plan – including the costing of such a plan – will require additional analysis that was beyond the scope of the current project (see Section 4.2).

For SDG&E, 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 3.2.2.

Workshop Key Finding #4: SDG&E and local communities should collaborate to find the most effective and cost-effective adaptation solutions that directly reduce exposure to SDG&E assets and enhance community resilience

Finally, workshop participants concluded that taking a programmatic approach in collaboration with other stakeholders is vital for choosing the optimal portfolio of adaptation measures, both for SDG&E and for the community overall. If adaptation decisions are made without broader picture considerations, the selected adaptation measures might not be the most cost-effective options, and could even have unintended impacts of their own. For example, SDG&E assets exposed to coastal hazards may be situated in areas where other important community assets are located. The most cost-effective response may be for the community to take action with protective structures or beach nourishment that would protect all of these assets together. Some SDG&E actions could have secondary impacts on the community. For example, building a protective flood wall or other structure might protect a given structure, but could raise aesthetic concerns or cause loss of an important recreational resource; or, intense efforts to increase redundancy or harden infrastructure might prevent funds from being spent on other priority activities. It is therefore important that adaptation decisions are made within a large decision-making context; SDG&E adaptation decisions should be made in coordination with the larger community. It is for these reasons that the priority adaptation actions discussed in the following section focus on first ensuring appropriate methods, data access, and collaborative partnerships are in place before specific decisions are made about SDG&E's procedures and assets.

For example, the identification of SLR exposure for low-lying coastal substations highlights broader community exposure to these hazards and, as a result, any adaptation measures applied to enhancing the resiliency of substation infrastructure would be embedded within a broader response to adaptation for the community surrounding the substation and served by it. Statistics on supply interruptions and maintenance call-outs due to increased saltwater corrosion resulting from SLR could trigger a broader discussion about potential to relocate critical infrastructure to higher ground in the longer term. 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 cost-effective outcomes.

3.2.2 Key Findings on Potential Flexible Adaptation Pathways at SDG&E

Based on the study research and workshops, the research team identified seven potential adaptation *actions* as outlined in Table 12. Four of these actions are considered priority near-term actions (see bolded actions in Table 12, below).

Table 12: Illustrative Adaptation Actions and Indicative Implementation Steps, with Priority Actions Bolded

Action Code	Action Description	Adaptation Measures
A	Harden Infrastructure	• Using inputs from analysis undertaken through assessment of Actions B-E, invest in infrastructure hardened to increase resilience to coastal hazards (e.g., higher flood-rated substation infrastructure)

B	**Enhance coastal storm prediction and response**	• **Integrate readily available coastal hazard risk mapping undertaken through the study with SDG&E's GIS system** • **Commission a storm hazard model to enhance the short-term predictive ability for extreme flood events days in advance of forecasted storm fronts hitting the region. Identify areas and assets that will be exposed to both present-day extreme flooding from storm events and potential future SLR flooding** • **Upgrade coastal monitoring network** • **Enhance mutual cooperation agreements for coastal storm response**
C	**Signposts & thresholds assessment**	• **Develop of suite of signposts to track, and thresholds that determine, when a critical decision point for triggering adaptation is reached (threshold).**
D	**Regional consultation**	• **Discuss with regional stakeholders, including the county, city, and regional offices of State agencies (e.g., California Coastal Commission), the San Diego Association of Governments, and the p and airport to formulate broader plans for opportunities and constraints that would contribute to community-wide resilience**
E	**Cost-benefit analysis methods**	• **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** • **Use inputs from the enhanced storm surge model (Action B) to fine-tune cost-benefit analysis** • **Use regional consultation inputs (Action D) to refine plans for financing actions (e.g., ability to cost-share adaptation initiatives)**
F	Grid enhancement	• Using inputs from analysis undertaken through assessment of Actions B-E, invest in grid enhancement technologies and operational practices (e.g., enhanced mesh networks)
G	Site or relocate assets	• Using inputs from analysis undertaken through assessment of Actions B-E, relocate assets to less-climate vulnerable locations • Incorporate climate change factors into new-infrastructure siting guidelines and procedures

Figure 13 shows a preferred adaptation pathways approach that begins with the four initial priority adaptation actions, namely Actions B, C, D, and E, as depicted by bolded colored dots and lines. Actions A, F, and G 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. 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 D and E initiate non-priority actions A, F, and G). The 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 bars are terminal stations which indicate that that an adaptation action is no longer needed or viable.

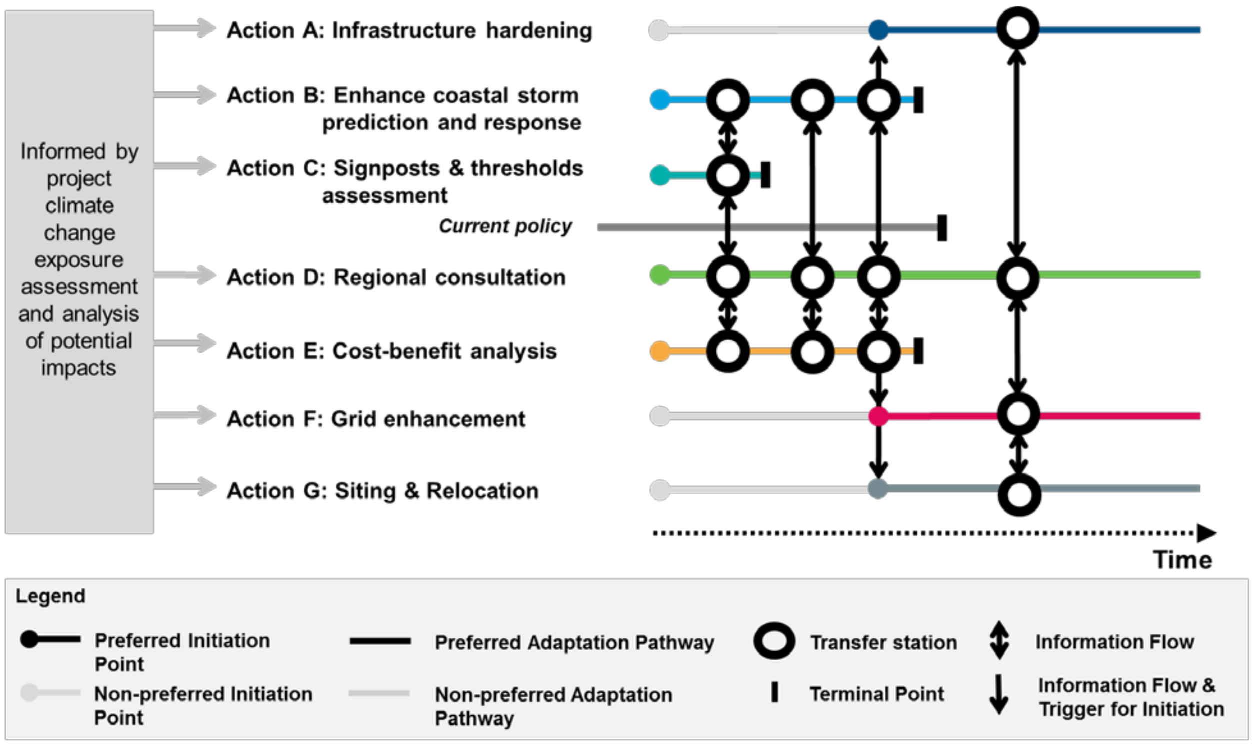

Figure 13: Initial flexible adaptation pathways map for immediate SDG&E adaptation actions

The four initial adaptation actions—Action B: Enhance coastal storm prediction and response, Action C: Signposts & thresholds assessment, Action D: Regional consultation and Action E: Cost-benefit analysis methods—are all "low regrets" climate change adaptation measures. That is, they enhance the ability of the utility to predict and manage present-day coastal climate hazards in SDG&E service territory (in a cost-effective and regionally engaged manner) that is valuable for both present-day, 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 and G.

Action B (Enhance coastal storm prediction and response) will help SDG&E make informed decisions long-term adaptation investments. This action would involve:

1. Establishment of a coastal storm modeling and prediction capability based on best available science and harmonized with national and state-level predictive models.
2. Integration of the outputs of the new storm modeling and prediction system with existing SDG&E disaster preparedness and response approaches.
3. Use of data collected during actual coastal storm events to inform the interpretation long-term coastal flooding and inundation driven by SLR scenarios, including those developed through this study.
4. Assessment of the lessons learned from using the system to inform developing a systematic suite of signposts and the thresholds that trigger adaptation action (see below).

Action C (Signposts & thresholds assessment) involves the analysis of appropriate signposts recommended to be tracked to signal when a key decision point is imminent that would trigger adaptation action. 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)
2. Local and regional adaptation thresholds (e.g., lack of formal local zoning to address SLR vulnerability by a set date)
3. Internal SDG&E "process/operational" thresholds (e.g., exceedance # of system outages/year due to flooding; lack of clear climate risk governance by a set date; lack of design standards that include climate by a set date)
4. External regulatory thresholds (e.g., regulatory agencies require system hardening to specific SLR levels)

Action D (Regional consultation) acknowledges that SDG&E is already engaged in several key adaptation initiatives, such as the San Diego Regional Climate Collaborative, as discussed in more detail in Appendix B. SDG&E 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 SDG&E to make adaptation decisions with a full understanding of complementary actions being taken by local and regional entities that could affect SDG&E operations. This Action will also give SDG&E an opportunity to ensure that local and regional decisions are made with a full understanding of potential impacts on the energy system.

Ongoing regional consultation (Action D) is also envisaged as Actions A, F and G are implemented. SDG&E'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 actions of another, and vice versa, at a given trigger 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 measures (Action E). Critically, this analysis must be cognizant of the fundamental basis of the flexible adaptation pathways approach that explicitly considers switching of adaptation measures, based on pre-defined triggers. As such, traditional cost- benefit analysis approaches that assume only one policy outcome is undertaken will not be appropriate (Schwartz and Trigeorgis 2004; Buurman and Babovic 2016). Rather, economic assessment techniques tailored to flexible adaptation pathways, 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.

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[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 and the resulting uncertainties in benefit/cost flows over time.

As shown on the left-hand side of Figure 13, 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 territory may be warranted.

Finally, investments in coastal climate change adaptation by SDG&E can be improved following completion of Actions B, C and E, as well as receiving substantive inputs from 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, and G. As shown in Figure 13, Actions B, C 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) 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. A significant number of SDG&E assets and services are exposed to coastal hazards related to climate change, including inundation driven by SLR, coastal wave flooding from storms, and coastal erosion. Areas of concern for the utility by mid-century are focused on hotspots located in low-lying areas around bays and estuaries and on the coastline adjacent to erodible cliffs and dunes. The scale of projected exposure increases markedly between mid-century and end of century as sea level rises.

2. The most significant direct impacts could occur from damage to substations near the San Diego and Mission Bays. If inundated with sufficient water to damage equipment, these substations could go out of service until flooding recedes and repairs can be made, potentially disrupting service to thousands of customers.

3. Other direct impacts could come in the form of increased maintenance or repair costs, rather than widespread service disruptions. The cumulative impacts of these increased costs could not be quantified in this study, but could potentially be significant given the large number of assets potentially exposed.

4. Indirect impacts of coastal climate change hazards on the economy and social fabric of the San Diego region could be extremely significant, with potential costs to customers of more than $25 billion under an extreme scenario by the end of the century. Furthermore, the communities around the substations could experience adverse consequences from loss of electric service to sewage pump stations, a hospital, San Diego International Airport and the Port of San Diego, and the Navy yard.

5. The research team found that taking an iterative and flexible adaptation pathways approach to adaptation, rather than implementing a full suite of adaptation measures upfront, will allow SDG&E to make better-informed decisions about adaptation investments as time goes on and more information is known about changes in climate, customer needs, the grid, new technologies, and other factors.

6. Immediate adaptation actions identified through this study for SDG&E are:

    a. Enhance coastal storm prediction and response;

    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 advances, there are a number of limitations to the findings due to the scope of the project 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 electric system will likely change significantly 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. However, with this assessment, SDG&E can make informed plans for the placement and management of future assets.

- While the research team considered some of the interdependencies with other critical infrastructure, more analysis of the potential feedbacks between the electricity assets and other critical systems, especially the tightly connected natural gas 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 measures for a given asset.

- The coastal hazards in scope of this study included wave flooding and erosion. However, all of those hazards may occur in conjunction with a storm which includes additional wind hazards. More extensive impacts may be experienced due to the wind associated with such storms rather than the flooding. Future research may wish to consider the vulnerability of the electric system to winds associated with storms.

- 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. For example, although the modeled depths of flooding at the substations are known, the research team was not able to compare those depths with the height and location of equipment within a substation. Safety concerns prevented the team from visiting the sites to measure heights, and information was not available by other means. 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 or group of customers could be impacted under a given scenario.

- The research team made several simplifying assumptions and lacked complete data with regard to the modeling of the estimated unserved energy of a utility service area due to climate-driven hazards under a range of exposure and cost scenarios (see Appendix C). Because the approach relied on VOLL values from the literature, rather than from a targeted survey of SDG&E customers, the estimated VOLL values could be improved for the application to SDG&E. VOLL estimates are sensitive to a variety of factors, and values from published literature that serve as appropriate estimates and reference points are subject to uncertainty (London Economics 2013). In addition, VOLL is commonly used to determine value of short-duration outages, but limited information on VOLL is available for long-duration outages (e.g., two weeks) such as those associated with a low-frequency high-impact event. Because the nature of costs changes over time, it is difficult to extrapolate from shorter-duration outage VOLL values to long-duration outage values (DOE 2016b). Additional research is needed on the evolution of customer costs over time during long-duration events.
- The flexible adaptation pathways provide a framework and initial set of actions for SDG&E to consider. Additional work is needed to expand on how these measures may best be implemented within the context of SDG&E's existing decision-making processes, which may in turn uncover additional supporting actions that would be beneficial.

4.3 Future Research Opportunities

During the project, the research team identified several research topics that could significantly benefit adaptation efforts in the energy sector.

The flexible adaptation pathways approach underscores the fact that perfect information about the future is not needed to take action in the short term. There are initial actions that can be implemented today to begin the adaptation process. Adaptation measures 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 measures would be particularly valuable at this stage. For example, if the Energy Commission or CPUC or both want to promote and expand adaptation measures, they could guide new research to 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).

The overall approach and methods used in this research could be applied to other California IOUs that face the challenge of reducing the risks from coastal climate change impacts. IOUs provide natural gas and electricity through similar physical transmission and distribution infrastructures. While customer base, service area, and management and planning processes can differ, this approach of generating an exposure analysis, identifying key impacts, and determining adaptation pathways to mitigate risk could be employed in similar assessments of California IOUs to inform their own adaptation and resiliency investments. Similarly, there is an opportunity through future research to strengthen understanding of how technology can be deployed in the electricity supply and distribution system to optimize resilience. Smart grid technologies could play an important role in increasing resilience, especially when linked to enhanced grid compartmentalization based on assessments of coastal hazard vulnerabilities. Emerging technologies could be used to identify outages and remotely reroute electricity to undamaged circuits and feeders. 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 grid resilience in the face of climate hazards, including coastal storms.

In addition, future research could investigate other changing factors that will affect overall vulnerability. Climate is not the only thing that will change in the future; population, demand, supply characteristics, and other factors mean that the electricity 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 their vulnerability 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 electricity assets, including incorporation of adaptation actions.

Additional research is needed to continue to develop a better understanding of potential indirect impacts. For example, because this study's approach relied on VOLL values from the literature, rather than from a targeted survey of SDG&E customers, the estimated VOLL values could be improved for the application to SDG&E and could be augmented by additional economic or other social science research. Getting a better handle on indirect impacts is important for several reasons. First, focusing only on direct impacts can understate the ultimate impact to the community and economy. Quantification of indirect impacts can help identify and prioritize where adaptation is needed most. Second, since making any industry or community truly resilient requires action by a wide variety of actors—both public and private—understanding both the direct impacts to the utility and the indirect impacts to the community can help foster collaboration and encourage the most cost-effective suite of adaptation actions.

Although the greatest gaps in understanding relate to the indirect impacts of climate hazards and the implementation of effective adaptation actions, additional research on modeling and projecting coastal climate-related hazards is also warranted. The study found important differences among 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 extent 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 is needed to improve model projections and reduce uncertainties.

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APPENDIX A: Detailed Exposure Methodology

The research team developed composite data sets to analyze the exposure of SDG&E assets to coastal hazards. The models available to assess projected hazards each have strengths (e.g., ability to run scenarios with and without coastal armoring management) 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 our 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 research team deemed this dataset has been superseded by more recent efforts, so the team 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 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 Pendelton.

  Use—The research 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 coastal erosion or impacts to sandy and cliff-backed beaches.

***Use*—**The research 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 runup (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*—**Our 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 our 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*—**Our team deemed this dataset insufficient since it did not incorporate SLR and was not available in time for this Task 3 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 our 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 erosion from USGS CoSMoS 3.0
  - Erosion of dune and low-lying inlets from USGS CoSMoS 3.0 COAST (plus geomorphic interpretation[16]) and SPAWAR (see data gap filling in Section 2.3.2.1)
- Tidal Inundation (periodic flood impacts)
  - USGS CoSMoS 3.0 (used maximum annual tidal 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

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

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.[17] 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.

[17] 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 SDG&E, the research team used GIS to intersect the hazard zones with the electricity point assets (distribution OH structures, dynamic protective devices, fuses, substations, surface structures, switches, transformer devices, transmission OH structures, and underground structures) and line assets (duct banks and pole lines) 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 0.01 mi. (0.02 km) of line assets exposed. Figure B-1, below, depicts the spatial extents of the CoSMoS and SPAWAR data.

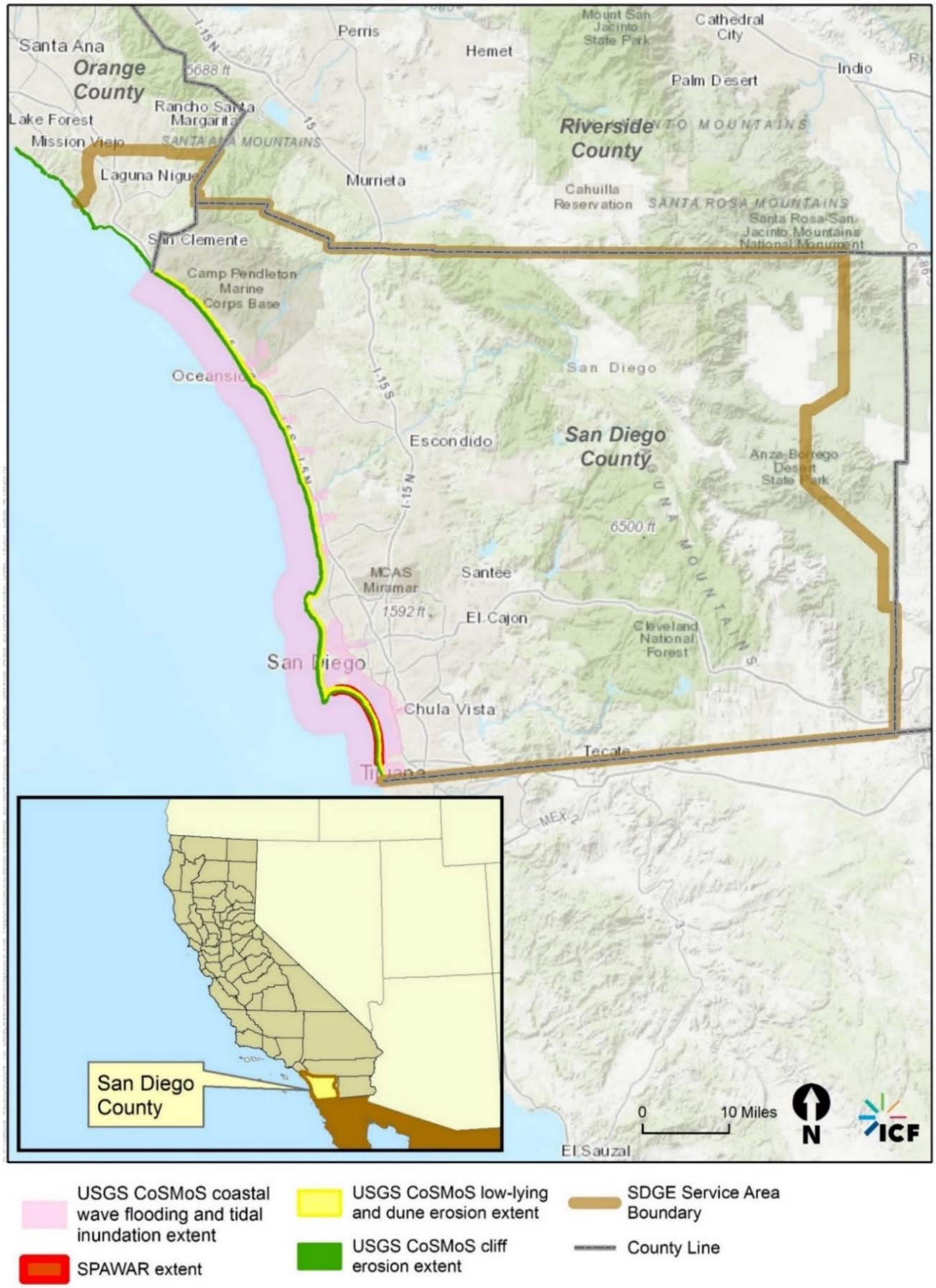

Figure B-1. Extents of CoSMoS and SPAWAR data. Sources: USGS; SPAWAR; Esri.

B.1 Coastal Wave Flooding

As shown in Table B-1 and Table B-2, below, large numbers of point and line assets are potentially exposed to coastal wave flooding. Note, however, that the exposed assets represent a small percentage of the overall system, since this hazard exposes only infrastructure near the coast.

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 ft.) SLR	2.0 m (6.6 ft.) SLR
Distribution OH Structure	238,290	1,094	1,453	3,407
Dynamic Protective Device	2,949	39	54	141
Fuse	31,148	150	270	707
Substation	363	8	12	19
Surface Structure	118,737	567	905	2,126
Switch	14,042	95	236	652
Transformer Device	165,810	732	1,079	2,586
Transmission OH Structure	24,367	204	245	558
Underground Structure	201,765	1,149	1,594	3,167

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	
Unit	mi.	km	mi.	km	mi.	km	mi.	km
Duct Bank	17,591	28,310	84.54	136.05	130.27	209.65	293.52	472.37
Pole Line	8,458	13,612	38.25	61.56	48.58	78.18	101.32	163.06

B.2 Coastal Erosion

A limited set of assets are projected to be exposed to coastal erosion, as shown in Table B-3 and Table B-4. No substations are expected to be exposed, but potentially critical aboveground assets such as transformer devices are exposed; details are provided below. In addition, our analysis determined that there are multiple specific anomalies 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; as a consequence, results for this scenario are not reported. The research team has alerted USGS to these issues.

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
Distribution OH Structure	238,290	7	87
Fuse	31,148	0	5
Surface Structure	118,737	16	55
Switch	14,042	0	1
Transformer Device	165,810	18	88
Transmission OH Structure	24,367	0	2
Underground Structure	201,765	11	120

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**
Duct Bank	17,591	28,310	1.18	1.90	7.31	11.76
Pole Line	8,458	13,612	0.08	0.13	1.44	2.32

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

- 66 mi. (107 km) of duct banks and nearly 18 mi. (29 km) of pole lines are exposed, which could be impacted by erosion, even if underground
- 674 transformer device are exposed
- No substations are exposed to low-lying erosion in our analysis

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
Distribution OH Structure	238,290	607	865
Dynamic Protective Device	2,949	21	21
Fuse	31,148	67	94
Surface Structure	118,737	294	387
Switch	14,042	38	45
Transformer Device	165,810	417	587
Transmission OH Structure	24,367	28	34
Underground Structure	201,765	741	905

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
Distribution OH Structure	238,290	693	1,034
Dynamic Protective Device	2,949	21	25
Fuse	31,148	74	118
Surface Structure	118,737	332	447
Switch	14,042	38	52
Transformer Device	165,810	481	674
Transmission OH Structure	24,367	31	46
Underground Structure	201,765	798	1,005

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
Duct Bank	17,591	28,310	46.49	74.82	59.24	95.34
Pole Line	8,458	13,612	9.72	15.64	14.98	24.11

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
Duct Bank	17,591	28,310	51.07	82.19	66.45	106.94
Pole Line	8,458	13,612	11.5	18.51	17.93	28.86

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 territory:

- 64 transformer devices are exposed.
- Approximately 8 mi. (13 km) of duct banks are exposed, which could be uncovered by erosion processes.
- No substations are exposed based on SPAWAR results.

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
Distribution OH Structure	238,290	1	3	30
Dynamic Protective Device	2,949	0	0	7
Fuse	31,148	1	2	8
Surface Structure	118,737	4	17	53
Switch	14,042	0	0	0
Transformer Device	165,810	3	18	64
Underground Structure	201,765	1	38	115

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
Distribution OH Structure	238,290	3	5	40
Dynamic Protective Device	2,949	3	5	8
Fuse	31,148	2	5	13
Surface Structure	118,737	12	39	60
Switch	14,042	0	0	8
Transformer Device	165,810	15	44	76
Underground Structure	201,765	22	82	135

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**
Duct Bank	17,591	28,310	0.21	0.34	1.57	2.53	6.57	10.57
Pole Line	8,458	13,612	0.00	0.00	0.04	0.06	0.35	0.56

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**
Duct Bank	17,591	28,310	1.14	1.83	4.08	6.57	7.9 7	12.83
Pole Line	8,458	13,612	0.00	0.00	0.06	0.10	0.53	0.85

B.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, 18 substations and over 2,000 transformer devices, which could be important aboveground assets:

- 18 out of the 363 substations are exposed

- 85 mi. of 8,458 mi. (137 km of 13,612 km) of pole lines are exposed
- More than 1800 out of over 118,000 surface structures 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
Distribution OH Structure	238,290	595	925	2,847
Dynamic Protective Device	2,949	25	38	130
Fuse	31,148	64	145	595
Substation	363	1	10	18
Surface Structure	118,737	269	512	1,844
Switch	14,042	41	87	574
Transformer Device	165,810	357	641	2,193
Transmission OH Structure	24,367	110	185	464
Underground Structure	201,765	634	1,025	2,814

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**
Duct Bank	17,591	28,310	43.68	70.30	76.59	123.26	255.99	411.97
Pole Line	8,458	13,612	23.1	37.18	33.83	54.44	84.97	136.75

APPENDIX C: Detailed Methodology for Modeling Electric Indirect Impacts

The overall approach to analyzing potential indirect impacts from climate-driven coastal hazards uses the exposure and direct impact result to inform a set of asset loss scenarios the research team used to model the economic cost to customers. In addition, the research team explored the potential cascading indirect impacts from the loss of electricity through a review of existing emergency management information.

C.1 Develop Asset Loss Outage Scenarios

Using the exposure analysis results, the research team worked with SDG&E to define a set of three specific climate hazard scenarios to analyze. The scenarios span a range of plausible conditions, including an extreme scenario. The research team developed the following three scenarios for the analysis:

C.1.1 Impact Scenario 1: Future Periodic Tidal Inundation

This scenario relates to future tidal inundation of substations from 2.0 m (6.6 ft.) of SLR, projected for the end of the century. Under this scenario, based on available data, there would be a simultaneous loss of 12 substations [one 69kV and eleven 12/4kV step-downs]. The outage anticipated from this tidal event would be 12 hours due to flooding around the high tide and subsequent time for restoration crews to complete their work. Major equipment failure or complications are not anticipated.

C.1.2 Impact Scenario 2: Future Storm Coastal Wave Flooding

This scenario is for flooding from a future coastal wave event associated with a 100-year storm in addition to 0.5 m (1.6 m) of SLR projected for 2050. Based on the flooding extents, under this scenario there would be simultaneous loss of 4 substations (one 69kV and three 12/4kV step- downs). The outage is considered severe, and the outage duration under this scenario is two weeks. This represents the duration of the flooding event itself, which could span multiple days, as well as time to repair significant impacts to the substations. For this scenario, it is possible substation component parts might need to be procured from outside the service area, given the extensive nature of the flooding and impacted assets.

C.1.3 Impact Scenario 3: Extreme Future Storm Coastal Wave Flooding

This scenario is for flooding from a future coastal wave event associated with a 100-year storm in addition to 2.0 m (6.6 ft.) of SLR projected for the end of the century; it represents a plausible worst-case event. Based on the flooding extents, under this scenario, based on available data there would be simultaneous loss of 13 substations (two 69kV and eleven 12/4kV step-downs). Like Impact Scenario 2, the outage is considered severe, and the outage duration under this scenario is two weeks, related to the duration of the flooding event itself and time to repair significant impacts to the substations.

C.2 Analyze Selected Scenarios

For each of the scenarios, the research team analyzed the potential indirect economic impacts to customers served by the affected assets. The analysis considered the distribution system design and customer types to estimate the potential impacts.

Although the distribution substations typically serve a certain set of customers, in many cases there is a contingency path available (Consolidated Edison 2014) for serving customers, should assets be lost. To account for this system contingency as much as possible, the research team worked with SDG&E to determine if customers served by an affected distribution substation can be served from other substations through switching of feeders or implementation of other controls. Based on data provided by SDG&E, the research team identified feeders that had alternative sources of supply. In the event of the loss of the primary substation in a particular scenario, service to customers could still be maintained as long as the backup supply source remained operational in that scenario. Service to customers would be lost only if both primary and backup substations failed simultaneously in the same scenario. This information was incorporated into the indirect economic impacts assessment.

The research team calculated the economic impact of the service disruptions by applying the estimate of the costs to consumers of interruption of service referred to as the VOLL to the estimate of unserved load derived from the modeling. The research team performed research of existing studies available in the industry to deduce appropriate VOLL estimates for multiple customer classes within the SDG&E Service Area and relevant outage durations. The research team calculated the expected energy demand on each feeder from data provided by SDG&E. Using this information, the research team calculated the Expected Unserved Energy (EUE) resulting from the service disruptions.

Cost of unserved energy is calculated using the following equation:

Cost of Unserved Energy ($) = VOLL ($/kWh) x Unserved Energy (MWh) x 1000

Where Unserved Energy (MWh) = Average Demand (MW) x Duration (Hours); Average Demand (MW) = Load Factor x Peak Demand (MW);

Peak Demand (MW) = 1.73 x Voltage (kV) x Current (A) / 1000.

An overall VOLL value for each scenario was calculated from the Medium/Large Commercial & Industrial, Small Commercial & Industrial, and Residential VOLL estimates based on customer class breakdown for each substation and feeder, where possible; see Table C-1.

Table C-1. Value of Lost Load estimates used in the analysis by customer type for each scenario

Impact Scenario	VOLL Estimates Used ($/unserved kWh)								
	Low			Medium			High		
	Medium/ Large C&I*	Small C&I	Residential	Medium/ Large C&I	Small C&I	Residential	Medium/ Large C&I	Small C&I	Residential
1	$12	$240	$1	N/A	N/A	N/A	$12	$241	$1
2	$13	$258	$1	$136	$2,756	$14	$269	$5,465	$27
3	$13	$258	$1	$136	$2,756	$14	$269	$5,465	$27

*Commercial & Industrial

Source: Based on values from Sullivan et al. (2009, 2015)

The research team compiled minimum and maximum estimates of VOLL for varying outage durations (up to 16 hours) and customer types, including Medium/Large Commercial & Industrial (over 50,000 annual kWh), Small Commercial & Industrial (under 50,000 annual kWh), and Residential. As VOLL studies generally support *reliability* analyses, the assumed outage durations are typically less than 24 hours.

To better understand opportunities for adaptation to future low-probability long-duration outages from combined SLR and coastal wave flooding, the research team needed to create estimates for customers' willingness to pay for energy over a 2-week outage. To accomplish this, the research team used a linear extrapolation using data on 8 and 16 hour outages to extrapolate to 336 hours (two weeks). Consolidated Edison used a similar technique as part of their post-Sandy Storm Hardening regulatory filing. Consolidated Edison used interruption costs for outages up to 8 hours in duration to linearly extrapolate to 290 hours.

Where the research team did not have sufficient information to determine energy demand by customer class for a particular feeder, the research team used customer data derived from the U.S. Energy Information Administration 2016 Form EIA-861 to calculate the weighted average VOLL for the feeder (EIA 2017). Form EIA-861 provides information on retail revenue, sales, and customer counts by state, balancing authority, and class of service for each electric distribution utility or energy service provider. The weighted average VOLL was applied to all customers on the feeder.

The research team calculated the indirect economic impact of service disruptions by using VOLL to estimate the value of unserved load derived from the modeling. For Impact Scenario 1 (12- hour outage duration), the research team calculated minimum and maximum estimates of unserved load using ranges of 12-hour outage duration VOLL values from the literature. For Impact Scenarios 2 and 3 (2-week outage duration), the research team used three estimates of VOLL to derive a range of unserved load values: (1) an estimate using the average 16-hour outage duration VOLL (derived from the literature), to represent a scenario where the VOLL values plateau after 16 hours; (2) an estimate using an average 1 week duration outage (derived using linear extrapolation), to represent a scenario where the VOLL values plateau after 1 week; and an estimate using the average 2-week outage duration (derived using linear extrapolation), to represent a scenario where VOLL values continue to increase linearly over time.

These three estimates provide a range of potential unserved load values for Impact Scenarios 2 and 3.

While the total cost of unserved energy continues to increase over the length of the outage, the value that a customer places on a kilowatt hour might at some point reach a plateau, as the customer ceases normal business operations and makes other related decisions that limit the continued escalation of VOLL. The point at which VOLL values might begin to plateau is highly uncertain and will likely vary based on region and customers. This inclusion of a plateau at one week is intended to capture actions that customers might take to limit activity and adapt to a reduced state of reliability and supply over an extended period of time (a period referred to as a "New Normal"), thus restricting the further increase of VOLL values over the remaining duration of the outage (NERC 2012). Existing studies on VOLL for long-duration outages are limited, and that knowledge gap should be an important area for future research.

C.3 Assess Potential Community-Wide Impacts from Loss of Service to Critical Customers

An outage, such as the Future Extreme Coastal Flooding scenario example analyzed above for customer economic impacts, would also likely have impacts beyond just economic effects. The magnitude and duration of the impacts have significant ramifications on response and recovery operations. Additionally, impacts that effect functionality of, and access to, lifeline systems (e.g., electricity, water, natural gas, liquid fuel, wastewater, and communications) and essential services (e.g., fire protection, law enforcement, and medical care) can generate increased demands and create unanticipated challenges. An example of this was the 2011 Southwest Blackout. Although a relatively short-duration event, the area experienced many unanticipated challenges. Availability of fuel for backup generators and other functions, for example, was limited by the inability to retrieve, transport, and disseminate the fuel. The lack of power hindered the ability to pull fuel from underground tanks, created long delays within the region due to the loss of traffic signals, and limited capabilities to distribute fuels at the consumer end. Several hospitals in San Diego suffered for lack of generator fuel during the event.

Energy interdependencies extend beyond local areas, as the systems are connected across California and throughout the western region. Losing a single piece can and has led to cascading electrical power outages and fuel shortages across wider systems.

This is all exacerbated when roads are inaccessible. Blocked roads and inoperative traffic signals limit the ability of people to move around to obtain goods and services and limit the ability of local governments and businesses to bring in additional supplies to meet demands, including the ability of the energy utility to access impacted assets for repair and restoration.

Some of the less obvious disruption concerns with regional events include:

- Inability to access funds due to loss of electricity for computer systems.
- Inability to provide gasoline due to loss of electricity
- Inability to pump and maintain natural gas and wastewater systems due to loss of electricity,
- Inability to maintain traffic signals due to loss of electricity, which are needed to reduce congestion for emergency/services vehicles or for evacuations
- Inability to maintain safety and communications systems (i.e., SCADA) due to loss of electricity, which can cause system control issues, reduce situational awareness during an event, and impede service restoration

- Inability to meet residential medical needs due to loss of electricity, especially when many patients are at home with medical equipment that needs to be powered.
- Limitation of capacity for railroads, ports, and airports that connect San Diego to the outside world.

APPENDIX D: Potential Adaptation Measures

A useful way of analyzing the adaptation measures is to cross-reference the measures published in previous literature. This both structures the analysis and allows comparison with initiatives nationwide. In particular, a report produced through the U.S. DOE's *Partnership for Energy Sector Climate Resilience (the Partnership)* is particularly helpful: *Climate Change and the Electric Sector: Guide for Climate Change Resiliency Planning* (DOE 2016a). SDG&E is an active member of the *Partnership (DOE 2017).* The *Partnership categorized* electricity-system 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 was expanded 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-2). 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 SDG&E 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 to do not infer implementation in whole, or in part, by SDG&E. Rather, as outlined in the body of this report, it is suggested that SDG&E work with regional stakeholders to develop a suite of adaptation measures that – when taken together – ensure an integrated adaptation response to the risks posed by coastal climate change hazards. This will require careful consideration of the relative contributions to adaptive efforts by organizations in the region with specific responsibilities for mitigating the risks of coastal hazards, including potential secondary impacts that may result over time from implementing such actions. For example, the implementation of a coastal protection structure to reduce coastal hazard risk in one location may reduce recreational amenity and disrupt the flow of beach sand resulting in erosion of down-drift beaches (USACE, 2013). As a result, what seems like a good adaptation idea in one place (or at one point in time) can, when all the consequences are taken into account be maladaptive – that is cause greater levels of climate vulnerability in another place or to another sector of the economy. It is for this reason that Action D: Regional consultation is suggested as an initial adaptation action in Section 3.2.2, Table 12. This sort of consultation and collaboration can make use of existing partnerships noted in Appendix E.

Further, the engagement of regulatory organizations will be important in this process to ensure that any 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 and related agencies. CEC or other agencies may wish to consider additional research to better understand how regulations might currently inadvertently inhibit resiliency efforts, or where newly-crafted ones could encourage more resiliency; for example, whether rules related to cost recovery, building standards, or smart grid technology are hindering or helping resilience goals.

Table D-1. Adaptation Measures within the Purview of SDG&E Implementation

Asset Type	Adaptation Measure	Example Cost or Cost Range	Study Analysis including Workshop Discussion
Hardening Assets			
Distribution	Undergrounding Distribution Lines	$100,000 to $8,200,000 per mi.	Feasible only in non-coastal erosion-prone areas. Elevated coastal water tables both a construction constraint and a safety hazard. Consolidated Edison commissioned a study to assess the costs and feasibility of this measure, but selected to pursue different hardening measures due to the high costs associated with the measure. Sources: DOE 2016a, Consolidated Edison 2015, DOE 2010.
	Install Submersible Distribution Switches	No Data	Workshop participants discussed opportunities to install distribution switches capable of operating while submerged
Transmission & Distribution	Upgrade wood poles	$16,000 to $40,000 per mi.	Wood-to-Steel Pole Replacement Program currently underway with a focus on enhancing wildfire resiliency. Source: DOE 2016a, SDG&E 2015a
	Substation Hardening	$600,000 per substation	Critical to consider hardening investments in the context of broader regional resilience investments Source: DOE 2016a.
	Elevating Substations	>$800,000 to >$5,000,000 to elevate	New South Bay substation in Chula Vista elevated to integrate SLR factors (see below). Sources: DOE 2016a, DOE 2010.
	Guying	$600 to $900 per pole	This is a common hardening method. Further investments could be based on any updates to FEMA VE-zone mapping within the SDG&E service territory to ensure investment targeting. Sources: DOE 2016a, DOE 2010.
	Strengthen Poles and Aerial Lines	No Data	Consolidated Edison is strengthening poles and aerial cables so that they are able to withstand winds of up to 110 mi./hr (177 km/hr). The utility also redesigned wires to fall off of poles when tree branches fall on them, preventing damage to surrounding homes and reducing the likelihood of live wires on the ground. This is the most common hardening practice for electric transmission and distribution systems. SDG&E could pursue these measures in areas that experience strong winds and in those that are surrounded by a large number of trees. Sources: Consolidated Edison 2015, DOE 2010.

Asset Type	Adaptation Measure	Example Cost or Cost Range	Study Analysis including Workshop Discussion

	Reconfigure Grid	No Data	Workshop participants discussed opportunities to prevent customers from losing service during substation outages by reconfiguring grid connections to provide customers with power in a way that is not dependent on substations that are at risk of flooding.
	Install Intelligent Interrupters	$729,000 per isolation switch	Workshop participants discussed opportunities to install intelligent interrupters, which can sectionalize areas that are at high risk for experiencing outages, thereby preventing the outage from increasing in extent. Consolidated Edison is already installing isolation switches to enhance resilience to coastal flooding. Source: Consolidated Edison 2015.
Transmission	Upgrade Transmission Lines	>$400,000 per mi.	Opportunities to apply the proactive grid management technologies applied to increase grid resilience to wildfire hazard, including enhanced compartmentalization of line systems to allow selective de-energization. Source: DOE 2016a.
	Undergrounding Transmission Lines	>$500,000 to $30,000,000 per mi.	See above. Sources: DOE 2016a, DOE 2010.
All assets	Submersible Equipment	>$130,000 per vault $71,000 per transformer	Workshop participants estimated that submersible equipment is up to 5 times more expensive. Consolidated Edison is installing submersible network protectors and transformers to enhance resilience to coastal flooding. Sources: DOE 2016a, Consolidated Edison 2015.
System	Install Microgrid	$150,000,000 for 40MW average load	SDG&E has considerable experience through its wildfire resilience enhancement program to apply to grid compartmentalization to mitigate coastal climate change hazards. Source: DOE 2016a.
	Advanced Metering Infrastructure	$240 to >$300 per smart meter installed	Smart meters can be a useful tool to enhance grid management and monitoring, especially when undertaken in concert with grid compartmentalization. Source: DOE 2016a.
Planning and Operations			
Generation	Drainage Studies	No Data	Workshop participants discussed opportunities to conduct drainage studies to determine whether drainage measures can prevent water retention at generation plants during coastal flooding events.
	Purchase Pumps	No Data	Workshop participants discussed opportunities to invest in pumps to remove water after a flooding event.
Transmission & Distribution	Backup Generators	$20,000 per substation	Not discussed as an adaptation measure during the workshop. Rather, emphasis on enhanced grid compartmentalization and reducing single points of failure on the grid. Source: DOE 2016a.
Asset Type	**Adaptation Measure**	**Example Cost or Cost Range**	**Study Analysis including Workshop Discussion**
All assets	Vegetation Management	$12,000 per mi.	Existing programs in place in response to wildfire hazard. Opportunity to integrate coastal hazard factors, particularly to reduce vegetation debris damage during flood events. Sources: DOE 2016a, DOE 2010.

Asset Type	Adaptation Measure	Example Cost or Cost Range	Study Analysis including Workshop Discussion
	Asset Inspection	No Data	Conduct regular inspection of assets threatened by coastal flooding or erosion. Source: DOE 2010.
	Design Future Assets to Account for Coastal Flooding	No Data	Workshop participants suggested that when designing assets (including access roads), SDG&E consider coastal flooding projections. Where flooding is inevitable, design sensitive assets (such as conduits and vaults) to be water-tight. Creating a mapping system that illustrates projected SLR during average and storm conditions, and using this information in planning processes is recommended (Seattle City Light 2016).
System	Demand Reduction Programs	$50 to >$1,000 per MWh	Not discussed as an adaptation measure during the workshop. Could include appliance recycling programs, demonstrations, education initiatives, weatherization incentives, and similar consumer behavior programs. Source: DOE 2016a.
	Notify customers when outages are expected	No Data	Workshop participants discussed opportunities to notify customers when outages are expected due to coastal flooding. Particularly, customers that are reliant on substations at risk of flooding should be warned about potential outages. When appropriate, collaborate with local governments to accurate information and improve public perception. Source: DOE 2010.
	Upgrade control centers and communication equipment	No Data	Significant investments already made by SDG&E to enhance control center in response to wildfire threat. Workshop participants concluded that no upgrades to the control center itself are required to address climate change hazards, but upgrading communication to enhanced monitoring systems may be required (see below). Source: DOE 2016b, DOE 2010.
	Enhance monitoring systems	No Data	Workshop participants discussed the opportunities for SDG&E to initially tie in its monitoring program to existing systems that monitor the coastal environment. For example, existing beach cameras used primarily for tourism and by surfers checking wave conditions. This strategy is also proposed by Seattle City Light (2016).
	Institute a utility-wide policy coastal flooding impacts policy		Institute a utility-wide policy for coastal flooding impacts that requires that future tidal flooding impacts be considered during the design of major proposed capital improvement projects (Seattle City Light 2016).

Asset Type	Adaptation Measure	Example Cost or Cost Range	Study Analysis including Workshop Discussion
	Integrate system changes to enhance resilience in long-range planning	No Data	Source: DOE 2016b.
	Update emergency operations plan	No Data	Sources: DOE 2016b, DOE 2010.

	Incorporate climate adaptation funds into general rate cases (GRCs)		Workshop participants at the SoCalGas workshop proposed that funds needed to plan for and implement climate adaptation measures be incorporated into GRCs. Consolidated Edison has also proposed this as a method to fund climate adaptation. Source: DOE 2016c.
	Use indemnity-based insurance	No Data	During the workshop, it was noted that insurance usually covers only high-value assets or high-cost events. This study found that most of the potentially exposed assets are distribution assets, which tend to be lower cost. Therefore, insurance may play a smaller role for this hazard. Source: DOE 2016b, Adaptation Workshop.

Table D-2. Collaborative Regional Adaptation Measures

Hardening Assets			
	Reinforce Floodwall	$220,000 per mi.	Seawall investment requires a regional approach that considers electricity infrastructure within broader community resilience enhancement. Source: DOE 2016a.
	Build New Floodwalls	$4,000,000 per mi.	See above. Source: DOE 2016a.
	Beach Nourishment	Cost varies on sand source and placement	Placing additional sand into the system through beach nourishment reinforces the natural protection to the upland afforded by the beach. Source: USACE, 2013. Beach nourishment in the San Diego Region is coordinated by the SANDAG Shoreline Preservation Working Group[18]
Asset Type	**Adaptation Measure**	**Example Cost or Cost Range**	**Study Analysis including Workshop Discussion**
	Marsh Sills and Stabilization	$2 per square meter	Marsh sills are underwater stone structures at the base of a vegetated slope, parallel to an existing shoreline. Marsh sills promote shoreline stabilization by encouraging sand to accrete between the sill and shoreline. This strategy is an option for SDG&E assets that are threatened by coastal flooding and are along a shore lined by marsh. Sources: The Nature Conservancy 2017[19], DOE 2016a.

[18] http://www.sandag.org/index.asp?committeeid=26&fuseaction=committees.detail

[19] This project, funded in support of the California Fourth Climate Change Assessment Report and sponsored by the Nature Conservancy, investigated 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.

Asset Type	Adaptation Measure	Example Cost or Cost Range	Study Analysis including Workshop Discussion
	Marsh Creation	$4.30 per square meter	Marsh creation may be feasible in in some of estuaries and bays around the SDG&E territory. Source: DOE 2016a.
	Vegetated Dunes	No Data	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 SDG&E assets that are along a shore lined by sandy beaches with dunes that are threatened by coastal flooding. Source: The Nature Conservancy
	Cobble Berms or Dynamic Revetments	No Data	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 SDG&E assets, and where coastal flooding threatens SDG&E assets that are along a shore lined by beach. Source: The Nature Conservancy 2017.
	Tidal Benches	No Data	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. Source: The Nature Conservancy 2017.
	Oyster Reef	No Data	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 runup. Source: The Nature Conservancy 2017.
	Eelgrass Beds	No Data	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. Source: The Nature Conservancy 2017.
	Lagoon Mouth Management	No Data	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 SDG&E assets that are threatened by coastal flooding and are nearby lagoons. Source: The Nature Conservancy 2017.
Planning and Operations			
	Conduct research on projected changes in climate	No Data	The importance of engaging in ongoing climate change research was stressed by workshop participants. For example, engaging in state-wide initiatives, such as Cal-Adapt, and also regional research undertaken by regional research centers (Sempra Energy 2016).

	Arrange mutual aid agreements	No Data	It was discussed during the workshop that mutual assistance agreements for disaster response between utilities are well-developed and work well. Participants discussed that there are opportunities to extend the concept of mutual assistance agreements to developing long-term adaptation measures, particularly where there is mutual benefit for sharing costs and benefits. For example, a flood protection structure that enhances the resilience of an electricity asset may also provide resiliency benefits to other non-SDG&E assets/services. Source: DOE 2016b, DOE 2010.
	Rebuild assets in a new location/ Managed retreat	Dependent on asset type. $6,000,000 for substation.	Cost depends on asset type, location, and design. Source: The Nature Conservancy 2017, DOE 2016b, DOE 2010.

APPENDIX E: Examples of Existing Adaptation Efforts Relevant to SDG&E

Many of the actions noted in Section 3.2 will build on or be facilitated by current adaptation-related activities at SDG&E, 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

There are several existing efforts underway at SDG&E that are, directly or indirectly, addressing climate risk, as described in the following subsections. These efforts are in addition to SDG&E's RAMP filing process.

Climate Vulnerability Assessment

As a part of the U.S. Department of Energy Partnership for Energy Sector Resilience (described within the section below), SDG&E developed a high-level climate vulnerability assessment. The assessment reviews SDG&E's vulnerability to four climate change stressors, including temperature, drought and rainfall patterns, wildfire, and SLR. However, the assessment does not describe adaptation measures to address these vulnerabilities.

South Bay Substation Project

SDG&E recently completed construction of the new South Bay substation in Chula Vista. This 230/69/12 kV substation replaces an older 138/69 kV substation that was undersized for current transmission needs (CPUC 2013a).

The project's Final Environmental Impact Report addressed the potential implications of SLR (CPUC 2013b). During project design, projected changes in sea level were considered. For that location, the research team considered a SLR of up to 1.4 m (4.6 ft.), which was the high end of the range recommended by the California Climate Change Center (California Climate Change Center 2009). In addition, the research team considered a maximum high tide of 2.25 (7.37 ft.), based on data from the National Oceanic and Atmospheric Administration (NOAA) (CPUC 2013b). Combined, the projected maximum SLR and high tide total about 3.7 m (12 ft.).

The final design included an elevated pad with a graded elevation ranging from 5 to 6 m (16 to 21 ft.) above mean sea level, which is several feet above the 4 m (12 ft.) of maximum projected SLR plus high tides (CPUC 2013b).

Wood-to-Steel Pole Replacement Program

Over the past several years, SDG&E has been implementing an initiative to gradually replace wood power poles with steel (SDG&E 2015a). This effort was aimed at reducing their vulnerability to fire, but it will also contribute to enhancing resilience to other climate change hazards, including coastal hazards. Steel tends to be more resilient to climate hazards in general, and steel poles do not require the same supporting equipment (such as guy wires) as wood poles. However, this equipment is susceptible to saltwater corrosion especially in areas of elevated and/or saline water tables.

Importantly, the Wood-to-Steel Pole Replacement Program demonstrates that climate-related hazards can be successfully addressed systematically within the utility. Once a clear risk is articulated, the utility can develop a process whereby new infrastructure is built to be more resilient against that hazard, and, if necessary, existing infrastructure can be gradually hardened. As outlined in Table 3, the lessons learned from the Wood-to-Steel Pole Replacement Program were discussed during the Adaptation Workshop.

Vegetation Management

SDG&E prunes trees surrounding power lines to prevent the trees from coming into contact with wires and sparking fires (SDG&E 2017a). Trees are cut to create a 3 m (10 ft.) clearance area around the distribution lines; in areas prone to wildfires, the clearance threshold is 4.6 m (15 ft.) or greater, depending on tree growth rates (SDG&E 2017a). SDG&E also uses a mobile application to track and manage tree maintenance schedules (SDG&E 2017a).

While this vegetation management is intended to prevent ignition during wildfires, it also reduces the likelihood of tree downings causing transmission and distribution line downings during coastal storm events (DOE 2016b).

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 nearly 200 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.

Santa Ana Wildfire Threat Index

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 2015b). 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 SDG&E 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.

Programmatic Adaptation Efforts at SDG&E

SDG&E has a range of current in-house programmatic adaptation initiatives. The utility's Climate Advisory Group formed in 2015 coordinates these initiatives by regularly bringing together representatives from 13 SDG&E departments (Sempra Energy 2016).

Two SDG&E meteorologists allocate 10% of their time to climate-related activities to better understand regional climate impacts. A portion of this time is allocated to participation in regional, state, and national initiatives and partnerships (Sempra Energy 2016).

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

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 2015)*. 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 SDG&E is able to 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'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 "The 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, SDG&E 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. SDG&E has also expressed willingness to 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 SDG&E 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 SDG&E is not currently a partner, SDG&E 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 the SDG&E 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, SDG&E could potentially collaborate with the Center to further investigate the utility's 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. SDG&E participation could ensure that potential impacts to the electric grid are fully understood, and that priority post-event actions 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.

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