THE ADAPTION BLINDSPOT: TELECONNECTED AND CASCADING IMPACTS OF CLIMATE CHANGE ON THE ELECTRICAL GRID AND LIFELINES IN LOS ANGELES

A Report for:

California's Fourth Climate Change Assessment

Prepared By:
Susanne C. Moser[1], Ph.D.
Juliette Finzi Hart[2], Ph.D.

[1]**Susanne Moser Research & Consulting**
[2]**U.S. Geological Survey**

Edmund G. Brown, Jr., *Governor*

August 2018
CCCA4-CEC-2018-008

ACKNOWLEDGEMENTS

A great number of people contributed to our study in crucial ways and we would like to thank them wholeheartedly for their time and expertise.

First, we would like to thank our Technical Advisory Committee (members listed in Appendix A) who contributed to our understanding of teleconnected and cascading impacts of climate change on L.A.'s lifelines through several group calls, individual interviews, participation in our workshops, in-depth work on our participatory systems model, and through informal conversations and contributions of reports and documents throughout the duration of the project. This project benefited in crucial ways from their deep expertise.

Additional interviewees and workshop participants listed in Appendix A complemented our understanding of the interconnected lifeline system. We greatly appreciate their input.

We would also like to thank Alice Hill, JD (Stanford Hoover Institution) and Marissa Aho (L.A. Chief Resiliency Officer) for their critical contributions at a public event held at the Rand Corporation (Santa Monica, CA) that was held in conjunction with our first workshop in December 2016. Rob Lempert, Ph.D. (RAND) graciously hosted and mc'ed that event. Emiliano Rodriguez Nuesch, Ph.D. (Pacifico) contributed his international expertise. Claudia Tebaldi, Ph.D. (National Center for Atmospheric Research, Boulder, CO) served as a guide to the most recent literature on our changing understanding of current and future climate extremes.

We would never have made as much progress on understanding the complex systems interactions of L.A.'s lifelines without system experts extraordinaire, Elizabeth Sawin, Ph.D. (Climate Interactive), who ably assisted with our first workshop, and Jessica Ruvinsky, Ph.D. (Bellwether Collaboratory), who offered inordinate amounts of patience and time in helping us with the participatory construction of a systems model of interacting L.A. lifelines.

Joey Mitchell, Victoria Govea, Terry Meyer, Jami Brackeen and Catherine Conroy and Sarah Attwood at IntegReview (an Institutional Review Board) provided most proficient support in ensuring that our human-subjects research protocol met appropriate ethical standards.

Logistical support in L.A. was generously provided by staff at Emergency Management and various workshop participants did double duty as note takers. Their help was essential.

Finally, our lead contacts at the California Energy Commission – Sonya Ziaja, Ph.D., JD and Susan Fischer Wilhelm, Ph.D. – offered enthusiastic support to this pilot study from the start and we thank them for their trust and investment in this research.

This research was supported by the California Energy Commission under Agreement Number EPC-15-080.

PREFACE

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

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

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

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

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report contributes to energy sector resilience by working closely with stakeholders to explore how climate-related vulnerability of the electric grid in Southern California can create teleconnected and cascading impacts to important resources and services.

ABSTRACT

Climate change impacts in California are expected to lead to more extreme heat days, shifts in precipitation, extended drought periods and increased wildfire risk, as well as more coastal flooding from storms and sea-level rise. Many communities are now actively preparing for these locally occurring impacts through climate adaptation planning. Yet communities are also vulnerable to impacts that originate from afar and can impact them via so-called "societal teleconnections," for example a sudden disruption in the electric grid in Arizona leading to electricity outages in California. Given that all communities rely on electricity for emergency response, economic activity, and daily life, such outages can then lead to cascading impacts on other sectors. The importance of such teleconnected and cascading impacts is magnified in large urban centers where many people are affected at once. Given electrical grid vulnerabilities to weather extremes and climate change impacts, Publicly Owned Utilities and Investor Owned Utilities are actively studying and addressing grid reliability issues. Yet oftentimes the next step is not taken to connect grid managers with those who must prepare and plan for the impacts on electricity-dependent lifelines such as water, transportation, communication, emergency response and public health. This exploratory study aims to fill this gap using a focused case study of Los Angeles. This study's three goals are to: (1) test the utility of a conceptual framework for assessing societal teleconnections (previously developed by the authors); (2) identify research needs and action barriers around teleconnected and cascading impacts via the electrical grid to inform state priorities; and (3) as these barriers get resolved, help other metropolitan areas and communities in California conduct similar analyses and augment their adaptation planning efforts. To reach these goals, the study employed multiple methods, including two day-long stakeholder workshops, interactive system modeling tools involving sector-specific stakeholders, conducting a literature review of climate change impacts of concern to grid and lifeline managers, and engaging a technical advisory group throughout to define and refine the project as it progressed. Cross-cutting findings include that: (a) energy and telecommunication are critically connected to each other and to other lifelines; (b) emergency management and public health services depend on inputs from all lifelines to be effective; (c) workforce availability is crucial to the ability to respond effectively, but it is already limited and dependent on many different upstream lifelines; and (d) maintaining a state of good repair on all equipment is essential to smooth functioning of all lifelines. Interdisciplinary, as well as applied and transdisciplinary climate science research priorities are proposed to address key knowledge gaps identified by study participants. A large number of action opportunities at the state, local, and utility/agency levels are also presented.

Please use the following citation for this paper:

Moser, Susanne, and Juliette Finzi Hart. 2018. The ***Adaptation Blindspot: Teleconnected and Cascading Impacts of Climate Change in the Electrical Grid and Lifelines of Los Angeles***. California Energy Commission. Publication number: CCCA4-CEC-2018-008.

HIGHLIGHTS

Among the most notable insights gained from this study regarding lifeline system interconnections and cascading impacts are the following:

- Prior to this study, **no unified or integrated map of the interconnected lifeline systems** of the City or metropolitan area of Los Angeles (L.A.) existed, motivating the creation of one through this study.
- There **are many critical mutual interdependencies** among the lifelines, and notable gaps as well. The primacy of electricity (followed closely by telecommunication) on which all other lifelines depend was nearly uncontested. Similarly, telecommunication companies are absolutely essential to proper lifeline functioning and yet they are notoriously difficult to engage, leaving a critical gap in the depth of knowledge about this lifeline system.
- There is an apparent **overconfidence in the controllability of individual (yet interconnected) lifeline systems**. Similarly, there is a lack of concern and lack of active effort to plan for climate change impacts among those who are responsible for the basic functioning, safety, stability, and well-being of communities.
- **Climate science has made significant advances** in understanding extreme events, yet **aspects of greatest interest to lifeline managers are still active research frontiers**.
- **Research needs** span basic, integrated, and applied research areas (e.g., knowledge gaps on singular and compound climate extremes); teleconnections and cascading impacts (e.g., fuller integration of systems models and greater inclusion of the social sciences in scenario development); understanding of legal contexts, liability questions, and standards; and material science needs. In addition, lifeline managers asked for various tools and secure integrated databases, as well as pilot and demonstration projects to explore resilience building in practice.
- **Action opportunities** to advance resilience of interdependent lifeline systems are seen in a variety of arenas: policy changes at the state level (e.g., open data policies for the telecommunication sector, adaptation planning mandates for the electricity sector); removal of institutional barriers wherever they manifest (e.g., internal transcendence of siloed approaches); participation in regional climate extremes scenario exercises; and taking preparedness action at the utility- or agency-level (e.g., improved communication efforts, workforce development).

LIST OF ACRONYMS

100RC	100 Resilient Cities (Rockefeller Foundation Initiative)
AB32	Assembly Bill 32 (Global Warming Solutions Act)
AQMD	Air Quality Management District
AR5	Intergovernmental Panel on Climate Change’s Fifth Assessment Report
ARCCA	Alliance of Regional Collaboratives for Climate Adaptation
ASCE	American Society of Civil Engineers
CA	California
CalOEM	California Office of Emergency Management
Cal-ISO (or CAISO)	California Independent Systems Operator
CDD	Cooling Degree Days
CEC	California Energy Commission
CIFRE	Critical Infrastructure Flood Risk Evaluation (Broward County, Florida)
CMIP5	Coupled Model Intercomparison Project Phase 5
CNG	Compressed Natural Gas
CNRA	California Natural Resources Agency
CNRM-CM5	Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5
CNG	Compressed Natural Gas
CPUC	California Public Utilities Commission
CUEA	California Utility Emergency Association
CWIRS	Countywide Integrated Radio System (L.A.)
DHS	Department of Homeland Security (federal)
DOE	Department of Energy (federal)
DSCA	Defense Support of Civil Authorities
DWP	Department of Water and Power (Los Angeles)
ENLA	Emergency Network Los Angeles
EMD	Emergency Management Department (Los Angeles County)
EPRI	Electric Power Research Institute
EV	Electric Vehicles
FEMA	Federal Emergency Management Agency (federal)
FERC	Federal Energy Regulatory Commission
FHWA	Federal Highway Administration
HadGEM2-ES	Hadley Centre Global Environment Model, version 2, Earth System
ICS	Incident Command System
IOU	Investor-Owned Utility
IPCC	Intergovernmental Panel on Climate Change
L.A.	Los Angeles
LARC	Los Angeles Regional Collaborative
MOU	Memorandum of Understanding
MWD	Metropolitan Water District
NCA3	Third U.S. National Climate Assessment

NERC	North American Electric Reliability Corporation
NIMS	National Incident Management System
OPR	Office of Planning and Research (California, Governor's Office)
PG&E	Pacific Gas and Electric Company
POU	Publicly Owned Utility
RCP	Representative Concentration Pathway
RMS	Risk Management Solutions, Inc.
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SCPPA	Southern California Public Power Authority
SDP&E	San Diego Power & Energy
SEMS	Standardized Emergency Management System
SLR	Sea-level rise
SMEs	Subject-Matter Experts
SWP	State Water Project
TAG	Technical Advisory Group
USGS	United States Geological Survey
VOAD	Voluntary Organizations Active in Disasters (national and local chapters)
VOIP	Voice Over Internet Protocol
WECC	Western Electricity Coordinating Council

TABLE OF CONTENTS

1: Introduction and Motivation

1.1 Rationale and Project Focus

In September 2011, an electricity transmission line in Yuma, Arizona tripped due to operator error and lack of situational awareness among several of the interconnected power utilities (FERC/NERC 2012). This disruption led to a chain of approximately 20 events over an 11-minute period, culminating in the shutdown of the San Onofre nuclear power plant in California. The power loss impacted Arizona, California, and Mexico, and resulted in sewage spills and water distribution disruptions in the City of San Diego, affecting more than 7 million people (Wilbanks et al. 2012a).

This series of events illustrates the challenges that can arise from both teleconnected impacts – i.e. consequences of weather extremes and climate change that originate in one geographic location and then translate their effects into impacts in another location – and cascading impacts – i.e. consequences experienced in one sector that affect one or more downstream sectors, which are dependent on the services of the initially-impacted sector. These consequences of disruptions in the electric grid thus affect critical lifelines and the communities they serve. Publicly Owned Utility Companies (POUs) and Investor-Owned Utilities (IOUs) as well as federal and regional oversight entities (e.g., the North American Electric Reliability Corporation [NERC] and its Western Electricity Coordinating Council [WECC] and the Federal Energy Regulatory Commission [FERC]) are actively studying and addressing grid reliability issues. Yet the next step is not always taken to connect management of these reliability challenges with the impacts downstream – notably, impacts to agencies responsible for ensuring that other critical lifelines are intact during and after extreme events, and remain functional through the more slowly unfolding but lasting impacts of climate change. Moreover, most efforts to date have focused on reliability issues in the face of a variety of natural and human-made threats but have not given adequate focus to the expected increase in climate-related extreme events as climate change continues to accelerate.

At the same time, local governments in California have made important strides in climate change vulnerability assessments and adaptation planning. However, the complex and cascading impacts of climate change on interconnected lifeline systems have been relatively neglected. We are not aware of any local government that has assessed its vulnerability to distant climate change impacts beyond the immediate surrounding area.[1]

[1] A reviewer brought our attention to the fact that the Federal Highway Administration (FHWA) supported a large series of climate change pilot programs (studies for State/County/Local Departments of Transportation to engage in climate change adaptation/resilience planning) in several rounds over a period of years. (No specific references were provided but see: https://www.transportation.gov/sustainability/climate/climate-change-impacts. The website had several non-functional links (e.g. to adaptation planning), so we could not find any reports that showed how long-distance impacts are integrated into local transporation adaptation planning.)

Such blind spots in local impact assessments and adaptation planning can be minimized with concerted effort and better understanding of the ways in which California utilities, economic sectors, and infrastructure are connected. Relevant information and assessment methods, however, have only been emerging over the past several years. Building on the energy sector's grid reliability studies already underway, this study aimed to use an existing systematic framework for assessing the long-distance linkages that can disrupt electricity services and cause ripple or cascading effects on critical infrastructures in the Greater Los Angeles (L.A.) region. Our project serves as a pilot study in how to integrate consideration of teleconnected and cascading phenomena in climate impacts assessment and adaptation planning in the state and its regions (Box 1).

Box 1:Definitions of Key Terms Used in this Study

Teleconnection – A linkage between weather changes occurring in widely separated regions of the globe (American Meteorological Society 2005).

Societal teleconnection – Human-created linkages [via people, structures, institutions and processes] that link activities, trends, and disruptions across large distances, such that locations spatially separated from the locus of an event can experience a variety of impacts from it nevertheless (Moser and Hart 2015).

Cascades – Impacts in one sector that affect one or more downstream sectors, which are dependent on the services of the initially-impacted sector (typically this happens in one region or location, such as a metropolitan area).

Dependencies – One lifeline/system/sector cannot function without critical inputs from another lifeline/system/sector.

Interdependencies – Lifelines/systems/sectors are mutually dependent on each other, whereby systems cannot function without outputs from one or more of the others and the latter cannot function with a service or output from the former.

Interconnection / interaction – A complex interweaving of one system with at least one more. Interconnection is a precondition to dependency and interdependency but does not necessarily have to involve them.

Lifelines (Lifeline Systems) – Systems or networks that provide for the circulation of people, goods, services, and information that are vital for the health, safety, comfort, and economic activity of a community (after Platt 1991). This understanding is echoed in Stevens' and Luke's (2016) more specific definition used in the Southern California Lifelines Working Group, which we adopt for the purposes of this report:

(Box 1 continued):

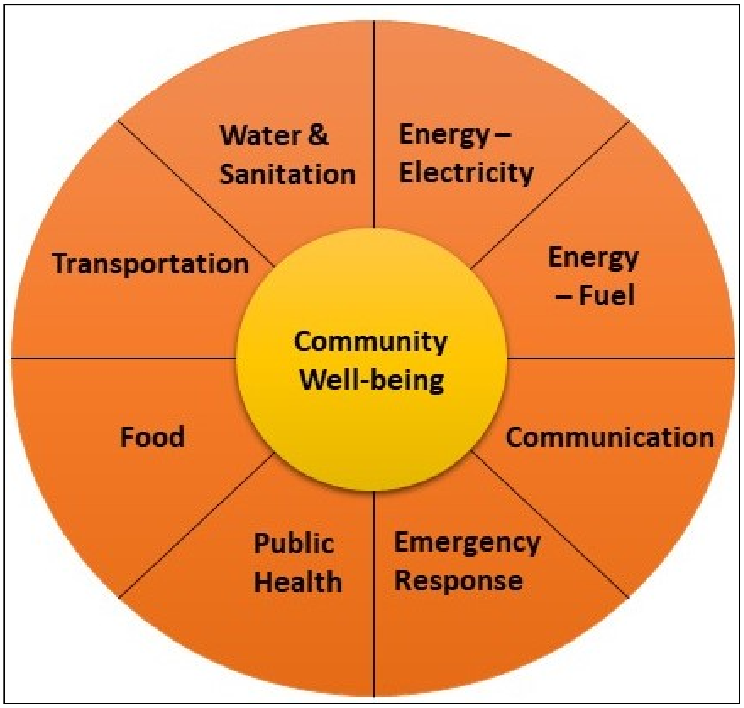
"A critical lifeline is shared infrastructure or interdependent supply chain delivering material or services on which many lives or livelihoods depend. It may include some or all of the following:

- *communications*
- *energy*
- *water and wastewater*
- *transportation*
- *high-volume common nodes of goods or services critical for community and economic recovery*
- *emergency services."*

While these sectors (lifelines) are included in most definitions, some writers are more explicit about *substantive* components of specific lifeline systems, such as detailing power/electricity and fuel for the energy sector or breaking out different components of the transportation sector (ports, airports, roads, rail, etc.). Yet other definitions are more explicit about *structural* components of the lifeline systems, emphasizing that they include distributive system components and key facilities, such as police stations, fire brigades, ambulances, emergency coordination centers and hospitals, and key structures, such as general medical care, food distribution networks, schools, or emergency shelters. Depending on the breadth of interest, some even include computer centers, financial institutions, major industrial/commercial, and other related facilities and services. Finally, most emphasize that lifelines are interdependent, often co-located, and can cross jurisdictional boundaries, pointing to the variable governance aspects associated with lifelines. In this report, we interchangeably use the terms "lifeline," "lifeline system," or "sector" to refer to the types of system under consideration (focusing mainly on the list given by Stevens and Luke; see Source: The Authors

Figure *1*), but to the extent they were mentioned in the course of our study, we also consider the role and functioning of key facilities and structures.

Infrastructure – Here used more narrowly than lifeline/lifeline system as the "hard" components (e.g., pipes, power stations, transmission wires, cell phone towers) of lifeline systems.



Source: The Authors

Figure 1: Dependence of community well-being on interdependent lifelines

1.2 Societal Teleconnections: Adaptation Blindspot and Analytical Lens

This study is motivated by a conceptual framework developed by the authors (Moser and Hart 2015) which aimed to make the consideration of long-distance interconnections and interdependencies accessible to decision-makers as they plan for climate change impacts. While extreme events like hurricanes Sandy (2012), Harvey (2017), and Maria (2017) brought cascading impacts to the fore, societal teleconnections that can transfer the impacts of distal extremes to a local community are not commonly assessed as potential threats in local adaptation planning efforts; hence the notion of an "adaptation blind spot."

In the 2015 framework paper, we defined "societal teleconnections" as "human-created linkages [via people, structures, institutions and processes] that link activities, trends, and disruptions across large distances, such that locations spatially separated from the locus of an event can experience a variety of impacts from it nevertheless" (Moser and Hart 2015, p. 13).

This definition of societal teleconnections is broadly consistent with other frameworks that attempt to assess and understand complex systems, especially their dynamics and interactions across space (Adger et al. 2009). (We discuss this literature in more detail in Section 3.) But our framework attempts to simplify this complexity so as to make it actionable in local adaptation planning. In other words, far from ignoring the great complexity of interactions in an increasingly interconnected, globalized world, our simpler, but still systematic framework aims to bring that complexity – at least in small increments – into the realm of practical application.

When we introduced our framework, we were not aware of a single decision-maker reaching for the burgeoning literature on telecouplings, a situation that is still largely unchanged as far as we know. This is not to say that infrastructure managers do not appreciate their dependence on distant resources or functional conveyance systems (such as L.A. water managers being deeply familiar with the water sourced from Owen's Valley or aware of the precarious situation that would result from a Delta levee breech, or electricity grid operators clearly cognizant of energy production outside of California). Typically, however, lifeline managers do not draw on the scientific literature that relies on complex modeling to help them manage resource flows or to plan for contingencies. This observation suggested to us that there is a need for (and further important work to be done – much like in other science-practice contexts) connecting this research with lifeline managers.

Our societal teleconnections framework consists of three core components and a cross-cutting one, defined as follows and depicted in Source: The Authors, adapted from Moser and Hart (2015)

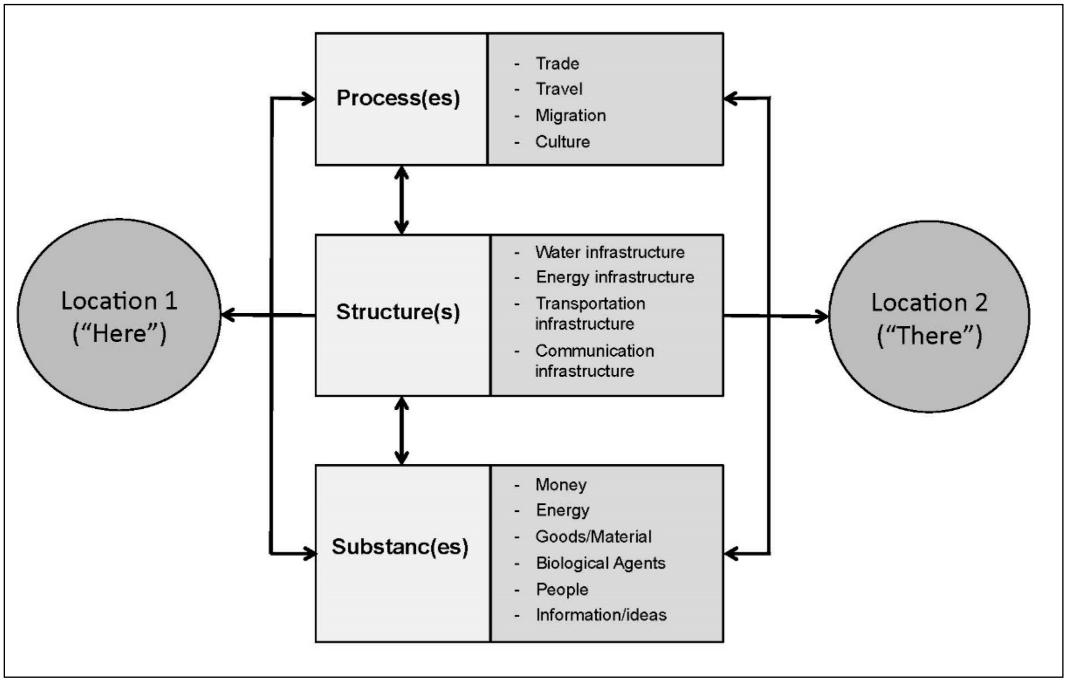
Figure *2*.

- A natural system or human-built construct that forms the conveying or transmitting physical *structure* (metaphorically, one may think of this as the 'hardware'). A finite set of types of physical structures include water, energy, transportation, and communication-related infrastructure such as roads, ports, culverts, pipes, canals/aqueducts, transformers, transmission lines, fiber optic cables, and so on.

- The *process* component details the reason, manner, or cause for the teleconnection (the 'software') and establishes a functional exchange or relationship between distant entities. Examples of a nearly infinitely large set of social processes include the market, travel or migration, human needs, and desires such as communication, learning, discovery, as well as social and cultural ties.

- A material *substance* or immaterial element such as information that is moved from one location to another in the course of a teleconnection. It is the only part in a teleconnection that physically moves (the metaphorical 'data'). There is a finite set of substance types including money/financial flows, energy, goods or materials, water, and other commodities sold by utilities, but also biological agents, people, and information, data, or ideas.

- Actors and governing institutions are involved in planning, designing, building or creating, operating, and maintaining each of the three core components. These actors, in turn, are enabled and constrained in their actions by applicable institutions, i.e., the social norms, cultural customs, laws, rules and regulations, standards, codes, and other relevant guidelines that govern the establishment or movement of structures, processes, and substances (Moser and Hart 2015, pp.15-17).



Source: The Authors, adapted from Moser and Hart (2015)

Figure 2: Basic Components of the Societal Teleconnections Framework. Actors and governing institutions – not highlighted – are embedded across the core components.

Each component of a teleconnection is vulnerable to disruption from climate change and other events (such as terrorist attacks or geohazards). For example, for the lifeline "water", the pipes and aqueducts are the *structures* and climate change impacts such as soil erosion and resulting debris flows or saltwater intrusion in coastal areas and resulting corrosion could undermine their structural integrity. The market (regulating demand and supply) for water is the *process* and increases or decreases in either driven by climate change could affect water pricing, which in turn may affect which users can afford to purchase water. Finally, the water that people ultimately get is the *substance* and climate change impacts such as extended heat, evaporation, drought, saltwater intrusion in coastal areas all affect the quantity and quality available to be delivered.

By disentangling these three components, it becomes possible to distinguish relevant climate change impacts and trace them to their respective geographies. It also becomes possible to locate more clearly where a disruption occurs and what the cascading impacts may be, as downstream sectors are fundamentally dependent on the "structures" connecting them and the "substances" moved or not moved along existing structures.

To what extent our simplified societal teleconnections framework is more accessible to practitioners than the more complex telecoupling approaches discussed above is one of the questions this study tries to answer.

1.3 Lifelines and the Electrical Grid in L.A.: A Pilot Study

We have chosen to bound our primary study area to the City of Los Angeles and its surrounding metropolitan area as our pilot study site. That said, a study on societal teleconnections inevitably implies that we look out from the study site to California, the Western United States, the rest of the country and the world to understand how L.A. is interlinked to other geographies. The L.A. region is the largest metropolitan area in California and the second largest in the U.S., and thus of critical significance. Moreover, as one of the inaugural members of the "One Hundred Resilient Cities" (100RC) (a Rockefeller Foundation initiative) and as a member of the international network of megacities from around the world (C40), progress in L.A. can gain widespread visibility and have significant impacts beyond its regional footprint as cities across the state, country and the world look to learn from others. The L.A. region is already involved in ongoing climate mitigation and adaptation science and policy initiatives. Highlights include:

- Downscaled regional climate modeling from the University of California, Los Angeles.
- The AdaptLA Coastal Impacts Planning Project, which provides cutting-edge science and technical assistance to coastal communities to plan for sea-level rise and coastal storms.
- The L.A. Energy Atlas, which boasts a website[2] with the largest set of publicly available disaggregated energy data in the nation.
- Much of this work is coordinated through the Los Angeles Regional Collaborative on Climate Action and Sustainability (LARC), which has developed a county-wide Framework for Regional Climate Action and Sustainability.
- LARC is also a pioneering member of California's Alliance of Regional Climate Collaboratives on Adaptation (ARCCA) and is thus linked to a broader group of adaptation professionals throughout the state.

The resilience and preparedness section of Los Angeles' *Sustainability pLAn* (City of Los Angeles 2015) describes the need to "increase electricity-based preparedness (e.g., electrical grid and grid updates, micro-grids, grid-tied to backup solar and streetlight solar-to-grid)." It also calls out the need to retrofit pre-1980 soft story and concrete buildings (in response to the threat of earthquakes) and addresses the need to reduce the heat island effect through cool roofs and pavement. Yet these targets are all discussed independently and there is no discussion of their interconnection and the need to address this in planning. Thus, while there is a considerable amount of work on the reliability of the electrical grid in L.A. and concurrently considerable work on the

[2] See: http://www.energyatlas.ucla.edu/.

climate science and preparedness, these efforts remain essentially disconnected vis-à-vis the upstream teleconnected and downstream cascading impacts to critical lifelines within the City (**Error! Reference source not found.**, above).[3] A first effort in linking across sectors in L.A. was made in the context of the AdaptLA Coastal Impacts Planning Project.[4] Participants were particularly interested in including social vulnerability considerations into their emergency response and adaptation plans. Such social vulnerabilities are typically superimposed (and often causally linked) to underlying structural inequities. For example, delayed maintenance and historic underinvestment in critical infrastructure, particularly in socio-economically disadvantaged neighborhoods and communities, is a significant problem undermining resilience (e.g., McNichol 2017), thus making it more likely that teleconnected and cascading events affect the poorest.

1.4 Goals of this Study

Societal teleconnections add a layer of risk that is currently not fully appreciated in most vulnerability assessments or in on-the-ground adaptation planning. Most communities that have begun adaptation planning are only assessing their climate vulnerabilities within their jurisdictional boundaries and are not yet assessing or addressing the interdependence and cross-sectoral nature of adaptation planning for *locally*-originating climate impacts.

In this study, we worked primarily with the City and County of L.A. to explore current and projected vulnerabilities to the electrical grid and the ensuing teleconnected and interdependent impacts to critical lifelines in the face of weather extremes and climate change impacts. The inclusive multi-jurisdictional, multi-sectoral design of the study aimed to address and bank on the interconnectivity of lifelines across metropolitan regions. It is practically insufficient for any one jurisdiction or sector to address teleconnections and sector interdependencies; it is also too expensive – and often prohibitive – for any one jurisdiction to think through the complexity of teleconnections by itself (a benefit of regional collaboration long discovered by California's Alliance of Regional Collaboratives for Climate Adaptation (ARCCA)). Thus, the metropolitan scale is a reasonable and sensible compromise to assess these interconnections that lead to teleconnected and cascading impacts. To account for the interjurisdictional upstream and downstream interconnections, we also included representatives from the City of Santa Monica in our workshops. This allowed us to explore how impacts within the City of L.A. would impact neighboring jurisdictions.

Moreover, L.A. is trying to institutionalize resilience at all levels and in every department. The emphasis is on changing thinking, not merely ensuring compliance.

---

[3] While we rely here explicitly on the definition and framework of the Southern California lifelines Working Group, readers may be aware of or interested in a guiding national framework for critical infrastructure (DHS 2013). See: https://www.dhs.gov/sites/default/files/publications/national-infrastructure-protection-plan-2013-508.pdf.

[4] See: http://dornsife.usc.edu/uscseagrant/adaptla/. One of us (Moser) led stakeholders from L.A. County through the basics of vulnerability assessments, with an emphasis on differential social impacts.

Disaster preparedness and infrastructure investment are already focus areas for the City. Thus, L.A. proved to be a willing and interested research partner.

The overarching goals of this project were as follows:

1) to test the utility of our conceptual teleconnections framework as a tool to assess vulnerabilities to remote climatic events and to assist lifeline managers in preparing for climate change;

2) to identify research needs and action barriers; and

3) if resolved, help other metropolitan areas and communities in California conduct similar analyses and extend their adaptation planning efforts.

Using a multi-methods approach, the study explored critical nodes of interconnection among critical lifelines as well as upstream dependencies and downstream cascading impacts that lifeline disruptions can cause for other sectors. Aided by a conceptual map of teleconnections and a participatory systems-modelling tool, the study examined the current and future climate vulnerabilities of lifelines in the L.A. basin. This project report presents our findings along with a list of research needs and recommendations for near-term actions that would help address the critical blind spot of societal teleconnections in local adaptation planning.

1.5 Overview of the Report

The report is organized as follows. Chapter 2 provides an overview and details on the key research tasks and the research methodology employed to complete them. As part of the study, we undertook an extensive desktop literature review, not only to contextualize the study, but to inform the empirical parts of our work with the latest scientific insights on climate science and extreme events. This literature review is presented in Chapter 3. Chapter 4 then synthesizes a large amount of empirical insights gained through interviews, workshops, and the participatory modeling approach. While significantly more information was collected, our goal in this chapter is to stay focused on higher-level insights. Chapter 5 summarizes the findings, assesses the utility of the teleconnections framework, and then offers a clearly organized list of research needs and action opportunities to advance resilience building and preparedness for future climate changes and extremes. We believe that the insights gained and the action opportunities will be of use to other regions and metropolitan areas beyond L.A.

2: Methodology

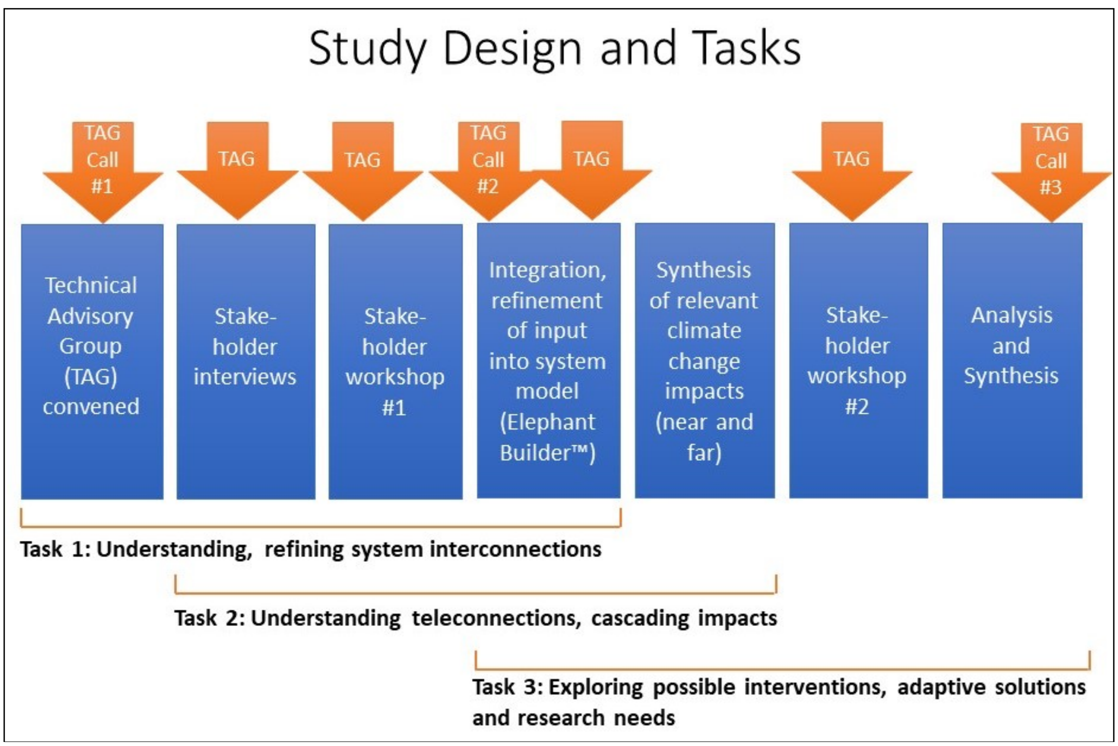
2.1 Overview

This project used an iterative, heavily stakeholder-driven and -involved approach, which employed several different methods to gather and integrate input and information before subject-matter experts were involved again to build on insights gained and take on subsequent tasks of the project. This transdisciplinary methodology was deliberately chosen for a number of reasons:

- By definition, different types of lifelines rely on different types of expertise – including technical, institutional, organizational, and geographical; our project aimed to bring these different perspectives and types of expertise together to create synergistic, higher-order insights about the interconnected lifeline system in the L.A. region.
- Given the ultimate project goal of identifying a user-relevant research agenda, we sought ways to tap the expertise and insights, as well as the knowledge gaps, of practitioners working on energy and other lifelines in real-life settings.
- Given the limited work in California's climate change assessments to date on cross-sectoral interdependencies and cascading (indirect) climate change impacts, we needed a study design that was open to discovery and adjustment over time.

Source: The Authors

Figure 3 illustrates our iterative approach. Including the multiple opportunities for stakeholder engagement, including through a Technical Advisory Group (TAG).



Source: The Authors

Figure 3: Overview of Project Tasks and Stakeholder Engagement in the Project

As Source: The Authors

Figure 3 illustrates, the project was designed around three interlinked and overlapping tasks:

- Task 1: Understanding and refining system interconnections;
- Task 2: Understanding teleconnections and cascading impacts; and,
- Task 3: Exploring possible interventions, adaptive solutions and research needs.

Below we address the methods used to complete each.

2.2 Research Tasks and Approaches

2.2.1 Identification and Mapping of the Interdependencies of L.A. (Task 1)

2.2.1.1 Study Co-Design with a Technical Advisory Group (TAG)

We built on existing relationships developed through the AdaptLA Coastal Impacts Planning project[5] and other L.A. region-based research and adaptation planning efforts to convene a team of expert stakeholders to serve as the project's immediate "customers" and as advisors and guides to the project's activities. This Technical Advisory Group (TAG) was comprised of a dozen individuals mostly from within the City and County of L.A. who are responsible for managing various lifelines that are critical to maintaining local functioning during acute weather events (e.g., extreme heat waves, wildfires, and storms) and chronic impacts from climate change (e.g., long-term droughts, sea-level rise, increased air temperatures, shifts in precipitation). The TAG also included representatives from the L.A. City Department of Water and Power (a public utility serving the City), Southern California Edison (a private utility covering much of Southern California), Cal-ISO, the City of L.A.'s Emergency Management Department, the Metropolitan Transit Authority, L.A. County Department of Public Health, and others (a full list of members is provided in Appendix A). In short, the study included individuals bringing both a sector-specific and cross-sector perspective, including from electric, gas, and water utilities, as well as telecommunication companies, transportation agencies, public health agency representatives, emergency managers, local government representatives responsible for adaptation and sustainability, universities, federal agencies, and entities involved in food provision.

The TAG was convened in person three times over the course of the project and was involved in all stages of the project (see Figure 2). Members helped refine the initial project design and focus (used in the project funding proposal), provided substantive insights into lifeline management and interconnectivity, participated in workshops (see below), and provided feedback on the draft final project report in parallel to it going through peer review.

The primary study area was defined as the City and County of L.A. However, the very nature of this study demands that other geographies be considered. These varied by lifeline sector, as we will discuss. We considered material flows across distance as well

[5] For more information, see: https://dornsife.usc.edu/uscseagrant/adaptla/.

governance systems associated with managing lifelines, thus, sometimes these extended geographies reached other parts of the state, other parts of the western U.S., other parts of the U.S. and – via supply chains – even other countries.

2.2.1.2 Expert Stakeholder Interviews

After the study protocol involving human subjects was approved by an Institutional Review Board[6], TAG members were interviewed individually – along with several additional experts they identified during the project launch – to build a first-order understanding of the lifeline system interconnectivity, system operations, climate change risks, preparedness, and adaptation efforts to date.

Nineteen full-length interviews were conducted by phone, with both authors present and asking questions (several other informants provided only limited information). Interviews were recorded with interviewees' consent and lasted between 45 minutes and 1.5 hours. Despite the strong focus of this project on the electricity system, the purpose of the interviews was to understand more fully how lifeline management is interconnected and vulnerable to electricity service disruptions. Specifically, interviews aimed to: 1) identify critical lifelines within the City and County of L.A.; 2) explore teleconnections and related climate vulnerabilities; 3) understand lifeline interconnectivities throughout the L.A. basin and what protections and redundancies are currently built into lifeline management; and 4) elicit recommendations on other important stakeholders to engage in future study activities.

The interview protocol was based on the Moser and Hart (2015) societal teleconnections framework underlying this study and sought to identify teleconnected and cascading impacts propagating through existing lifeline pathways under interviewees' control, identifying the structures, processes, and substances that combine to form the connection. The full interview protocols – for both electricity and other lifeline systems – are included in Appendix B.1 and B.2.

Utilizing interview-derived insights of the lifeline system and its management, we "mapped" teleconnections, cascading impacts within and across sectors.[7] The interviews revealed ample procedures in place to manage within-system and within-sector disruptions, caused by natural and human-made events, but also a general *lack* of thinking to date about adaptation to climate change impacts. Recognition of teleconnected/upstream dependencies was variable, as were established interactions across lifeline sectors.

---

[6] IRB review was provided by IntegReview. Protocol #EPC-15-080.

[7] We recognize that there are national security and privacy issues involved in geographically "mapping" teleconnections. Thus, the term "mapping" is used here not in the sense of creating catographic maps of critical infrastructure, but metaphorically to identify types of teleconnections and cascades of interconnections that should be carefully assessed and whose climate vulnerabilities managers can plan and prepare for while generating public co-benefits.

2.2.1.3 First Teleconnections Stakeholder Workshop

Insights gained from the interviews informed the design of Workshop 1, which involved 23 individuals, including TAG members and a range of additional experts (see Appendix A for the full list of project stakeholders involved).

The first workshop focused on identifying upstream (teleconnected) and downstream (cascading) system dependencies, using

- an extended scenario exercise of a progressively longer electricity outage (1 day, 3 days, 8 days) to explore impacts on all lifelines in the greater L.A. region (Box 2);
- an introduction to and exercise involving basic stock-and-flow system models; and,
- small-group and whole-group discussions to study within- and cross-sector dependencies.

The scenario exercise was received with skepticism among some about the realism of the scenarios but was nevertheless appreciated by all as a heuristic (i.e., as an approach or aid to learning, discovery, or problem-solving) to think through complex system interactions and dependencies. It revealed the importance of the human factor as well as of institutional arrangements above and beyond the interconnectivity of hard infrastructure. While insights were still mostly sector-specific, the workshop initiated thinking about interconnectivities and about potential solutions.

For the systems modeling exercise, the workshop engaged Dr. Elizabeth Sawin (Climate Interactive)[8], an expert in interactive systems modeling, to provide a brief introduction to systems modeling in general and stock-and-flow diagrams in particular (see, e.g., Aronson and Angelakis, no date), and then to help guide participants through a set of participatory mapping exercises (e.g., NCCPE, no date; IFAD 2009) to capture cross-sectoral interdependencies and teleconnections.

The focus on stock-and-flow diagrams was chosen for this first workshop to help participants sharpen awareness of and better understand their system dependencies (e.g., upstream inflows of resources such as electricity, water, food, emergency response supplies, or fuel as well as downstream outflows of resources that are crucial to others, such as workers able to come to work) and available stocks of resources and back-up supplies that buffer against loss of inflows. Discussions began to reveal system dynamics and potential interventions to maintain system functionality and greater resilience in case of a major disruption. Workshop participants realized that what makes a stock vulnerable to disruption lies in the whole chain of interconnections, not just in the stock itself. Discussions of potential interventions also revealed that the best way to increase resilience of an entire interconnected system lies in improving the stocks (i.e., the reserves or buffering capacity), and the next best intervention is in working with

[8] See: https://www.climateinteractive.org/about/staff/#Beth.

upstream and downstream partners to improve the ability to affect inflows and outflows when the need arises.

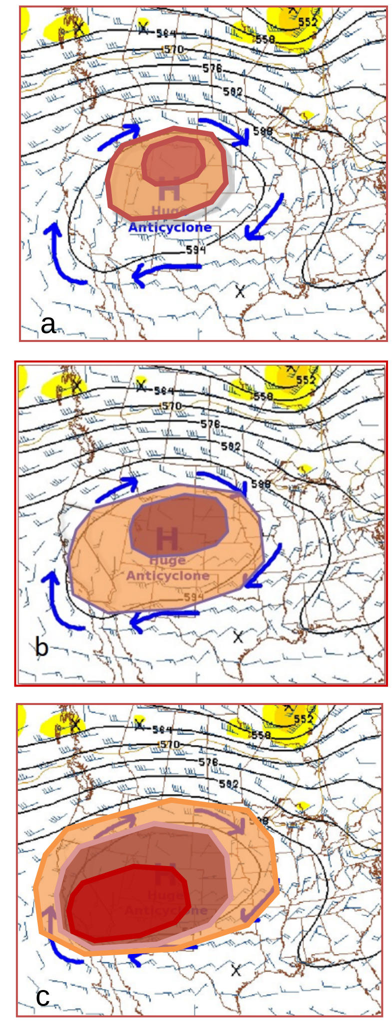
2.2.1.4 Participatory Systems Modelling: The Elephant Builder™

The final method employed to complete the first task was not planned but arose serendipitously as a tool to deepen our own and study participants' understanding and ability to visualize the interconnected lifeline system that underlies the proper functioning of the larger L.A. region.

Through Dr. Jessica Ruvinsky of Bellwether Collaboratory, LLC[9], we were introduced to The Elephant Builder™, a collaborative systems-modelling tool. We used it after the first workshop to capture the work done by sector/lifeline break-out groups and link their functioning to the upstream and downstream connections identified (Source: Jessica Ruvinsky **Figure *3***).

[9] See: http://www.bwclimate.com/#what.

Box 2: Exploration of Cross-Sector System Disruptions due to Power Disruption in L.A. Metropolitan Region



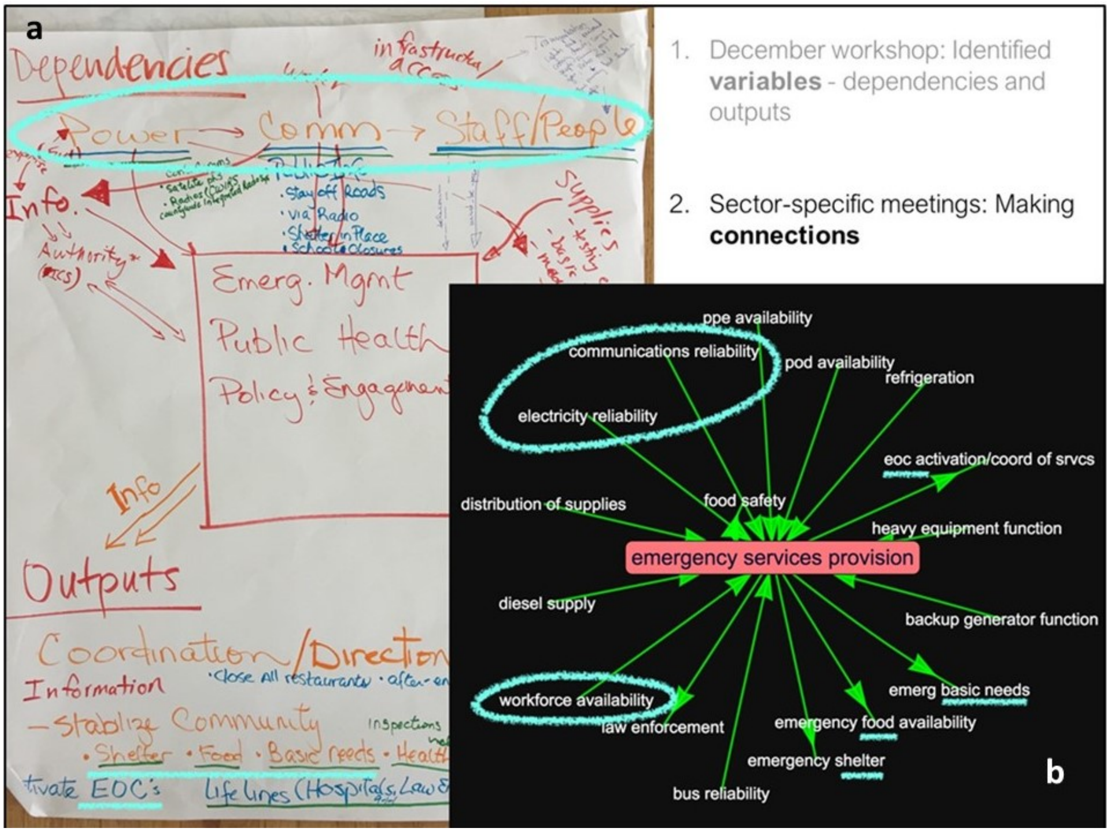
During the 1st workshop, participants participated in a scenario exercise in order to help identify the upstream dependencies and the downstream outputs and services of their respective agencies. Participants first identified these upstream and downstream components under normal circumstances with electricity provision operating at full capacity. This helped provide a baseline for what each agency needs from and provides to others.

They then stress-tested these dependences under increasing challenges from distal and then local origins. In the first disruption, participants imagined that a heatwave over Colorado led to a transformer being blown out. This lead to a 1-day power outage in the L.A. metropolitan region (Box Figure a).

In the second phase of the scenario exercise, workshop participants had to imagine that the outage persisted for 3 days. The heat wave spread over a larger area, sparking wildfires in multiple locations throughout the Southwest, which led to three key transmission lines being destroyed. Power thus could not be restored in the L.A. region for 3 days (Box Figure b).

In the final phase, participants envisioned that the heat wave had spread to LA. so that there was now an extreme heat crisis right over the L.A. metropolitan region. Transformers, transmission lines and other key infrastructure were damaged and thus power outages persisted for a total of 8 days (Box Figure c).

We asked participants to suspend disbelief and not focus on the validity of this particular scenario. The goal was to push the discussion so as to extract as much information as possible about the level of agencies' preparedness, their back-up capacities, their perceptions of the capabilities of other agencies to manage the crisis and recover full functioning, and thus to uncover break points in the interdependent lifeline system of L.A.



Source: Jessica Ruvinsky

Figure 3: (a) Information about lifeline interconnections from the scenario exercise collected on flipcharts in Workshop 1 was (b) entered into the Elephant Builder systems modelling tool and refined during in-depth meetings with sector experts.

Complementary to the stock-and-flow diagrams used in Workshop #1, the Elephant Builder draws causal loop diagrams (Lannon, no date; Kim 2016). Causal loop diagrams – as the name suggests – depict what affects a variable, and what this variable affects in turn. They also show the direction (increase or decrease) of that causal influence and whether or not there are any delays in the interaction between the two variables of interest. The depiction of causal loop diagrams and associated directions of that causal influence allows for the identification of "system archetypes," i.e., the underlying structure of systems that explains observable dynamics or repetitive patterns of behaviors (Kim 1992).

At the heart of system archetypes are "reinforcing" (positive feedback) and "balancing" (negative feedback) loops. The former involves dynamics in which an initial change in one variable feeds back through the system to amplify itself, driving further change in the same direction. Reinforcing feedbacks can lead to systems moving out of control and ultimately to system collapse. By contrast, balancing loops involve negative (limiting) feedbacks whereby a change in one variable causes a counteracting change in another variable. Balancing loops ultimately help systems to vary only within a limited range and ultimately to retain system stability. In essence, the Elephant Builder builds a causal loop diagram of a complex system (made up of many subsystems, in this case lifelines) and searches it for causal feedback loops (reinforcing and balancing), which drive the behavior of the system.

The learning curve involved in becoming familiar with and being able to expertly operate the Elephant Builder software is not insignificant. We thus opted to work with Dr. Ruvinsky to enter information into the tool as we explained the visualized system interconnections already identified and elicited additional insights from our expert project participants (TAG members, interviewees, and workshop participants) to correct or refine the causal connections within and across lifelines already depicted. In numerous post-workshop meetings (sometimes more than 2 hours in length), we were able to capture digitally the interconnected lifeline system of L.A. County to a geographic map that would show the physical structures located on the L.A. landscape. The result of this exercise is a mental model of how experts view the functional relationships between the systems they manage. It synthesizes a single causal network model – something, we learned, does not exist at this time for the L.A. region.

This mental model of critical lifeline interdependencies brings attention to systemic behaviors, i.e., the instability in the system as a whole caused by reinforcing feedback loops in any one subsystem (e.g., one particular lifeline or critical interconnection between two lifelines). These are the parts of the system which, when they go wrong, result in things getting worse (usually through interactions of more than one sector). For example, power failures can disrupt the proper functioning of telecommunication wires, which may disrupt the Supervisory Control and Data Acquisition (SCADA) functions[10] that regulate electricity provision, thus worsening the power failure.

Using this participatory system model as a dialog tool with our expert stakeholders helped generate important insights, including the:

- identification of critical system interactions ("nodes");
- observation of common patterns of system dynamics, particularly those that make the system as a whole vulnerable (i.e., vulnerabilities that would not be visible from looking at a subsystem alone);
- identification of "actionable" system interactions, i.e., nodes where one sector can affect the direction of the interaction of two intersecting lifelines and thereby control its condition; and
- recognition of the importance of and opportunities for lifeline sectors collaborating to maintain not just their own reliable service, but overall system functioning.

These conversations also revealed what is commonly or insufficiently thought about in terms of cross-sector connections. For example, while public health officials think about the need for food, water, and shelter and the related electricity needs, we learned that the electricity needs of morgues had not been thought about. Moreover, they revealed

---

[10] SCADA is the control system architecture underlying remote supervisory control of multiple devices. They involve computers, sensors, networked data, and graphical data interfaces (Berry 2011).

that individual lifeline sectors essentially were established, grew, and changed over time relatively independently, in a bottom-up fashion. No single overarching entity has designed, guides, or provides regulatory oversight of the multiple interconnected systems evolving simultaneously. The resulting functioning of the larger interconnected system of lifelines surfaced as an emergent property which works – at least based on outside observation and normal day-to-day experience – remarkably smoothly. Yet the gaps revealed through these conversations also suggested that the system contains precarious elements and has not been tested in a profound and/or extended real-life emergency (like the ones explored in the Workshop 1 scenario exercises or by disruptive climatic events recently experienced elsewhere in the US, such as hurricanes Harvey or Maria).

2.2.2 Assessment of Climate Exposure of Prioritized Lifelines and Identification of Preliminary Adaptation Strategies (Task 2)

The second main task of the project directed our attention from the systems at risk to the climatic hazards posing threats to them. It involved a literature search (Section 2.2.2.1) and the second stakeholder workshop (Section 2.2.2.2) to link these climatic threats to the exposed systems and collectively prioritize system vulnerabilities, brainstorm adaptive responses and what may prevent implementing them, and identifying research needs.

2.2.2.1 Assess Teleconnected Climate Exposure of Prioritized Lifelines

Utilizing publicly-available scientific information, we developed a high-level teleconnections exposure assessment of the prioritized lifelines. This entailed a literature review for climate hazards that the TAG had prioritized as the most useful foci for this pilot study, namely heat, drought, and wildfire. Other hazards, however, emerged over the course of the second workshop, so we extended the literature review. We also consulted with Dr. Claudia Tebaldi at the National Center for Atmospheric Research[11], an expert in climate change modeling of extreme events, for additional guidance.

The resulting literature review did not aim to be comprehensive but focused on selected climatic hazards that emerged as particularly relevant for the lifelines considered in this study. For electricity, our review extended to the entire Western United States, given electricity sources and markets and related infrastructure, while threats to other sectors were mostly contained geographically to California.[12]

Over the course of our study, a number of devastating weather events occurred across the US, including Hurricanes Harvey in Houston and Maria in Puerto Rico and the Thomas Fire in Southern California. These events provided graphic evidence of teleconnected and cascading impacts of climate-related disruptions. In addition, the

---

[11] See: https://staff.ucar.edu/users/tebaldi.

[12] A comprehensive literature review that would account for all societal teleconnections – given globalized interconnections of many sectors – was considered impractical and beyond the scope of this pilot project. One example is transformers. Several interviewees mentioned that they are imported from South America. An exposure assessment of the entire supply chain was not conducted as part of this study.

Trump Administration made several moves to deliver on its promised infrastructure policy proposals, such as streamlined and shortened permitting procedures and the promotion of public-private partnerships to fund infrastructure (Gallston 2018; Office of the President 2018). These announcements generated growing attention in the press, among NGOs, think tanks and professional societies, and in the academic literature on infrastructure-related topics (e.g., financing, equity, standards, priorities). Our literature review includes relevant observations from these concurrent events.

2.2.2.2 Second Teleconnections Stakeholder Workshop

The results of the literature review and the in-depth sector meetings to build the participatory systems model informed the design of the second stakeholder workshop. The same individuals invited to Workshop 1 were again invited, but schedules did not permit the same set of individuals to attend. Over the course of the project, additional experts had been identified and they were also invited to the second workshop. In the end, 22 individuals attended (Appendix A).

The second workshop focused on climate change vulnerabilities, adaptation options, action barriers, and research needs. It also was used to share preliminary insights gained through the work to date. Workshop participants used this information in a suite of interactive exercises to:

- deepen the exploration of lifeline exposure and assess potential impacts along the teleconnection pathways;
- assess lifeline system sensitivities and adaptive capacity along the pathway to get a fuller understanding of their vulnerabilities;
- name existing and brainstorm possible additional adaptation strategies that are capable of addressing additional projected vulnerabilities due to teleconnections and expected climate change;
- pinpoint critical action barriers; and
- identify research needs to assist and inform future lifeline management with improved understanding of both system vulnerabilities and climate hazards.

The discussions deepened the understanding of lifeline inter- and teleconnections, but also generated input into the third major task of the project.

2.2.3 Development of Research and Action Recommendations for Addressing Societal Teleconnections and Climate Impacts Interdependence (Task 3)

The final task was to synthesize the collected information to answer the ultimate goals of the project, i.e. to define action barriers and research needs (Section 2.2.3.1) and to present our synthesis to our TAG for review and comment (Section 2.2.3.2).

2.2.3.1 Define List of Barriers and Research Needs for Teleconnections

We distilled and synthesized action barriers and research needs faced by our study participants to assess and reduce their teleconnected and cascading vulnerabilities through adaptation planning. To organize and categorize the action barriers, we used an existing framework to categorize adaptation barriers (Moser and Ekstrom 2010) used in other California Climate Change Assessment studies.

2.2.3.2 Review and Revision with Stakeholder Expert Team

We reconvened the expert stakeholder team by teleconference during the peer review period to present study findings, including the list of action barriers, research needs, and recommendations. Their critical feedback is integrated into the final project report to help the State better understand cross-sectoral, teleconnected climate vulnerabilities and how to support local communities in preparing for them.

In the following chapter, we discuss the literature to provide the relevant context for discussing projection findings in Chapter 4.

3: Climate Change Risks to Interdependent Infrastructure Systems: A Literature Review

As explained in the previous chapter, this literature review does not aim to be comprehensive, either topically or geographically, but instead provides focused context and background to the topics addressed in this pilot project, namely:

- climate change threats to lifelines in the L.A. region, with recognition of the teleconnected risks that the region faces (Section 3.1);
- teleconnected and cascading impacts of climate change on complex, interconnected systems (Section 3.2); and
- existing approaches to assessment and modeling of complex, interconnected risks (Section 3.3).

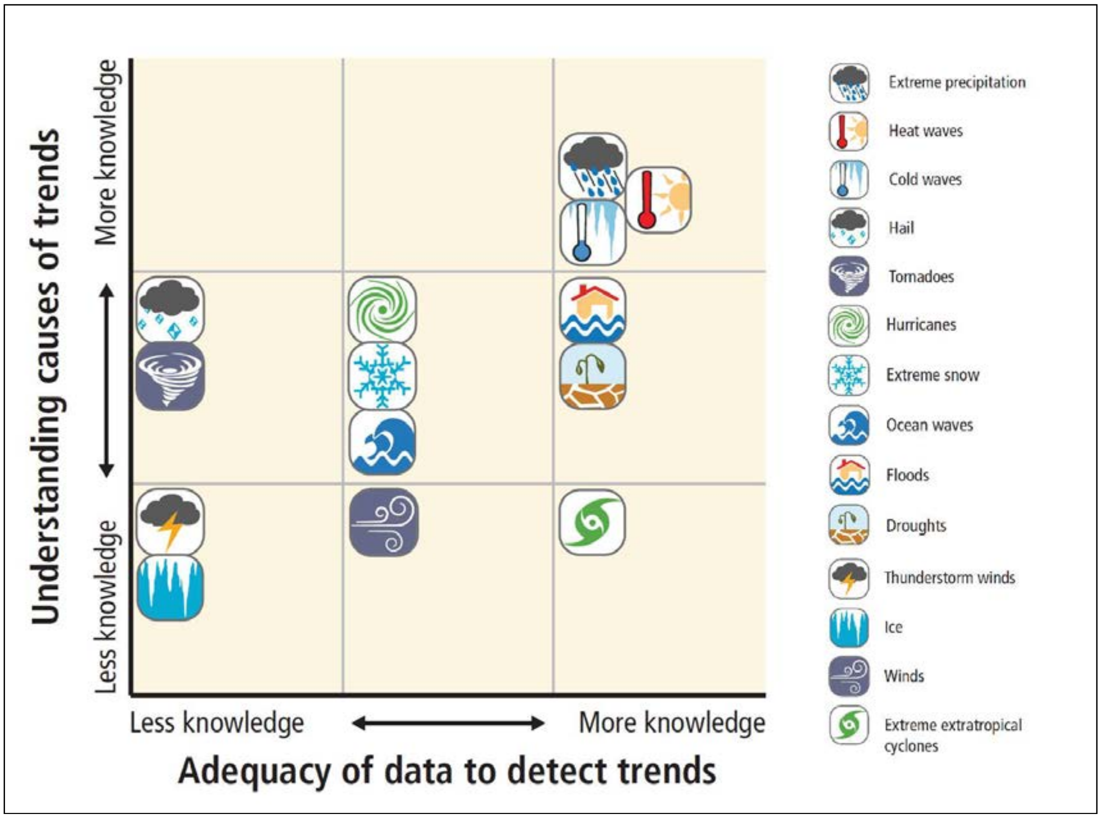
3.1 Climate Science and the Risks of Lifeline System Disruptions

3.1.1 Overview

Compilations of available assessments of the impacts of climate variability and change on existing infrastructure provide consistent messages as to the type of climatic hazards that matter to infrastructure systems but give divergent views as to how serious these consequences might be. Our reading of the literature suggests that the closer the assessment is to the on-the-ground, geographically specific situation in which impacts could unfold, the graver is the anticipated impact (even as climatic uncertainties grow) – in economic terms as well as in terms of day-to-day disruptions and human impacts. This will be illustrated with examples below.

This is not an unexpected observation, as location-specific impacts are lost in nationally, continentally, or globally synthesized assessments, given differences in expected climate change impacts and different infrastructure systems at risk. Moreover, there are regional differences in the amount of available information, the ability to clearly detect, explain and attribute observed events to climate change, and – thus – the level of scientific confidence in impact assessments. Source: Romero-Lankao et al. (2014), p.1447

Figure 5 illustrates these differences in scientific understanding for a variety of climatic events that could be highly relevant to initiating events impacting infrastructure.



Source: Romero-Lankao et al. (2014), p.1447

Figure 5: Scientific knowledge of trends in hydroclimatic extreme events observed over North America (ability to detect and explain trends)

3.1.2 The Global Picture of Infrastructure-Relevant Climate Change Impacts

In Table 1, we present relevant key findings from the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), which are quite vague for the energy, water and transportation sectors, but clearer for urban infrastructure where all these lifelines intersect (Arent et al. 2014; Revi et al. 2014; Dasgupta et al. 2014; Romero-Lankao et al. 2014). The urban chapter in particular includes some findings that recognize the interconnectivity of infrastructure impacts not typically reflected in assessments of singular sectors. This interface of infrastructure across multiple sectors is of growing concern in research over the past decade (Ayyub 2015).

Our study clearly emphasizes the urban context – the L.A. region – but our interest in teleconnections makes clear that impacts on rural areas far from Los Angeles from which the metropolitan area sources its water, energy, and food cannot be neglected (Güneralp et al. 2013). Moreover, critical infrastructure (such as electricity transmission lines, fuel pipes, roads, and fiber optic cables for telecommunication) traverses rural areas. The Fifth Assessment Report recognizes this growing spatial and functional interrelatedness of rural and urban areas through human migration (permanent and cyclical), commuting, transfer of public and private remittances, regional and international trade, inflow of investment, diffusion of knowledge through new information and communication technologies, and spatial intermingling of rural and urban economic activities. It is less clear on the exposure of infrastructure in rural areas that convey critical services to urban areas.

Table 1: Key Findings from IPCC AR5 Regarding Infrastructure

Climate Stressors and shocks	Many climate stresses that carry risk—particularly related to severe heat, heavy precipitation, and declining snowpack—will increase in frequency and/or severity in North America in the next decades (very high confidence). Water resources are already stressed in many parts of North America due to non-climate change anthropogenic forces and are expected to become further stressed due to climate change (high confidence). Observed impacts of these stresses on […] infrastructure, and access to services in North American urban and rural settlements have been attributed to sea-level rise, changes in temperature and precipitation, and occurrences of such extreme events as heat waves, droughts, and storms (high confidence).
Infrastructure (general)	Much of North American infrastructure is currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (medium confidence). The impacts of climate change on the critical infrastructure and territorial integrity of many [countries] are expected to influence national security policies (medium evidence, medium agreement). “Assessments of the impacts of climate change on infrastructure take a general or urban perspective and do not focus on rural areas, though rural impacts can be inferred” (Dasgupta et al. 2014, p. 628). Specifically mentioned for rural areas are damages to roads and bridges; reduction of reservoir storage capacity due to increased sedimentation; changes in the operation of existing water infrastructure; impacts on dams, reservoirs, and irrigation infrastructure; and failures in the reliability of water allocation systems (based on water use rights) due to reductions of streamflows.
Energy sector	Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (robust evidence, high agreement). Climate change will affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling), or the locations (coastal regions, floodplains) involved (robust evidence, high agreement). Climate change may influence the integrity and reliability of pipelines and electricity grids (medium evidence, medium agreement).
Water sector	Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (robust evidence, high agreement), but the economic implications are not well understood.
Transportation sector	Climate change may negatively affect transport infrastructure (limited evidence, high agreement)

Urban areas	Many global risks of climate change are concentrated in urban areas (medium confidence). Climate change will have profound impacts on a broad spectrum of infrastructure systems (water and energy supply, sanitation and drainage, transport and telecommunication), services (including health care and emergency services), the built environment, and ecosystem services (medium confidence, based on medium evidence, high agreement). City-based disaster risk management with a central focus on risk reduction is a strong foundation on which to address increasing exposure and vulnerability and thus to build adaptation (high confidence, based on medium evidence, high agreement). Reducing basic service deficits and building resilient infrastructure systems (*water supply*, *sanitation*, *storm and waste water drains*, *electricity*, *transport and telecommunications*, *health care*, education, and *emergency response*)* can significantly reduce hazard exposure and vulnerability to climate change, especially for those who are most at risk or vulnerable (very high confidence, based on robust evidence, high agreement). Well governed cities with universal provision of infrastructure and services have a strong base for building climate resilience if processes of planning, design, and allocation of human capital and material resources are responsive to emerging climate risks (medium confidence, based on medium evidence, high agreement).

Source: Findings are quoted verbatim and compiled by topic from Arent et al. (2014, pp.662-663), Revi et al. (2014, pp.538-540), Dasgupta et al. (2014, pp.616-617), and Romero-Lankao et al. (2014, pp.1443-1445). * Sectors italicized in this IPCC finding are those also included in this study.

Since the Fifth Assessment report, studies in climate extremes have rapidly advanced (Hay et al. 2016). They suggest that both extreme heat and heavy precipitation events will continue to increase, thus increasing many of the risks to infrastructure listed above. Confidence is highest for more intense, earlier, and extended heat extremes (e.g., Camargo and Anji 2016; Schoof and Robeson 2016).

These general findings provide useful context and serve awareness-raising functions but are insufficient for planning purposes. The conditional statement of the last key finding of the IPCC on urban areas is particularly noteworthy, however: "Well governed cities… have a strong base for building climate resilience if processes of planning, design, and allocation of human capital and material resources are responsive to emerging climate risks." As a conditional statement, it is easy to agree, but the IPCC assessment remains silent on what exactly it means to be "well governed," how cross-sector lifeline management might look, and what "building climate resilience" might mean.

3.1.3 Infrastructure-Relevant Climate Change Impacts on the US Southwest

Similar and complementary insights to the IPCC's, although more specific and refined, emerge from the Third US National Climate Assessment (NCA3) (Melillo et al. 2014). We synthesize them in a similar fashion as above to illustrate how the greater regional specificity (the focus here is on the Western and Southwestern US) reveals a greater level of concern about the impacts of climate change on infrastructure (Table 2).

Table 2: Key Findings Regarding Infrastructure from the Third National Climate Assessment (2014)

Direct impacts on climate, variability and extreme events (i.e., initiating events of disruptions of infrastructure)	Very heavy precipitation events have increased nationally and are projected to increase in all regions. The length of dry spells is projected to increase in most areas, especially the southern and northwestern portions of the contiguous United States. Short-term (seasonal or shorter) droughts are expected to intensify in most U.S. regions. Longer-term droughts are expected to intensify in large areas of the Southwest, southern Great Plains, and Southeast. Sea-level rise, storms and storm surges, and changes in surface and groundwater use patterns are expected to compromise the sustainability of coastal freshwater aquifers and wetlands. Increasing air and water temperatures, more intense precipitation and runoff, and intensifying droughts can decrease river and lake water quality in many ways, including increases in sediment, nitrogen, and other pollutant loads. Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas. These trends are expected to continue, increasing the likelihood of water shortages for many uses. Increasing flooding risk affects human safety and health, property, infrastructure, economies, and ecology in many basins across the United States. Snowpack and streamflow amounts are projected to decline in parts of the Southwest, decreasing surface water supply reliability for cities, agriculture, and ecosystems. Increased warming, drought, and insect outbreaks, all caused by or linked to climate change, have increased wildfires and impacts to people and ecosystems in the Southwest. Fire models project more wildfire and increased risks to communities across extensive areas.
Energy sector	Extreme weather events are affecting energy production and delivery facilities, causing supply disruptions of varying lengths and magnitudes and affecting other infrastructure that depends on energy supply. The frequency and intensity of certain types of extreme weather events are expected to change. Higher summer temperatures will increase electricity use, causing higher summer peak loads, while warmer winters will decrease energy demands for heating. Net electricity use is projected to increase. In the longer term, sea-level rise, extreme storm surge events, and high tides will affect coastal facilities and infrastructure on which many energy systems, markets, and consumers depend. As new investments in energy technologies occur, future energy systems will differ from today's in uncertain ways. Depending on the character of changes in the energy mix, climate change will introduce new risks as well as opportunities.

Water sector	Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production. In most U.S. regions, water resources managers and planners will encounter new risks, vulnerabilities, and opportunities that may not be properly managed within existing practices. Increasing resilience and enhancing adaptive capacity provide opportunities to strengthen water resources management and plan for climate change impacts. Many institutional, scientific, economic, and political barriers present challenges to implementing adaptive strategies.
Transportation sector	The impacts from sea-level rise and storm surge, extreme weather events, higher temperatures and heat waves, precipitation changes, Arctic warming, and other climatic conditions are affecting the reliability and capacity of the U.S. transportation system in many ways. Sea-level rise, coupled with storm surge, will continue to increase the risk of major coastal impacts on transportation infrastructure, including both temporary and permanent flooding of airports, ports and harbors, roads, rail lines, tunnels, and bridges. Extreme weather events currently disrupt transportation networks in all areas of the country; projections indicate that such disruptions will increase.
Urban Areas	Climate change and its impacts threaten the well-being of urban residents in all U.S. regions. Essential infrastructure systems such as water, energy supply, and transportation will increasingly be compromised by interrelated climate change impacts. The nation's economy, security, and culture all depend on the resilience of urban infrastructure systems. In urban settings, climate-related disruptions of services in one infrastructure system will almost always result in disruptions in one or more other infrastructure systems. City government agencies and organizations have started adaptation plans that focus on infrastructure systems and public health. To be successful, these adaptation efforts require cooperative private sector and governmental activities, but institutions face many barriers to implementing coordinated efforts. Projected regional temperature increases, combined with the way cities amplify heat, will pose increased threats and costs to public health in southwestern cities, which are home to more than 90% of the region's population. Disruptions to urban electricity and water supplies will exacerbate these health problems.
Cross-sector vulnerabilities	Energy, water, and land systems interact in many ways. Climate change affects the individual sectors and their interactions; the combination of these factors affects climate change vulnerability as well as adaptation and mitigation options for different regions of the country. The dependence of energy systems on land and water supplies will influence the development of these systems and options for reducing greenhouse gas emissions, as well as their climate change vulnerability. For example, projected warming of water in rivers and lakes will reduce

	the capacity of thermal power plants, especially during summer when electricity demand skyrockets. Jointly considering risks, vulnerabilities, and opportunities associated with energy, water, and land use is challenging, but can improve the identification and evaluation of options for reducing climate change impacts.

Sources: Findings are verbatim and compiled from the executive summaries of multiple NCA3 chapters: Urban Systems, Infrastructure, and Vulnerability (Cutter et al. 2014), Water Resources (Georgakakos et al. 2014), Energy Supply and Use (Dell et al. 2014), transportation (Schwartz et al. 2014), Energy, Water and Land Use (Hibbard et al. 2014), Coastal Zone Development and Ecosystems (Moser et al. 2014), and Southwest (Garfin et al. 2014).

At the level of these overarching findings, the NCA3 still does not provide sufficient technical detail about key characteristics of the initiating events that can cause infrastructure service disruptions. However, the NCA3 is more explicit about the challenges faced from cascades of impacts across multiple infrastructure systems, and about the challenges associated with coordinating adaptive responses across different levels of government, private and public entities, and across different sectors.

Little insight can be gained at the national level on the planning-relevant characteristics of events, such as:

- *duration* of the initiating climatic event (e.g., length of heat wave, length of drought);
- *intensity* of the initiating event (measured variously, depending on the type of event, e.g. rainfall amount/hour or day; extreme daily/seasonal high and low temperatures; sustained and gusty wind speed);
- *geographic extent* of initiating event (e.g., acres of wildfire; counties experiencing extreme heat);
- *number of simultaneous events* (e.g., number of wildfires in a given region); or,
- *compound impacts* (e.g., coastal and fluvial flooding occurring simultaneously; extended heat and extreme long-term drought).

Some recent research is beginning to address some of these lifeline relevant climatic characteristics (e.g., Bartos and Chester 2016; Moftakhari et al. 2017), but generally, this area of research into projecting compound risks is still relatively new. To the extent it is available for California or the Greater L.A. region, we cite it in the following section.

3.1.4 Infrastructure-Relevant Impacts on California and the L.A. Region

Spatially or temporally downscaled information as well as translation of climate model outputs into planning-relevant information (e.g., number of heating or cooling degree days, hourly temperature data) are often required or at least desirable for local planning purposes, but also more difficult to obtain and challenging to project with scientific confidence (Wilby and Dessai 2010). Moreover, certain impacts of relevance for disaster preparedness and infrastructure planning and operation is often not available. Examples include combinations, sequences, and higher-order and/or interactive hazards such as:

- landslide risk after extended drought periods, followed by wildfires and heavy downpours (as was experienced in California in recent years);
- change in coastal erosion rates given higher sea levels (accelerating loss of land buffers and increasing flooding risks);
- smoke after wildfire (threatening the proper functioning of solar power panels and transmission lines); or
- changes in wind patterns due to large-scale climate change and regional or local climate variability such as Santa Ana wind forecasts.

Some geographically specific information is available from California's climate change data portal (see: www.cal-adapt.org/tools), even if it does not (yet) provide details on complex hazards, combinations of hazards, or some of the lifeline-planning relevant variables. For the L.A region, Cal-adapt and other recent studies offer the following projections for 2050 and 2100[13] (Table 3).

Table 3: Projections of particular climate extremes for the L.A region for 2050 and 2100

Initiating events	2050	2100
Extreme heat (defined as daily Tmax > 35°C, or 95°F)	By mid-century, many land areas may experience increases of roughly 20-40 additional extremely hot days per year (with little difference between emission scenarios) The distributions of future daily maximum temperatures are similar to the baseline distributions, shifted by the change in average temperature	By end-of-century, the number of extremely hot days increases most under RCP8.5. With the exception of the highest elevations and a narrow swath very near the coast, where the increases are confined to a few days, most land locations are projected to experience an additional 60–90 extremely hot days per year
Average number of extreme heat days above local threshold (L.A. County heat threshold: 89.7˚F)	17-24 days (Representative Concentration Pathway (RCP) 4.5 and RCP 8.5)	25-49 days (RCP 4.5 and RCP 8.5)
Frequency and seasonal timing of hot days	Increasing number of extremely hot days and earlier in the year (as early as April, as opposed to July-September, for the hottest days)	Further increasing number of extremely hot days and earlier in the year (as early as April, as opposed to July-September, for the hottest days)

[13] We reference projections to 2050 to capture the most common planning horizon and design life of some infrastructure, but also provide information for 2100 due to the long-lived nature of many types of infrastructure already in place or that has been or will be built soon and will still be in place in 2100.

Average number of Cooling Degree Days (CDD) (the number of degrees that a day's average temperature is above 65^o Fahrenheit (18^o Celsius), i.e., the temperature above which buildings need to be cooled) (Average CDD 280, 1961-1990)	662-881 days (RCP 4.5 or RCP 8.5, HadGEM2-ES and CNRM-CM5 models)	906-1412 days (RCP 4.5 or RCP 8.5, HadGEM2-ES and CNRM-CM5 models)
Wildfire - Annual Mean Hectares burnt (Average Area burnt 31.5 ha/yr, 1961-1990)	38 - 37.5 ha/yr (RCP 4.5 or RCP 8.5, central population growth scenario)	36.9 - 35.3 ha/yr (RCP 4.5 or RCP 8.5, central population growth scenario)
Sea-level rise[14]	50% chance that sea level will be 0.7 ft higher than in 2000 (RCP 8.5) 66% chance that SL will be 0.5 to 1.0 ft higher than in 2000 (RCP 8.5) 0.5% chance that SL will be 1.8 ft higher than in 2000 (RCP 8.5) H++ scenario[15] (non-probabilistic): 2.6 ft higher than in 2000	50% chance that sea level will be 2.2 ft higher than in 2000 (RCP 8.5) 66% chance that SL will be 1.3 to 3.2 ft higher than in 2000 (RCP 8.5) 0.5% chance that SL will be 6.7 ft higher than in 2000 (RCP 8.5) H++[13] scenario (non-probabilistic): 9.9 ft higher than in 2000
Projected population increase	1.2-3.1 million (over base year 2010; range of projections for 2060) in L.A. County	n/a
Impacts on electricity infrastructure and demand	The overall vulnerability of L.A.'s electricity infrastructure to rising air temperatures is 2-20% loss of rated component capacity by 2060. Long-term service reliability is more susceptible to population growth and changes in technology than to rising air temperatures	n/a

[14] For maps of areal extent of flooding due to SLR and storm surge, see Cal-adapt or the Our Coast Our Future site at www.ourcoastourfuture.org/ and Ballard et al. (2016).
[15] The H++ scenario was defined in Griggs et al. (2017) as an extreme SLR scenario, which results from inclusion of ice decay dynamics in SLR models, in addition to the common components of thermal expansion of ocean waters and additions to the water volume from icemelt and groundwater discharge into the oceans.

	The only infrastructure in the region that is not at risk of experiencing air temperatures above 40°C (104°F) are the components within a few miles of the western-facing coast of Santa Monica Bay. Inland regions, specifically the San Gabriel Valley and the Antelope Valley, are projected to experience the highest temperatures at up to 54°C (129°F). East El Monte and Pomona are the most at risk of service interruptions due to substation overloading (load factor ⩾2), followed by Calabasas to Malibu, and the southern Foothills, Pasadena, Alhambra, and East L.A. regions. All could be offset by varying amounts of added capacity.	

Sources: Cal-adapt (accessed March 2018), as well as Burillo et al. (2018); Griggs et al. (2017), OPC (2018), Lopez et al. (2018)

Burillo et al. (2018) produced regionally downscaled temperature projections to assess impacts on the Los Angeles region's electricity grid and demand. Sources: Burillo et al. (2018), their Figures 3 and 4, p.8 and 9, respectively

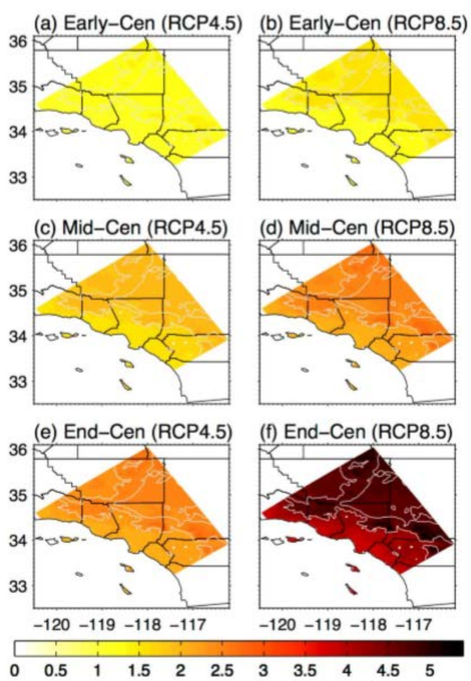
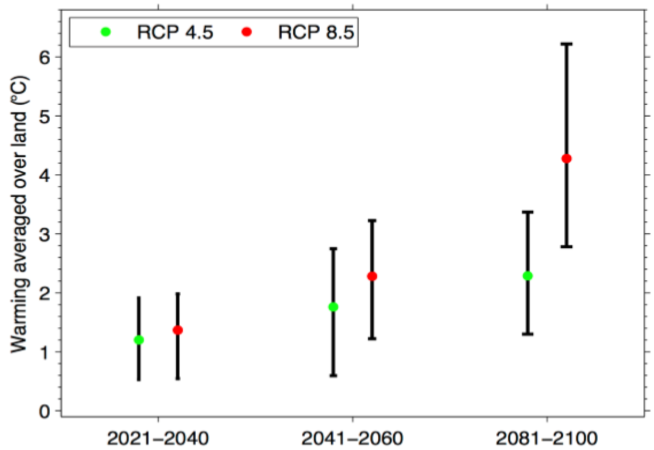


Figure *4* (on the left) shows the downscaled annual mean surface warming for three time periods and two emissions scenarios, while the figure on the right places the downscaled model ensemble means for each time slice and scenario side by side.



Sources: Burillo et al. (2018), their Figures 3 and 4, p.8 and 9, respectively

Figure 4: Ensemble mean of downscaled annual-mean surface warming (°C) for early-, mid-, and end-of-century periods 2021–40, 2041–60, and 2081–2100 (left); Land-averaged annual-mean surface warming (°C) downscaled from each GCM for early century (2021–2040), midcentury (2041–2060), and end-century (2081–2100) under "mitigation" (RCP4.5, green dots) and "worst-case" (RCP8.5, red dots) scenarios (right).
Dots = ensemble mean across all GCMs; vertical bars = full range of GCM results.

Other recent studies suggest that anthropogenically-driven climate changes (i.e., events attributable to human-caused climate warming) will cause heat wave clusters over the western United States to emerge from the noise of natural variability as early as the 2020s and will increase significantly over the 21st century (Guirguis et al. 2018, Lopez et al. 2018, Gershunov and Guirguis 2012).

Moftakhari et al. (2017) also made important advances in producing compound flooding projections for mid-century from coastal/sea-level rise driven and riverine/fluvial flooding, which result in a significantly earlier crossing of failure probability thresholds for coastal protection infrastructure.

Reliable information is not yet available for high wind events and understanding of fire weather-relevant Santa Ana winds is still in flux (Guzman-Morales et al. 2016). Earlier studies on the future frequency of Santa Ana winds revealed significant uncertainty, although models showed the potential for a shift of Santa Ana Occurrence to later in the season (Hughes et al. 2009; Miller and Schlegel 2006).

California's Fourth Climate Assessment includes several additional studies focused on climate change impacts on or relevant to vulnerable infrastructure including several studies that are related and may be used as comparisons to our Los Angeles-focused work.[16]

[16] Relevant studies in the California Energy Commission (CEC) portfolio include those by Cayan and colleagues, Westerling, Dale and Wei, Levinston and Gilbert, Brooks and colleagues, and Barnard and colleagues. In CNRA's portfolio, relevant studies include by Herman, Doremus and colleagues, Lauland and colleagues, Petrow and colleagues, and Stacey and Riordan.

3.2 The Study of Climate Impacts on Complex Systems: Teleconnected and Cascading Impacts

The literature reviewed so far tends to either study climate change trends and extreme events or climate change impacts on a particular sector even as researchers recognize that impacts in one sector can have cascading effects on one or more others, and thus should be examined together (e.g., Evans and Fox-Penner 2014). In this study, we are interested in the climate impacts on a sector over long geographic distances and the transfer of those impacts to other sectors. Understanding these types of complexities is a growing focus in academic research.

As we described in Chapter 1, for the purposes of this study, we distinguish two types of climate impacts on interconnected systems:

- *Cascades* – impacts in one sector that affect one or more downstream sectors, which are dependent on the services of the initially-impacted sector[17]; and
- *Teleconnections* – impacts that originate in one geographic location and then translate their effects into impacts in another location[18].

Below we review selected literature on understanding cascading and teleconnected impacts of climate change.

3.2.1 Telecoupling

Some years ago, researchers increasingly interested in coupled human and natural systems (frequently applied to land use/land system science, food systems, sustainability, and ecosystem services) developed a framework called "telecoupling" (e.g., Liu et al. 2013, 2016; Bruckner et al. 2015; Sonter et al. 2017; Eakin et al. 2017). The telecoupling framework is a special case of the larger class of integrated assessment models as it extends integrative place-based studies with a more dynamic, multi-scalar process understanding (Friis et al. 2015; Liu et al. 2015b) and aims to understand the socioeconomic and environmental interactions between two or more areas or systems across distance.

Some in the literature distinguish telecoupling from teleconnections as follows (based on Friis et al. 2015, p.132):

- *Teleconnection* describe distal environmental and socio-economic drivers of change (e.g., Adger, Eakin and Winkels 2009; Seto et al., 2012);

---

[17] We strongly lean on the definition of cascading events offered by Pescaroli and Alexander (2015, pp.64-65), who defined "cascading effects [as] the dynamics present in disasters, in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social or economic disruption … Cascading effects are complex and multi-dimensional and evolve constantly over time … Low-level hazards can generate broad chain effects if vulnerabilities are widespread in the system or not addressed properly in sub-systems."

[18] For this definition we build on Adger et al. (2009).

- *Telecoupling* capture the feedbacks and multidirectional flows that characterize interactions between systems (e.g., Eakin et al., 2014; Liu et al., 2013, 2014).

Core elements of a telecoupled system typically include one or more sending, receiving and spillover subsystems, as well as agents, flows, causes, and effects. Researchers are interested in connections across organized systems at different scales, across space, and over time. Given the rapidly escalating complexity of assessing such interconnected systems, telecoupling studies typically involve quantitative systems modeling which helps to reveal complex relationships, including amplification, offsetting, spatial overlaps, feedbacks, and emergent properties. Such interactions cannot be detected by traditional studies that examine sectors or systems separately (Liu et al. 2015a). For example, Fang et al. (2016) question whether energy sustainability can be achieved without taking telecoupled interactions of and among energy systems into account. They also allow for the assessment of multiple management objectives, synergies and trade-off analysis, mediation among conflicting goals and, hence, assisting with conflict resolution, clarification and (re)assignment of governance responsibilities, and the design of policies and practices that address the concerns of multiple constituents (Liu et al. 2015b).

Beyond these basic components and characteristics of telecoupled systems, Liu (2017) proposed a meta-coupling framework that combines assessment of three layers of connectivity:

- human-nature interactions within a system (intracoupling),
- human-nature interactions between distant systems (telecoupling), and
- human-nature interactions between adjacent systems (pericoupling).

This growing complexity makes clear that the relevance of practical application may be overstated. While telecoupling studies may be generally interesting to decision-makers, the systems they tend to manage are siloed subsystems and planners tend to lack the capacity to apply the overarching insights directly. Moreover, most studies of this sort are not tailored to the planning or management needs and scales of local or utility/lifeline decision-makers. Importantly, the data and computational requirements associated with the tools used in telecoupling studies (e.g., Tonini and Liu 2017) are significant, and for some resource managers they may simply be prohibitive. That said, electric utility, transportation, and water managers already use computationally-demanding models within their sectors, so telecoupled system models may not be beyond their reach. None of them, however, are required or necessarily empowered to build and maintain models of telecoupled systems.

3.2.2 Nexus Studies

Related and occasionally overlapping fields of study relevant to our own are those that examine the simultaneous impacts of climate or global environmental change on two or three sectors, such as water and energy, or climate, water, food, and energy (e.g., McMahon and Price 2011; Howells et al. 2013; Fang et al. 2015; Gallager et al. 2016; Howarth and Monasterolo 2017; Romero-Lankao et al. 2017; Bijl et al. 2018). These studies are collectively referred to as nexus studies. They overlap with telecoupling studies when they consider long-distance relationships; they are distinct, when they do not.

Nexus studies tend to fall into three groupings, which focus on different aspects of the interconnectivity and draw on different theoretical and disciplinary approaches (based on Weitz et al. 2017), including a:

- focus on risk and security to avoid worsening of resource scarcity and inducing conflicts;
- focus on economic rationality and optimization to improve policy cost-effectiveness and resource-use efficiency, as well as to optimize allocation of resources across sectors; and,
- focus on nexus governance to counter the dominant technical-administrative approaches of the other studies by explicitly addressing trade-offs, improving policy integration across sectors, and treating governance as a fundamentally political process among different actors with distinct perceptions, interests and practices.

The previously mentioned NCA3 was the first national assessment that included several nexus chapters and single-sector focused chapters that nevertheless recognized these complex interactions (Hibbard et al. 2014; Moser et al. 2014; findings included in Section 3.1.3 above). They fell into the first of these three categories. These and other nexus studies bring to the fore the importance of coordination and collaboration among sectors, institutions, and actors in devising adaptive strategies and policies, given the cascading impacts of climate change themselves as well as the mutual influence across sectors via enacted climate mitigation and adaptation strategies.

As Weitz et al. (2017) note:

> although all three nexus perspectives argue that cross-sector coordination and collaboration is desirable (for distinct reasons), they do not explain what conditions would enable or hinder collaboration and coordination between sectors, institutions and actors. […] the nexus literature provides little insight on how dynamics beyond the sectoral boundaries of water, energy and food, influence the nexus […]. Finally, […] the nexus literature generally overlooks how trade-offs are negotiated, decisions taken in practice and the ideological assumptions behind policy options. […] A technical and administrative view dominates both the literature and conceptions of policy coherence in practice; yet political and cognitive factors are essential for connecting technical nexus analyses to actual decision-making and policy processes (p.166).

Besides the conceptual and theoretical constraints, Ernst and Preston (2017) note a far more fundamental set of challenges that constrain nexus studies in the context of adaptation to climate change:

- insufficient data and information,
- path dependence; and,

- institutional fragmentation and disorganization.

They find these constraints particularly pronounced in nexus studies at the local and regional scales “owing to complex, and poorly integrated, governance structures.” Increasingly, researchers focus on the governance dimension of complex systems to improve policy coherence and facilitate greater coordination of risk management (Lenschow et al. 2016; Eakin et al. 2017; Weitz et al. 2017; Oberlack et al. 2018).

Technical studies of cascading impacts on infrastructure systems are increasingly common in engineering and systems science. Many of the academic studies in this category assess the reliability of one or two lifeline systems in the face of catastrophic disruptions from climatic or other events (e.g., terrorist attacks, extreme weather events, cyberattacks, earthquakes) (e.g., Krishnamurthy and Kwasinski 2016; Miara et al. 2017; Forzieri et al. 2018). Several recent studies propose frameworks of how to simultaneously assess the resilience and reliability of multiple interdependent lifeline systems (e.g., Ramaswami et al. 2012; Guidotti et al. 2016; Turoff et al. 2016; Reiner and McElvaney 2017), but applications of such frameworks are still limited, and uptake by practitioners rare at best.

The teleconnections framework introduced in Chapter 1, which is used and tested in this study, aims to overcome some of hurdles to use in practice and by practitioners so as to make adaptation planning more robust. In the next section, we explore how others have attempted to assess and address complex risks in practice.

3.3 Assessing Complex Risks in Practice

3.3.1 Context and Challenge

The review so far has surfaced a number of critical insights:

- as assessments of climate risks move from the global and national levels to site-specific/place-based lifelines/infrastructure, the scientific uncertainty increases and confidence in climate projections correspondingly decreases, but the expected magnitude of risks to infrastructure increases;
- there is growing academic interest and more frameworks and tools available to assess both complex risks across sectors and geographic and temporal distances, and multiple risks occurring in one place, but these approaches are still relatively new and are not always connected to the assessment of climate change risks; and,
- the greater the complexity of coupled and interdependent systems, the greater the need for computer-assisted modelling.

These insights raise significant questions as to what is available to practitioners (e.g., lifeline planners, investors, operators and managers, and emergency and public health managers) to assist them in exploring whether current planning, design, disaster preparedness, and operational procedures are sufficient to meet the challenges of accelerating climate change, and, if they are not, how to adjust them.

First, it is important to recognize that the collective audience of lifeline planners, investors, operators and managers (“practitioners” for short) is diverse in several ways:

- they deal with different types of infrastructure, built for different design lives and actual lifetimes and are governed by different sets of rules, regulations, standards and procedures;
- they address different aspects of building and maintaining infrastructure;
- they are dependent on different supply chains, with different temporal dynamics and different vulnerabilities from climate change;
- they have varying degrees of control over all the infrastructure assets their functioning depends on (e.g., owned vs. leased assets); and
- they focus on different scales and aspects of the lifeline system, ranging from federal regulatory commissions, to regional councils, to state oversight bodies, to private and public-sector utility owners, and locally-based operations managers of small- to medium- to large-scale infrastructure systems.

Accordingly, perspectives, needs, staff capacity, training, professional backgrounds, and familiarity or ease with climate science, complex systems and associated data and tools vary widely. Moreover, day-to-day demands are already taxing on these practitioners in the context of increasingly common, disruptive climate extremes and continuously aging infrastructure (NASEM 2017).

It is critical to understand this context and challenge as we ask what tools are available to lifeline "practitioners" to assess the growing risks to their interdependent infrastructure systems.

3.3.2 Approaches to Assessing and Depicting Complex System Interactions

Over the course of our study, we encountered a variety of efforts that aim to address the complex challenges at the heart of this study, albeit all with their own limitations.

For example, in the electricity sector, there are extensive efforts to understand, assess, and improve the reliability of electricity provision. The North American Electric Reliability Corporation (NERC) and its regional coordinating councils, national laboratories, and the Electric Power Research Institute (EPRI) are deeply engaged in grid reliability studies and standard setting vis-à-vis a wide variety of threats, including – sometimes – climate change (e.g., FERC 2016; NERC 2016; Joselow 2017a; Macknick et al 2016; Sobczak 2017; WECC 2016).

Meanwhile, vulnerability assessment guidance from DOE (2016) urges utility owners to assess their "system vulnerabilities," i.e., their dependence on others, as well as the potential of electricity outages that can affect others across large regions, but beyond this does not provide much guidance on how to assess teleconnected and cascading climate change impacts. It offers a wide range of tools and web-based resources, but no specific tools for assessing teleconnected vulnerabilities. California's Public Utilities Commission published a white paper to augment DOE's vulnerability assessment guidance, but only vaguely alludes to cascading impacts, and does not mention teleconnected impacts (Ralph-Douglas 2016).

Each electric or water utility as well as transportation agency or communication service provider runs its own systems model. These models are a foundation for automated and active system operation and response in case of disruptions. These models are focused on the system the owner/operator is in charge of, but do not go beyond system boundaries.

Alternatively, sectors, local communities, or system operators may be assisted by the network models of large consulting firms and research institutes (e.g., catastrophe risk modeling by firms like Risk Management Solutions (RMS)[19] or robust decision-making modeling by organizations like RAND[20]) to assess the compounding or cascading risks that particular regions or systems face. Over the course of our study, we became aware of just three examples in the US where local communities assessed the interdependencies of various lifelines on which they all critically depend: San Francisco (Lifelines Council 2014), Miami (Jurardo 2017), and a related study focusing on food system resilience in Baltimore (Biehl et al. 2017). The San Francisco study of interdependent lifelines used an earthquake-generated large-scale, long-lasting disruption to assess its vulnerabilities, whereas the Miami Critical Infrastructure and Flood Resilience project is considering climate change impacts – especially sea-level rise – directly. Miami – a Rockefeller Foundation-supported member of the 100 Resilient Cities (100RC) initiative – is approaching critical lifeline interdependencies with the help of the Dutch research institute, Deltares, which developed a participatory expert knowledge elicitation and visualization tool called *CIrcle*[21] to explore critical infrastructure vulnerabilities (Vaidya and Hounjet 2017).[22] The Baltimore assessment considers weather disruptions and is the only study of the three in which distal climate disruptions are considered for local food system reliability.[23]

Beyond such concerted efforts, there are "boutique" systems modeling approaches – like the ones used in this report – that can best be described as dialogue support tools rather than decision support tools. Systems modelling as offered by *Climate Interactive*[24] or participatory systems modeling tools like *The Elephant Builder*[25] or potentially other agent-based modelling approaches bring relevant subject matter experts together to

---

[19] See: http://www.rms.com/.

[20] See: https://www.rand.org/topics/robust-decision-making.html.

[21] See: https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/.

[22] See also: https://www.deltares.nl/en/news/effects-of-floods-on-critical-infrastructure-in-south-florida-analysed/

[23] See also: https://www.jhsph.edu/research/centers-and-institutes/johns-hopkins-center-for-a-livable-future/projects/food-system-resilience/.

[24] See: https://www.climateinteractive.org/tools/.

[25] See: https://elephantbuilder.com/.

- help build a common understanding of mutual dependencies;
- learn about archetypal system behavior (such as reinforcing/positive and counterbalancing/negative feedback looks destabilizing and (re)stabilizing systems, respectively); and
- explore and identify opportunities for intervening in complex interdependent systems (Kim 1992).

Clearly, each of these approaches have distinct advantages and uses, but also limitations (Table 4).

Table 4: Benefits and limitations of available complex system risk assessment tools

Scale of Application	Benefits & Uses	Drawbacks & Limitations
Academic research at various scales (global to local/system level)	Provides fundamental insights; yields principles	High complexity; high data/computing/modeling demands, typically not applicable at the operational level
National or large-scale regional system reliability studies	Provides categorical insights into system vulnerabilities, helps identify regional priorities; useful to setting national standards and guidelines	Available nationally for electricity only; different approaches are used in other sectors/lifelines, thus difficult to integrate seamlessly; to the extent private utilities (e.g. telecommunications sector) are involved, results are not publicly shared
Utility systems models	Primary use in day-to-day, near- and longer-term planning and operation	Not typically connected to other sectors' system models; private utilities tend not to share information, particularly of system vulnerabilities or response shortfalls
Sector/local/system level complex system/catastrophe risk/network models (developed by large consulting firms)	Used in specific locale or by an entity or in supply-chain specific applications; highly customized	Data intensive, computationally demanding; high cost, resulting in such sophisticated risk models to be out of reach for many if not most cities, at least at the start of the process
Local/systems or multiple interdependent systems models (boutique approaches)	Helpful to develop shared basic understanding in mutual interdependencies and to surface barriers to collaboration	Labor intensive, not necessarily quantitative, so not directly applicable to day-to-day computer-assisted operations

Source: The Authors

The next chapter, drawing on interviews and the use of dialogue support tools, yields insights into what can be learned from such interaction that is otherwise not apparent or accessible, lest disasters reveal the latent and often costly vulnerabilities the hard way.

4: Findings

4.1 The Interconnected Lifeline System of the L.A. Region

Critical lifelines in L.A. – and everywhere – are governed and operated as independent units such as a utility or agency but are intrinsically connected and dependent upon one another in terms of necessary resources and provided services. As noted by one of the TAG members – "Southern California Edison (SCE) and the Los Angeles Department of Water and Power (DWP) provide electricity, but electricity provides everything else." While true, this only presents one side of the story; most (if not all) of the interconnections within a city's lifeline system are not unidirectional. Through Supervisory Control and Data Acquisition (SCADA) systems, the ability to provide reliable electricity, for instance, is in turn dependent on these communication system-powered data centers to regulate transmission and distribution systems, which is itself dependent on a reliable energy source. Identifying these multidirectional interconnections is critical for ensuring that a system is prepared for emergencies, as well as the impacts of longer-term and chronic climate change.

In this chapter we provide key findings from the empirical work of our study. These findings lay the foundation for the subsequent chapters in which we identify how our teleconnections framework can be useful, along with a series of proposed research priorities and action opportunities.

4.1.1 Mapping L.A.'s Interconnected Lifeline System

Through the expert interviews, workshops, and sector follow-up meetings, we strove to develop a "mental model" of the interconnected lifeline system in L.A as no such depiction currently exists for the L.A. region, but was identified as a need during the TAG interviews. We used the Elephant Builder collaborative systems modeling tool (see Section 2.2.1.4 for a description) as a dialogue support tool to develop this mental model of the inputs and outputs, as well as the interconnections among the various lifelines. Not surprisingly, once all the data were assembled into one place, a very complicated and highly interconnected depiction of the lifelines in L.A. emerged (

). Even then, it is also important to note that the nodes and connections identified during our discussions are not exhaustive of all possible nodes and connections. The process of collectively developing a model of how lifelines are interrelated is similar – in principle – to how climate or other types of complex models are built: subject matter experts determine what the important connections are and describe their causal nature. This pilot study could not independently verify these connections, but multiple sectoral representatives engaged with each other in the workshops and follow-up sector meetings to extend, correct and refine the model. This work was intended to provide an initial starting point and to guide cross-lifeline dialogue, not to replicate the physical world. Future studies could build on it and build it out in quantitative ways, if desired.

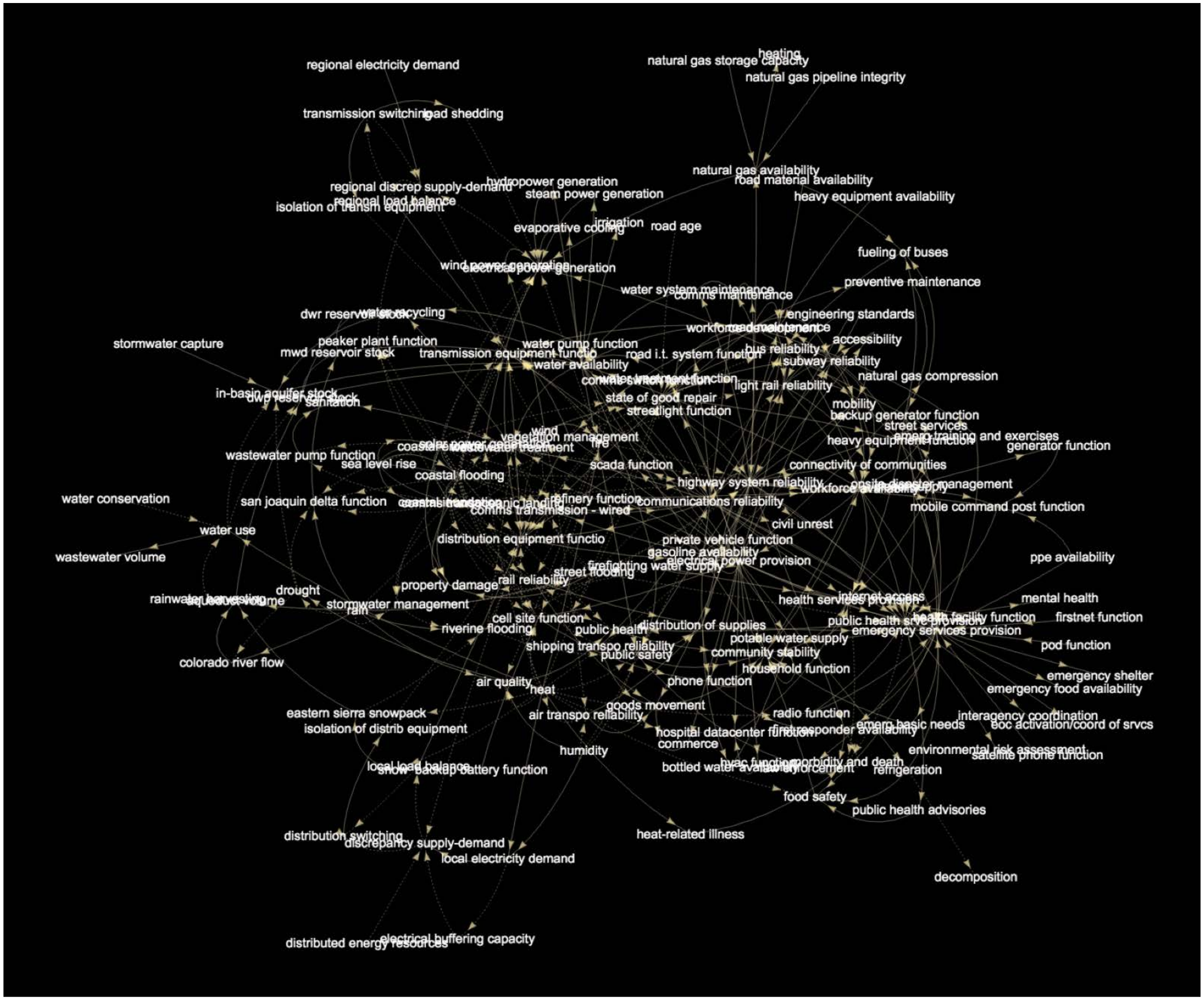
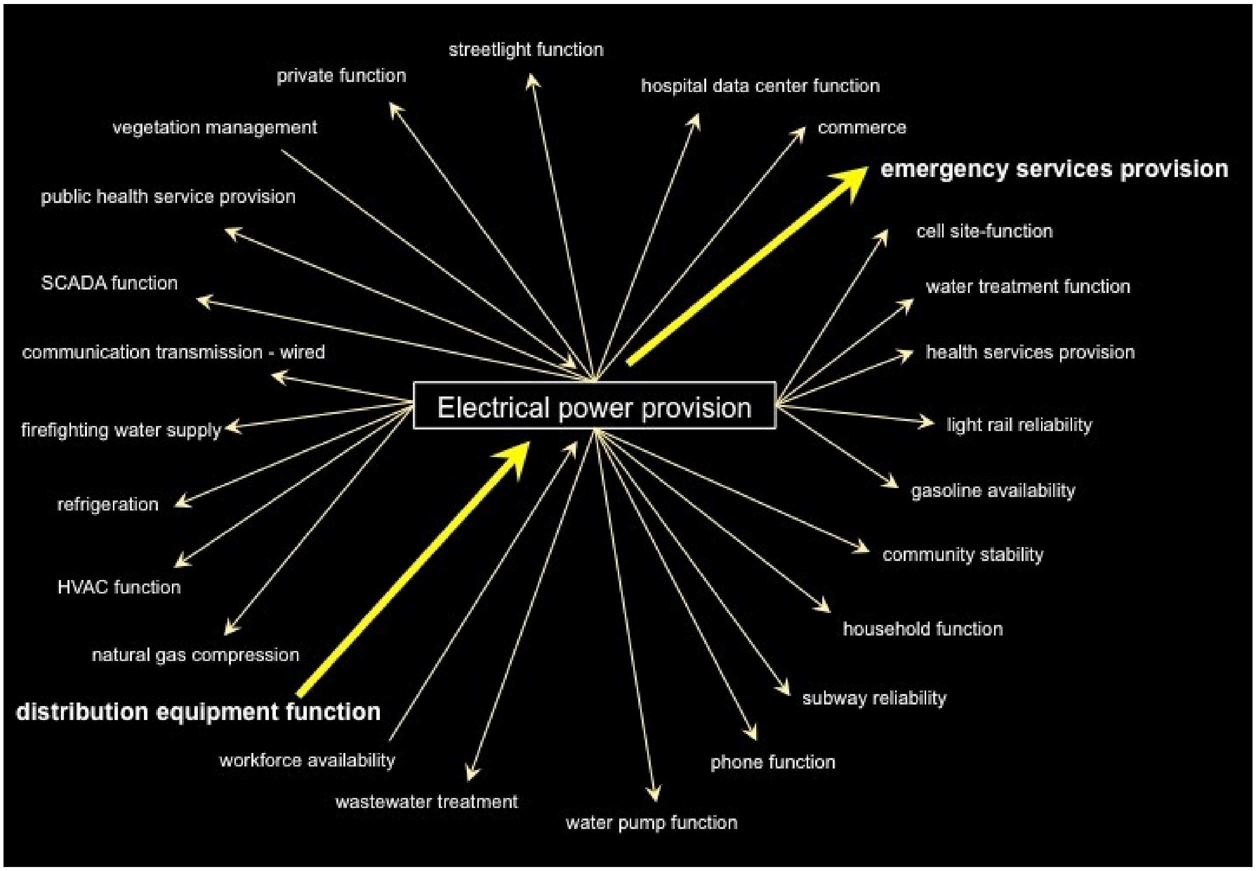


Figure 5: The Integrated Lifeline System of the L.A. Region (as depicted in the Elephant Builder) This image provides a visualization of all the nodes, and connections among the nodes, identified by study participants, as organized by the Elephant Builder. The direction of the arrows indicates a causal mechanism – a change in Node 1 causes a change in Node 2 in either the same or the opposite direction. For instance, increasing humidity leads to more heat-related illness (increases are shown as solid lines); alternatively, greater water conservation leads to reduction in water use (decreases are shown as dashed lines).

This graphic of the entire integrated lifeline system examined in this study is intentionally shown in a way that does not allow the reader to decipher every word in the figure; rather, the depiction is meant to demonstrate the complexity of the system as a whole. The model findings are broken down in more detail in subsequent sections.
Source: The Authors

In an initial analysis, we examined the first-degree upstream inputs and downstream outputs for each lifeline independently. To illustrate what such an analysis reveals, we use the node *electrical services provision* (the final step in the delivery of energy to customers – homes, businesses, etc.) and examine the co-created mental model for the inputs and outputs from that node (Source: The Authors

Figure *6*). (Note, nodes in the Elephant Builder are indicated in italics.) The main upstream inputs directly linked to *electrical power provision* were identified as *workforce availability* and *distribution equipment function*, while all other connections were identified as downstream outputs. Each of the inputs and outputs represented here has a positive sign, that is, a change in the upstream variable causes a change in the downstream variable in the same direction. Thus, as *distribution equipment function* increases, so does *electrical power provision*, which in turn increases *emergency services provision* (shown in bold yellow in Figure 8).



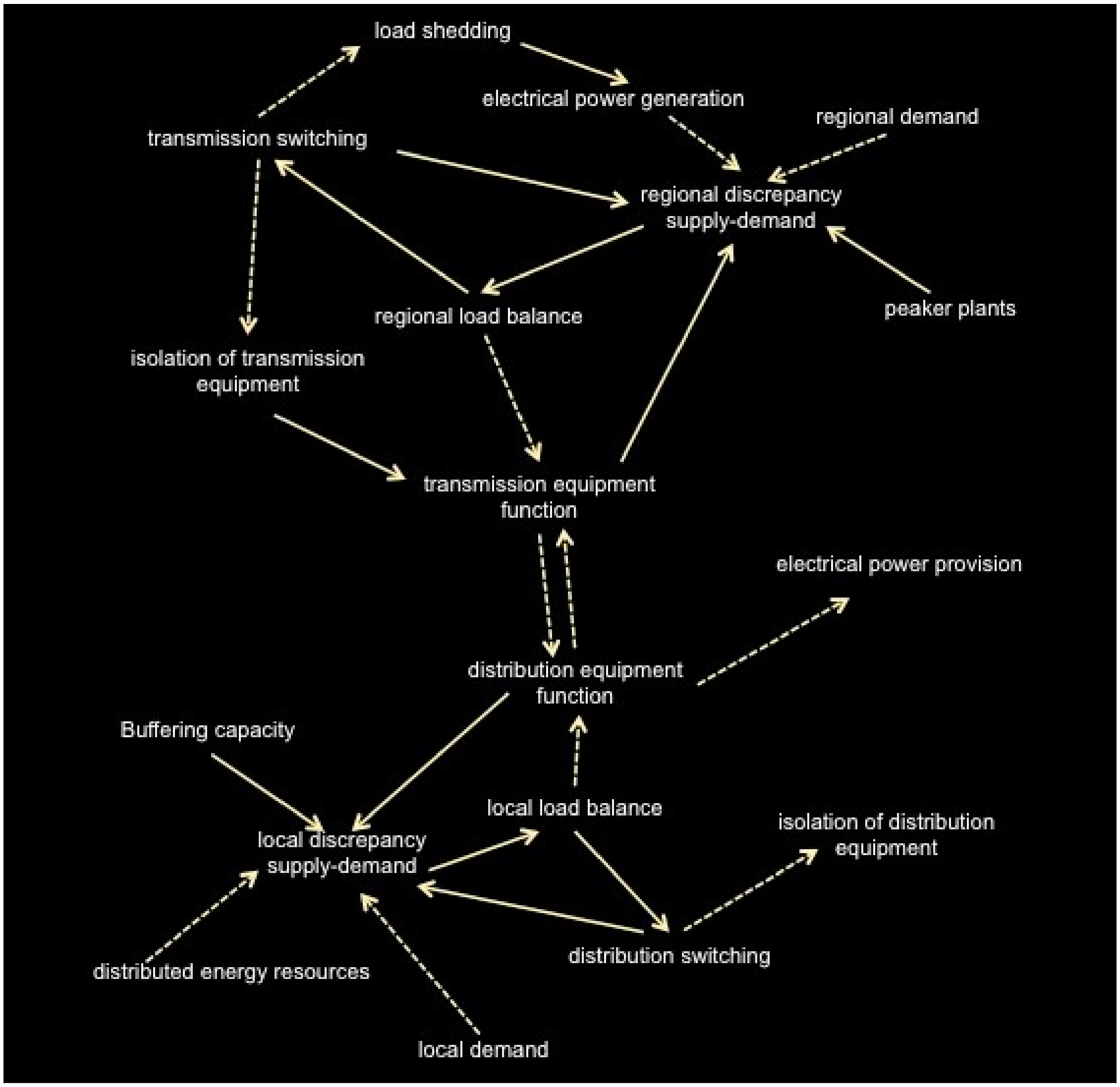
Source: The Authors

Figure 6: Electrical Power Provision and its First-Degree Connections Shown in the Elephant Builder. The figure shows upstream inputs on which it depends (inward pointing arrows) and the downstream outputs it affects (outward pointing arrows).

This first-degree view, however, does not fully capture the important upstream connections that allow DWP and SCE to provide the energy utilized by customers in the L.A. region. *Distribution equipment function* – the workings of the substations, power lines, and poles that deliver electricity to the end user – depends upstream on *electricity generation* and on the balance between electricity coming into and going out of the system (*load balance*). Thus, to fully comprehend the upstream connections that have important consequences for electrical power provision to the L.A. region – and subsequently to the downstream lifelines – it is important to also identify the upstream connections for *distribution equipment function* (Source: The Authors

Figure *7*). What emerges from these interconnections related to electrical services provision is an understanding of the delicate balance that occurs among supply, demand, load balance, and their impact on efficient and reliable energy transmission (Source: The Authors

Figure *7*).



Source: The Authors

Figure 7: Depiction of Upstream and Downstream Dependencies of the Electricity Sector, Centered around Equipment Function (arrows follow the same pattern as in earlier figures).

Through interviews, workshops, and the iterative visualization process, we strove to capture the most critical upstream inputs and downstream outputs for each lifeline and the connections among them. From these discussions and analyses, four important cross-sectoral findings emerged:

- *Energy and telecommunication are critically connected to each other and to other lifelines – an example of a feedback loop.* Because communication depends on electricity and electricity depends on communication, any one communication [or electrical] failure can snowball into bigger communication [or electrical] failures. Their ability to function both during short-term emergencies and longer-term recovery is critical for a functioning community. Priority needs to be put on ensuring redundancy and reliability of communication systems – for each and among all lifelines.

- *Emergency management and public health services depend on inputs from all lifelines to be effective*. Their functioning is especially linked to reliable telecommunication and energy provision.

- *Workforce availability is dependent on many different upstream lifelines.* This is another example of a feedback loop – it is one of the key pathways through which failures in one lifeline can cascade to another. The ability for workers to get to their respective sites of employment (and/or to be able to perform their work responsibilities from remote locations) so that they can dispatch their responsibilities is critical for effective functioning of all lifelines. Moreover, outdoors maintenance workers are directly exposed to potentially hazardous conditions, such as high heat, wildfire, or flooding.

- *Maintaining a state of good repair on all equipment is essential to smooth functioning of all lifelines.* All lifelines require functioning equipment that is in a state of good repair. This underscores the importance and urgency of ongoing discussions in the US on infrastructure maintenance and investments.

After establishing the connections across sectors, we explored vulnerabilities to climate extremes using interviews and workshops.

4.2 Climate Vulnerabilities of the Interconnected Lifeline System of the L.A. Region

Throughout the course of this study, we worked with the TAG and key stakeholders to identify each lifelines' exposure to present-day and future climate change related impacts and extremes (Table 5). While a detailed, comprehensive vulnerability assessment was not undertaken, this exercise allowed us to identify an initial subset of vulnerabilities to climate change among the various lifelines.

Table 5a: Overview of Climate Change Impacts and Extreme Events to the Energy Lifeline

	Climate Change Impacts						
Node	**Coastal Erosion**	**Coastal Flooding / Sea Level Rise**	**Drought**	**Wildfire**	**Increasing Heat**	**Wind**	**Change in Precipitation**
Distribution Lines	Infrastructure impacted if located in coastal zone			Lines / poles can burn down/melt	Daytime heat - excess demand; nighttime heat - impacts transformer recovery	Blow over poles/lines; blown over vegetation can lines/poles	Potential for lightning strike during severe rain storms
Transmission Lines	Infrastructure impacted if located in coastal zone			Lines / poles can burn down/melt	Daytime heat - excess demand; nighttime heat - transformers can't cool down	Blow over poles/lines; blow over vegetation that impacts lines/poles	Potential for lightning strike during severe rain storms
Steam Power Generation	Infrastructure impacted if located in coastal zone	Infrastructure impacted if located in coastal zone	Overdrawn groundwater	More particles in water, impacts filtration	High heat decreases efficiency		
Utility-scale Solar					High heat decreases efficiency		
Hydropower Generation	Infrastructure impacted if located in coastal zone	Infrastructure impacted if located in coastal zone	Impacts available reserves	More particles in water, impacts filtration			Increased run-off to ocean, impacts available reserves

Source: The Authors

Table 5b: Overview of Climate Change Impacts and Extreme Events to the Transportation Lifeline

	Climate Change Impacts						
Node	**Coastal Erosion**	**Coastal Flooding / Sea Level Rise**	**Drought**	**Wildfire**	**Increasing Heat**	**Wind**	**Change in Precipitation**
Highway System Reliability	Erosion of roads and associated supporting infrastructure	Flooding of roads; scour of associated supporting infrastructure		Road-related infrastructure (traffic lights, culverts) directly impacted by wildfire; indirectly by landslides following fire	High heat impacts infrastructure (culverts, pavement)	Potential impact on bridges	Potential for street flooding during peak runoff events
Light Rail Reliability	Erosion of tracks and associated supporting infrastructure	Flooding of rail lines		Rail-related infrastructure (overhead electric cables) directly impacted by wildfire; indirectly by landslides following fire	High heat impacts infrastructure (tracks / electrical grid disruption)		Potential for track flooding during peak runoff events
Rail Reliability	Erosion of tracks and associated supporting infrastructure	Flooding of rail lines		Rail-related infrastructure (overhead electric cables) directly impacted by wildfire; indirectly by landslides following fire	High heat impacts infrastructure (tracks / electrical grid disruption)		Potential for track flooding during peak runoff events

Bus Reliability	Erosion of roads and associated supporting infrastructure	Flooding of roads			High heat impacts infrastructure (culverts, pavement)		Potential for street flooding during peak runoff events
Ports - Goods Movement	Erosion of roads and associated supporting infrastructure	Flooding of roads and rail			High heat impacts infrastructure (see above rail / roads)		Potential for street / track flooding during peak runoff events
Airports - Passenger and goods movement		Flooding of runways, roads and associated buildings	Airlines only permitted to land if there is sufficient water to recharge planes	Smoke may impact visibility	Higher temperatures and high heat extremes require longer runways (to gain necessary lift for take-off)	Impact on air traffic	Extreme rainfall can impact air traffic

Source: The Authors

Table 5c: Overview of Climate Change Impacts and Extreme Events to the Water Lifeline

	Climate Change Impacts					
Node	**Coastal Erosion**	**Coastal Flooding / Sea Level Rise**	**Drought**	**Fire**	**Increasing Heat**	**Change in Precipitation**
Snowpack			Loss of snowpack reduces slow release water storage	Less snow and earlier melting of snowpack increases wildfire hazard	Higher temperatures render precipitation as rainfall; immediate runoff; loss of storage	Reduction in snowpack - less water stored; snow later in year leads could lead to rapid runoff that cannot be stored, lose water to ocean
Colorado River Flow			Less water in Colorado River		Increases in evaporative loss	Reduction in snowpack - less water stored; snow later in year leads could lead to rapid runoff that cannot be stored, lose water to ocean
San Joaquin Delta Function		Saltwater intrusion to Delta	Less water in Delta; subsidence from overdraft		Higher heat increase drying of wetlands; increases in oxidation/sinking	High rainfall/fresh-water run-off events temporarily stave off saltwater intrusion; earlier runoff impacts timing and location of freshwater/saltwate r interface
Aqueducts			Less water in aqueducts; vulnerable to subsidence from			Less water in reservoir (see below) - leading to

			overdraft in aquifers & Delta			less water in aqueduct
Reservoir Stock	Infrastructure in coastal zone impacted	Infrastructure in coastal zone impacted	Diminished water during drought	Ash from wildfire can contaminate/ choke reservoirs	Increases in evaporative loss	Diminished storage with rapid run-off
In-Basin Aquifer Stock		Potential for saltwater intrusion if in coastal zone	Overdraft during drought years; leads to subsidence in aquifer & Delta			Diminished infiltration with rapid run-off

Source: The Authors

Table 5d: Overview of Climate Change Impacts and Extreme Events to the Telecommunication Lifeline

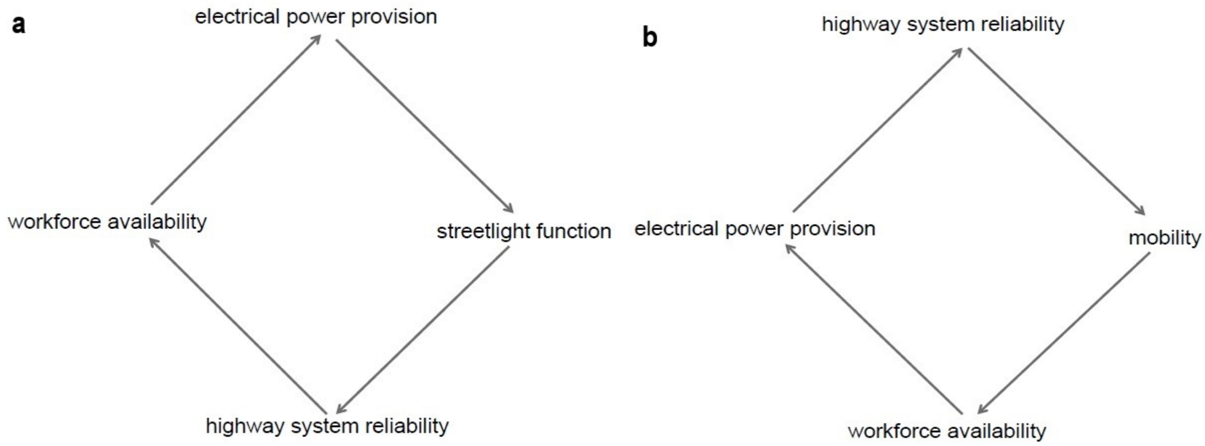
	Climate Change Impacts					
Node	**Coastal Erosion**	**Coastal Flooding / Sea Level Rise**	**Fire**	**Increasing Heat**	**Wind**	**Change in Precipitation**
Wireless Switches	Infrastructure impacted if located in coastal zone	Infrastructure impacted if located in coastal zone	Switches can burn down/ melt	High heat decreases efficiency		
Cell Sites / Small Sites	Infrastructure impacted if located in coastal zone	Infrastructure impacted if located in coastal zone				Extreme rainfall and runoff (flashfloods) can cause scour affecting cellphone tower sites
Fiber Cables	Infrastructure impacted if located in coastal zone	Flooding can make access to underground cables for maintenance difficult	Aboveground cables can burn down/melt		Aboveground cables can be blown over; blown over vegetation can impact cables	
Transoceanic Landings	Erosion can expose landing sites	Vulnerable to flooding along coast				

Source: The Authors

4.2.1 First-Degree Climate Exposures of Lifelines and Downstream Cascading Impacts

An important first observation is that many climate impacts affect multiple lifelines; thus, each of these lifelines will respond to each impact on their own services and assets, potentially limiting their availability to be responsive to the needs of other lifelines. On the other hand, without simultaneously addressing each lifeline's impacts, they could not serve each other at all. Existing interconnections can lead to cascading downstream impacts that reverberate throughout the entire lifeline system. Here, we use the example of a wildfire to illustrate how one climate impact (wildfire) can reverberate throughout the lifelines and subsequently lead to a suite of secondary impacts and feedback loops. As we describe each step in the path, the associated lifelines (as mapped in the Elephant Builder) are identified in parentheses:

- During a wildfire, transmission lines, distribution lines, and substations located in exposed/affected areas can burn down and/or other important equipment can melt, leading to local power disruptions (*electrical services provision);*
- If the lines are in a remote location, it could take time to access the affected area, leading to subsequent power disruptions and load imbalances. Slow access to remote sites can be due to geographic distance, difficult travel conditions, or transportation corridors also being impacted by the wildfire and rendered impassable (*electrical services provision, highway system reliability);*
- With downed power lines, streetlight function could also be reduced, leading to mobility issues and thus impacting the ability for workers (from any lifeline) to get to their respective emergency operations centers, normal work locations, or remote emergency work locations (*electrical power provision, streetlight function, highway system reliability, workforce availability*, Source: The Authors **Figure 8**);
- Community members in the affected area are dependent on receiving communications and instructions from emergency managers to know if/when they should evacuate. Often, electricity and telecommunication lines are co-located. Thus, one can assume that telecommunication lines will also be exposed to the fire; burnt/burning poles and/or cell towers impacted by the wildfire can impact the ability of local residents to access internet, TV, or cell/Voice Over Internet Protocol (VOIP) communication systems. Lack of communication can lead to either:
    - Local community members not recognizing the immediate danger they are in; they then choose to stay in their homes and are placed in immediate danger. This can either lead to injuries or loss of life or the need to engage first responders for search and rescue (*telecommunication reliability, emergency services provision, first responder availability, morbidity and death*); and/or
    - Local community members do not know if they are in a danger zone. Mass panic and evacuations lead to traffic congestion on roads that are needed by firefighters or that limit those truly in harm's way from evacuating in a timely manner (*highway system reliability, telecommunication reliability, emergency services provision, first responder availability, morbidity and death).*



Source: The Authors

Figure 8: Reinforcing Loops Demonstrating the Impact of Electrical Power Provision on Different Sectoral Functions: a) Electrical power impacts streetlight function, which in turn impacts highway system reliability and then impacts workforce availability; and b) highway system reliability disruption impacts mobility, then impacts workforce availability, feeding back into impacts to electrical power provision.

California communities have battled and responded to wildfires for as long as the state has been populated. All emergency managers are trained to respond to these types of events (among others) by employing Incident Command System (ICS) protocols as well as the California-specific Standardized Emergency Management System (SEMS), which have playbooks for how to respond to these types of natural disasters. During the interviews, emergency managers, public health officials, and other lifeline representatives discussed how they participate in tabletop exercises and full-scale exercises, as well as trainings, to be prepared for response during a wildfire. But, as noted by one of our stakeholders, plans do not account for surprises that arise during disasters. Moreover, another workshop participant noted that the injects – or the inclusion of realistic scenarios – during tabletops and full-scale exercises are usually only sector-specific. The different sectors are brought together for the exercise, but the scenarios are not cross-sector. Thus, these types of trainings do not go far enough at present. In the 2017 Sonoma County and Ventura/Santa Barbara fires, variations of the above scenario played out (St. Paul 2017). Full after-action reports are not yet available for review, but they are expected to include an analysis of the communication challenges encountered. Interviews with emergency management professionals following both events point to how quickly these weather/climate events can escalate.

One can imagine any number of scenarios that cascade from just these few listed above**.** Through the causal complexities elucidated through our discussions and mapping with the Elephant Builder, we identified 139 nodes (see Appendix C for list of identified nodes) with 343 connections, 17,158 unique loops and countless potential paths among any of the 139 nodes. This map now exists for the L.A. region and is available to be queried by all L.A. City lifeline managers[26]. To elucidate the loops and pathways above, for instance, we asked: What are the pathways downstream of fire? L.A. lifeline managers – independently and across sectors – could ask this (and similar questions) and then review these loops and assess where capacity within L.A. is sufficient, and where more attention/resources should be focused (see Box 4 in Section 5.3.3 for the example of the Southern California Critical Lifelines Workgroup).

While we did the best initial pass that we could in identifying all the various lifelines and interconnections – pulled from the sector interviews and the workshop exercises – this map would also benefit from review and updating by all lifeline managers to make it reflect the L.A. lifeline landscape to the best extent possible. But, of course, the Elephant Builder modeling on its own (or even the most complicated telecoupling modeling) will not solve the potential disruptions among the various lifelines on its own; it is merely a mean to an end. Ultimately, all such mapping exercises are dialogue support systems that facilitate conversations among lifeline managers to improve coordination and hopefully preempt the loss of life and property as we move forward into an uncertain climate future. Indeed, when the TAG and stakeholders were asked to identify what the biggest takeaway or lesson learned from these workshops, most indicated that just being in the room with other subject matter experts and exploring these potential interconnections together was the most valuable takeaway. Many publicly committed to work to establish inter-lifeline working groups to continue these important discussions.

4.2.2 Duration of Climate Impacts

The duration of individual weather/climate impacts will have important consequences for the ability of the lifelines to deliver the services they are required to provide. At the first workshop, stakeholders were presented with a scenario in which a growing heatwave over Colorado led to disruptions of power to the L.A. region for 1, 3, and 8 days. Each sector was asked to describe how the length of these power outages would impact their own lifeline; subsequent discussions focused on how these individual lifeline disruptions could impact other lifelines downstream.

4.2.2.1 One to Three-Day of Power Disruption

Between 1-3 days of power outage, most stakeholders felt comfortable that their various lifelines were either equipped or had considered the contingency plans for dealing with a power outage of this length. The most challenging issue anticipated was not knowing what caused the outage at first or how long it would take to restore power. A selection of important discussion points is summarized below.

Impacts to Electrical Power Provision

- 24 hours is not enough time to get back-up generators to prioritized recipients so critical lifelines are on their own for the first 24 hours. The California Independent System Operator (Cal-ISO) will tell the affected utilities how much load to shed; the Emergency Management Department (EMD) will tell the utilities the order in which they should shed loads to minimize disruptions to critical lifelines (to the extent that is possible);

[26] Contact Dr. Juliette Hart (jfinzihart@usgs.gov) for access to the Elephant Builder and for further information on initial analyses which are not fully described in this report.

- After three days, power generators can be moved to key locations for protection of life and safety (e.g., libraries as cooling centers);

Impacts to Transportation

- For the first 24 hours, the assumption is that light rail or highway systems may be impacted so people who are at work don't go home; people who are at home don't go to work;

- Lack of functioning traffic lights increase the possibility of traffic gridlock;

- Most gas stations do not have back-up generators, which will impact the ability for people to get gas if they need to evacuate due to an associated emergency. There are publicly-owned gas stations, however, that prioritize government operation vehicles;

- Needed emergency workers may not be able to get to emergency sites when needed;

Impacts to Telecommunication

- Assuming traditional communication modes (phone, cellular, internet) go down, if you have enough gas in your car, you can get information over car radio. Even if electricity is out, emergency managers will still give press conferences in the hopes that people will be able to find some way of getting the information;

- While the internet is still working, the assumption is that people can access Twitter or Facebook to get real time information about evacuations and gathering sites;

- While cellular systems are still functioning, reverse 911 or some other city/county-based communications system will be able to provide community members with the relevant information;

Impacts to Emergency Services

- L.A. has 43 school districts. Some are so large that parents may not be able to come get their children; children will need to shelter in place. Department of Public Services deals with unattended minors if they are not picked up within 24 hours. Parents and children (at school) may be separated for extended periods of time;

- Emergency management coordinates with Red Cross to set up food sites;

- High demand on firefighters and other first responders requires that EMD ensures they have enough water and safe food;

- Displaced people need to be sheltered in places that provide cooling, have sufficient water supplies, and are properly equipped;

Impacts to Public Health

- Department of Public Health (DPH) will close all food service facilities (restaurants etc.) as lack of refrigeration results in food safety issues;

- By day 3:

  - DPH coordinates with Emergency Management to inform people of how/where to get food and to check food safety. Order food supplies from outside via existing agreements for emergencies;
  - DPH needs to do inspections in the middle of an emergency to ensure the food is safe;

Impacts to Health Services

- Most hospitals should have back-up power for critical operations at the hospital (i.e., red outlets that are connected directly to back-up systems). The assumption is that the back-up systems will have enough fuel to run for a 24-hour period and that the systems have been tested on a regular basis to ensure they will function during an emergency;
- After three days, hospital administrators will begin to be concerned about the ability of clinics and hospitals to handle additional cases.

4.2.2.2 Eight Days of Power Disruption

A clear tipping point emerged among all of the City's lifelines between days 3 and 8 of continued power disruption. The scenario specified that the L.A. region would be increasingly affected by growing cooling needs as the heat wave spread over the region into the L.A. region. Thus, dwindling supplies were met with growing needs for essential life support.

The most pressing impact is that at this point, the city reserves of water will begin to run out. Municipal water supplies will no longer be considered safe as energy is needed to filter and treat water. Individual residents will then need to be supplied with either bottled water or propane so that they can boil their own water. But whether either can be supplied from outside in sufficient quantities will depend on how much longer the outage persists.

The ability to bring in supplies also begins to become more challenging. However, assuming transportation corridors are functioning (at least for emergency personnel) and planning agreements are in place in advance of the emergency, 8 days provides enough time for resources to be mobilized from afar and transported into the region.

Beyond day 3, it is assumed that those who can get out of the area will evacuate on their own. Those who cannot – or will not – evacuate will make their current situation work to the best extent that they can. However, the longer the power outage, the more concerns there are with people dying in their homes, especially those with chronic health conditions, the elderly, and very young children. For those in shelters, without proper maintenance and oversight, shelters can become sites of infection if not properly managed. It is also expected that by this stage, community stability will start to degrade and the threat of riots and/or civil unrest will escalate.

During other workshop discussions study participants felt strongly that the degree of vulnerability and the ability to respond to such crises depends in essential ways on the strength of governance across departments and at the highest levels. While strong governance affects levels of preparedness, it also can provide trustworthy leadership in prolonged durations – an essential quality that may help prevent complete chaos and civic unrest. Highly effective and transparent communication is a similarly crucial component of emergency response and will be essential in such an extreme situation.

Thus, while a short-lived climate event that leads to a 1- to 3-day disruption in critical lifelines poses challenges, a prolonged event lasting many days – such as a heatwave over the entire western US and uncontrolled forest fires or heavy precipitation events that lead to debris flows (also referred to mud- or landslides) –taxes the critical lifeline system potentially to its breaking point. Similarly, multiple repeat short-lived events in a short timeframe can pose equal challenges as resources to all the lifelines may not be fully restored before they are responding to yet another emergency. In this way, sequences of extreme events can undermine coping and adaptive capacity.

4.2.3 Combination and Sequence of Climate Impacts

Recognizing that most future climate impacts will not occur in isolation, it is equally important to understand which combination and sequences of events are considered the most disruptive to lifelines, both alone and in the system together. Below, we identify the scenarios described by the TAG that are the most threatening.

4.2.3.1 Heat/Drought Followed by Wildfire followed by Heavy Precipitation, Flooding and Landslides

All lifeline experts identified the combination of increased heat during a drought year, leading to enhanced wildfire risk, followed by heavy precipitation, heavy runoff, and flooding (and possibly followed by landslides) as one of the most potentially disruptive combination of weather/climate events. Collection of the data for this workshop occurred before just such a sequence of events unfolded in Fall 2017/Winter 2018 in Ventura and Santa Barbara counties. The loss of lives and property was considerable but it is too soon for cost estimates of total damages. With the projected trends in climate for this region (e.g., increasing temperatures and more extreme drought cycles, followed by heavy rain events), this combination of events is a crucial one for which to develop better forecasting and improve preparedness in the coming decades.

4.2.3.2 Sea-Level Rise, Coastal Storms and Coastal Erosion

Most of the discussion during the workshops was focused on heat / drought / fire since these were determined by the TAG and stakeholders as the most critical to the electrical grid. However, the confluence of sea-level rise, increasing "sunny day" tidal flooding, and increased coastal erosion from the above in tandem with coastal wave-driven storms, can cause serious impacts to critical infrastructure located along the coast (e.g., data storage ("cloud") centers, substations, roads). Further, these chronic changes in combination with increased riverine flooding during heavy rainfall events would only exacerbate potential impacts.

4.3 Long-Distance (Teleconnected) Exposure to Climate Change and its Implications

As local climate impacts can lead to on-site and cascading lifeline disruptions, it is also important to identify each lifeline's upstream, long-distance (teleconnected) exposure to climate change as these impacts will ripple through the system and affect the downstream utility's functionality. Depending on whether that upstream impact could be managed effectively or not, further downstream impacts may then ensue.

All lifelines have dependence on materials and supplies (i.e., the *substance* – or "data" – as described in our teleconnections framework, section 3.2.2) and the effective transfer of these substances through the *structures* ("hardware") and causal *processes* ("software") that are in place (Figure 6). Each of these various components are vulnerable to climate impacts. We identify some key teleconnections for each lifeline below. As possible and appropriate, we discuss the teleconnections in relation to whether they are impacting a process, substance, or structure. It is interesting to note, however, that most of the examples are vulnerabilities to substances or structures. Processes, and the actors and institutions associated with those processes, are more likely to be directly affected at the local scale. While this list is not comprehensive, these are the teleconnections that were identified by stakeholders as most critical and as such are a good starting point as priorities for independent and cross-lifeline discussion and planning.

4.3.1 Energy Systems

4.3.1.1 Energy Substances Vulnerable to Climate Change

There are several key components utilized in energy provision that originate overseas and thus are vulnerable to climate-related teleconnected impacts. For instance, conductors are often made in the U.S., but the aluminum utilized in the conductors generally comes from one of two locations overseas (Chile or Argentina). This means that as local utilities run out of aluminum to build more conductors, they are dependent on timely delivery of aluminum from either of these countries. Climate change can impact many different parts of this supply chain:

- The sites where the aluminum is extracted, for example by limiting either the ability to extract the aluminum or the ability of workers to get to extraction sites,
- Raw material is processed into the aluminum grade needed for the final product,
- The transport of the extracted aluminum from the mine to a shipping facility so that it can be sent to the U.S. Local rail/tracks, roads, etc. are vulnerable to all local climate impacts in the same way as we describe above for City of L.A. systems,
- Once arriving in the U.S., transport of the aluminum to the factory where conductors are manufactured are also vulnerable to local climate impacts to the rail/tracks, road etc. along the transportation route as described here for L.A.
- Once manufactured, delivery of the conductors to the utility in need can again be impacted by all the local climate impacts along the delivery route.

As another example of upstream supply chain teleconnections, transformers are designed to the specifications of individual utilities and are not generally made in the U.S. Utilities will often have reserves of "critical spares." However, with climate change and the potential concatenation of events as described above, the number of spare transformers may not be sufficient for response, in part because they are very expensive. Equally, as more transformers are needed, delivery of these transformers are then subject to the local climate impacts from the site of origin to the delivery point as described above for conductors. Moreover, competition for the production of parts may either increase delays or cost.

4.3.1.2 Energy Structures Vulnerable to Climate Change

Local utilities (e.g., SCE) only generate a small fraction of the energy that is distributed to their customers locally. The energy that ultimately reaches each household can originate from out of state, and due to the distribution of energy through the regional coordination councils, potentially reach far across the country and into Canada. We discuss the regulatory pathway below when describing the processes and governance, but from energy generation to local distribution, there are a multitude of electrical grid assets that are vulnerable to local climate impacts; each component is again vulnerable locally as described for the L.A. region, i.e., power lines in the Southwest are vulnerable to the impacts from increasing high heat, drought, and wildfires, just as they are in L.A.

4.3.1.3 Energy Processes Vulnerable to Climate Change

While the ultimate cause for the energy sector lies in the industrialization of society and the dependence on energy for all its activities, the specific ways in which power is generated, distributed and, managed ties back to energy policies and the institutions that govern the process. In fact, energy generation and transmission are regulated by a suite of interconnected regulatory agencies. At the federal level, the FERC "is an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC also reviews proposals to build liquefied natural gas (LNG) terminals and interstate natural gas pipelines as well as licensing hydropower projects." FERC's role is to manage the pricing and loading order; i.e., who is able to come onto the transmission lines and their load. The NERC is overseen and regulated by FERC as well as Canadian and Mexican authorities as they have regions in both of those countries. Their role is to oversee the reliability of the electricity system and they do so through a series of seven Coordinating Councils across North America. California participates in the Western Electricity Coordinating Council (WECC). The WECC ensures that all transmission lines are operating effectively. Ultimately, once electricity crosses the CA state line, California Independent System Operator (CalISO or CAISO) manages the generation and transmission dispatch across the regional electricity pool generation and transmission dispatch across the regional electricity pool. For the L.A. region, SCE and DWP then distribute the electricity to the customers.

Each one of these organizations manages different portions of the full electrical grid; thus, managing for the local impacts of climate change at any point along these interconnected systems is dependent on how the organization at that point in the grid responds to climate change. Most are committed to developing renewable energy to help mitigate the effects of climate change. For instance, as noted on its webpage, CAISO "is committed to supporting important energy and environmental policies while maintaining reliability through a resilient power grid system. "[27] The WECC conducted an assessment of climate change risks to energy reliability in its region (Helmuth et al. 2014). The DOE also conducted a study on the U.S. energy sectors vulnerabilities to climate change and extreme weather (DOE 2013). However, there are few publicly accessible adaptation plans for these organizations so, at the time of this report, it is difficult to discern if there are concrete actions in place to respond to the vulnerabilities that have been identified. This warrants further exploration in subsequent work.

[27] See: http://www.caiso.com/informed/Pages/CleanGrid/default.aspx,

4.3.2 Water Systems

4.3.2.1 Water Substances Vulnerable to Climate Change

The substance most vulnerable to climate change is, of course, water. With increasing drought, the availability of water in reservoirs and natural reserves will be diminished. Changes in precipitation patterns, such as a decrease in snowpack and more frequent heavy rainfall events, will impact run-off and storage capabilities across the state, thereby also impacting water reserves. For the City of L.A., which is currently predominately dependent on external water sources, these teleconnected climate impacts will decrease water availabity within L.A.

Water will also be impacted in terms of quality through climate change-related processes such as saltwater intrusion in coastal areas, resulting in either additional needs for water treatment or diminished supplies of drinking water.

4.3.2.2. Water Structures Vulnerable to Climate Change

Stakeholders observed in the workshop that at present, and even without considering further climate change, the CA aqueduct's capacity is diminished by half due to subsidence caused by heavy aquifer pumping during the drought. Subsidence also affects levee stability and the level of protection they afford against flooding. As droughts occur more frequently and persist for longer, subsidence is expected to increase, aggravating existing "hardware" challenges.

Another example is related to water pipe repairs. Currently, no steel is being manufactured in California. Water distribution pipe repairs and upgrades must therefore rely on steel from other areas. As with the energy sector, it is possible to stockpile a variety of pipes, but water utilities must balance costs associated with stockpiling as well as the challenge of finding limited space to store these pipes in the L.A. region. As steel and/or pipes are imported from elsewhere, they are vulnerable to the climate impacts at their site of origin. In addition, study participants suggested a potential lack of steel in California could have the cascading impacts of affecting structures important for water purveyance and availability.

4.3.3.3 Water Processes Vulnerable to Climate Change

California recently made the water conservation rules established during the 5-year drought permanent (see AB 1668[28] and SB 606[29]). This is an example of how governance – as a process – can affect the flow of water. Similarly, L.A. decided to decrease its reliance on imported water (GLAC Region Leadership Committee 2014)[30], and instead become more reliant on local water sources. This implies significant investment in water recycling/reuse infrastructure as well as related activities to make water reuse publicly acceptable. But in the face of climate change, this could diminish the region's vulnerability to fluctuations in water availability far away.

---

[28] See: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB1668.

[29] See: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB606.

[30] See also: http://h2o4la.com/ and http://dpw.lacounty.gov/wmd/irwmp/About.aspx.

Previously, we discussed how climate change itself can cause shifts in supply and demand, thereby affecting the price of water and the ability of different customers to afford purchasing water for their diverse uses (e.g., urban versus agricultural users).

4.3.3 Telecommunication Systems

4.3.3.1 Telecommunication Substances Vulnerable to Climate Change

The substances, or "data," being transported in the telecommunications context, of course, is data and information. Due to the limited involvement of the telecommunications sector in our study, we have only limited insights on the different teleconnections components in this sector. We are not aware of a direct climate change impact on information itself. (Only in the most indirect sense and via many intervening variables, one might argue that climate change as a cultural and political phenomenon, has been a major contributor to the "post-truth" era in which we now live, thus undermining the quality and reliability of the information being conveyed.)

Workshop participants did make the connection to cyberattacks and the consequent lack of data transmittal, insecure data transmittal, or transmittal of viruses and trojan horses – a good example of how preparedness for one type of hazard is linked to (though does not necessarily substitute for) preparedness for another.

4.3.3.2 Telecommunication Structures Vulnerable to Climate Change

There are seven fiber optic lines that service California, all of which are co-located with other infrastructure (five along major highways and two along railways, Source: Paul Banford (replicated in Business Insider)

Figure *9*) and cross a variety of ecoregions, each vulnerable to climate impacts in their own ways. One subset has a hub at Salt Lake City and diverges as it enters California alongside I-80 around Mystic, CA near Lake Tahoe (High Sierra Mountain range) and another enters California along I-15 near the Mojave National Preserve (high desert). One other subset of lines travels along the US/Mexico Border entering California near Yuma, AZ (Sonoran Desert ecoregion). Each of these lines are vulnerable to different climate impacts along the length of their lines – e.g., high heat and wildfire exposure throughout the state. Equally, the transoceanic cable landings and cables located in the coastal zone are vulnerable to impacts of coastal erosion and flooding from sea-level rise.

Another type of structure vulnerable to climate change impacts is "the cloud," i.e. data storage centers. As one interviewee put it, "the cloud is in the ground." What was meant is that data storage centers – highly reliant on water used for cooling – are frequently located along coastal waters, and as such become increasingly vulnerable to flooding and inundation.

Source: Paul Banford (replicated in Business Insider)

Figure 9: Snapshot of the Fiber Optic Cables that Cross the United States

4.3.3.3 Telecommunication Processes Vulnerable to Climate Change

A number of regulatory and governance issues, which – while not directly related to climate change – were identified that can increase the vulnerability of the structures and substances to climate impacts. For instance, a relaxation of regulations has had the effect of leading to poor workmanship. If poles or assets are not built to the right standards, they will likely be less resilient to climate stressors. Current rules favor rebuilding telephone poles or cell phone towers damaged in a wildfire or storm to pre-existing conditions rather than upgrading them to less fire-prone or wind damage-prone replacements.

As another example, the lack of an open data policy impacts the ability of different utilities to share information about assets during emergencies. This hampers the ability to quickly respond or plan ahead in close coordination with other lifeline sectors.

4.3.4 Emergency Management

4.3.4.1 Emergency Management Substances Vulnerable to Climate Change

During emergencies, through points of distribution (or PODs) emergency managers are expected to be able to provide access to food, water, and medical supplies, among other critical lifesaving substances. Many of these supplies can be stored for some amount of time, but as with all supplies, a determination must be made on how many supplies can be stored and still be cost effective. Emergency managers are then also dependent on supplies coming in, especially as the length of the emergency increases. The City of L.A.'s Emergency Management Department proactively conducted a supply chain dependencies assessment for a suite of sectors critical to effective emergency services provision. They examined the supply of fuel/gas, food provision, consumable medical supplies, pharmaceutical supplies, and water. In this effort, they formed relationships with suppliers and developed formal agreements that specify what they need from each supplier. One notable finding from this study is that most food enters the L.A. region through San Bernardino. The lack of redundancy in food shipment routes into L.A.

is a source of considerable vulnerability should there be a massive wildfire or other climate impact that impacts transportation / rail routes in that area.

Most pharmaceuticals, whether distributed by emergency services during events or via health service professionals on a daily basis, come from outside the L.A. region. The medical supply chain is particularly vulnerable to teleconnected climate impacts as many pharmaceuticals are developed in only a small number of locations. This has recently received media attention following the crippling of lifelines on Puerto Rico following Hurricane Maria. The U.S. Food and Drug Administration identified 30 "critical" products that are made on Puerto Rico, 14 of which are only made there. During this winter's particularly virulent flu season, ill people flocked to emergency rooms in L.A. and throughout the U.S., hospitals experienced a shortage of IV bags and parenteral solutions. This combination of a weather/climate impact that occurred far from the shores of Los Angeles, had therefore potentially life-threatening impacts during a concurrent flu outbreak.

Another "substance" that needs to be able to freely and quickly move around in case of emergency are emergency personnel. This essential link in effective disaster response points to the reliance on functioning communication, transportation, food and water to support the work of first responders and emergency management personnel.

4.3.4.2 Emergency Management Structures Vulnerable to Climate Change

According to the California Emergency Response Infrastructure Climate Vulnerability Tool[31] – a research project conducted in parallel to this study for California's Fourth Climate Assessment – L.A. County has 100 emergency management facilities, 252 fire service facilities, and 80 health care and public health facilities. Some of these are located in flood zones, others could be impacted directly by wildfire. While the threat to physical structures was perceived as smaller relative to threats to processes and substance, the critical importance of these structures in case of emergency requires ongoing vigilance and efforts to maintain them in a state of good repair, so that they can reliably function when they are most needed.

4.3.4.3 Emergency Management Processes Vulnerable to Climate Change

Municipal budgets are often a battleground for competing interests. Stakeholders noted that during the financial crisis in L.A. in the late 2000s, a number of city agency budgets – as well as entire departments – were cut. The City's Emergency Management Department (EMD) – a department with less political clout than, say, the Police Department – was one of those agencies which had severe staffing and budget cuts. Staff levels have remained very low since – disproportionately low given the size of the population they are mandated to protect. Without adequate staffing and funding, EMD – as with any other downsized agency – will have to make decisions on what to prioritize. Interviewees suggested EMD is at its financial and staffing limits today. And while it can draw on other City and County personnel in emergencies to help out, most other city and county personnel are not trained emergency first responders and cannot take on the crucial coordination roles required in disasters. Thus, there is enormous pressure for just over two dozen of EMD staff to maintain proper functionality – a number clearly insufficient for a long-duration event as explored in our scenario exercise.

---

[31] See: https://public.tableau.com/profile/rand4185#!/vizhome/CJ302-1000_CERI-Climate_20180227/Title.

As the need to respond to more frequent extreme heat events, fires, and other emergencies increases, the budgetary and staff constraints diminish the critical role EMD can play in L.A., leading to a more vulnerable population, with all the ensuing cascading effects that can arise from this.

4.4 The Daily Work of Ensuring System Reliability

While most of the stakeholder interviews and discussions were focused on what could go wrong, there was also considerable discussion about the safeguarding practices that are in place to ensure system reliability. The energy lifeline – as well as other lifelines – have many procedures, technologies, and systems in place at present to respond to disruptions and emergencies. During longer-lasting or predictable electricity disruptions, the energy utilities can plan in advance and have rotating power outages to manage load balances accordingly. While this may frustrate customers during the planned outage, this management system allows the load to be managed and stay balanced, limiting the potential for more severe disruptions. Similarly, even if the timing of a potential disruption is unknown, if the event is something the utility has experienced before, they often have procedures in place to plan. This usually entails some variation of:

- trouble call comes in;
- computer algorithms reroute electricity to minimize customer impact (e.g., load shedding in order to avoid damage to equipment);
- human control-room operator oversees/alters procedures as need arises;
- problem is diagnosed; and,
- crews are dispatched to fix problem, clean and replace equipment.

For weather-related events that occur with some predictability (e.g., when it will occur, for how long and how severe), work can be done in advance to plan. The plan usually entails:

- setting up alternative pathways for electricity to flow in response to the coming problem in the control room; while,
- staging equipment in needed areas, giving people time off prior to event because they will be needed later, moving suppliers to potentially affected regions, and moving equipment to warehouses.

The biggest challenge is when there is a whole system breakdown and the system needs to get back up and running (a.k.a. "black starter"), because it takes electricity to generate electricity. These events are rare (for instance, one occurred during the Northridge earthquake (1994)), but when they do occur, there are procedures in place to bring the system back up to full function. They involve:

- visiting and checking all stations;
- once transformers are deemed safe for operation, checking all lines;
- checking receiving stations to ensure they are functioning; and,

- checking the distribution.

Should an event exceed the capacity of the local utility to manage the disruption, all energy utilities have mutual aid agreements in place (largely formalized, written agreements) with both neighboring utility companies and beyond.[32] Utilities are actively considering different ways to make mutual aid most effective. For instance, rather than having crews drive across the country to provide support, there is now discussion of a “bucket brigade” approach. For instance, if a fire occurs in L.A., utility workers from Arizona could come to support the CA utility. Utility workers from another state (e.g., New Mexico or Texas) would then come to fill in in Arizona to support on site utility operations while the local workers were deployed, and so. Similar emergency procedures are in place for other sectors, with unique variations.[33]

Most of the lifeline representatives interviewed (Appendix A), particularly those from the energy, water, public health, and emergency management sectors, also discussed the considerable training they receive in planning for emergencies and triggering their ICS protocols. This can range from tabletop exercises exploring single events to full-scale exercises such as those conducted annually by Southern California Edison. These larger training exercises can also be bolstered by “just in time” training to quickly bring staff up to speed in advance of an emergency.

4.5 Gaps in the Interconnected Lifeline System of the L.A. Region

We close this chapter with a discussion of some of the gaps that were identified in the interviews and workshops in assessing the high-level climate vulnerabilities to the lifeline system in L.A., as well as the teleconnected and cascading impacts. Research needs and action opportunities in response to these gaps, are discussed in Chapter 5.

4.5.1 Physical Structures

As evidenced by the number of cascading impacts and upstream teleconnected impacts discussed throughout this section, ensuring a state of good repair on all infrastructure/assets for each lifeline is critical. This, of course, faces some significant challenges, not the least of which is lack of capital to fund system maintenance. The American Society of Civil Engineers (ASCE) estimates that the U.S. needs to spend of $4.5 trillion by 2025 to fix critical infrastructure (ASCE 2017).

Maintaining infrastructure becomes even more important as this critical infrastructure is exposed to more and more climate impacts. Short of resolving the deferred maintenance challenges, communities will have to spend their resources in stockpiling back-up equipment as finances allow and/or rebuilding impacted infrastructure, with the goal of building it back better. Yet a number of lifelines indicated that, following an emergency, current practice (and

[32] Similar mutual aid agreements exist among emergency management agencies. It was beyond the scope of this pilot study to examine in detail what is (and is not) covered in them, how they get established, and whether there are sectors that do not use this mechanism at all.

[33] We were not able to obtain relevant information on the telecommunication sector, thus cannot address their standard procedures.

codes) favor building back to the prior status. For instance, if a wooden utility pole burns down at a remote site that is vulnerable to wildfire, the permitting processes are structured so that it is much simpler to replace the wooden pole with another wooden pole. If the utility wanted to replace that wooden pole with a pole less prone to being burned down (e.g., a steel pole), one stakeholder estimated it would take ~10 years to get through the permitting process.

The connectors required to connect back-up generators to the power system of specific building or facilities create a physical gap in the system. They frequently do not fit, thus disallowing power to be generated and delivered even though a back-up system is present.

4.5.2 Staff Capacity

City and county budgets are always constrained, with difficult decisions being made every day on what should or should not be funded. As such, cities also struggle with finding enough resources to maintain and train existing staff. There are not even 30 staff responsible for the Emergency Management coordination of the City of L.A., a city of multiple millions!

But interviews in each sector revealed staff shortages, and sometimes highly specialized staff assignments that make it difficult to assign them to different responsibilities in case of emergencies.

Another crucial staff issue revealed through the interviews and workshops was the crucial importance to ensuring staff can get to work. Many employees do not live near their places of employment, and during emergencies their deployment may require substantial travel. If the transportation system is disrupted, the most important resource – the people – to get back up and running is hindered from coming to work.

4.5.3 Historical Legacies

In California, water rights affect everything: water availability, water management, politics, environmental regulations, and so on. As L.A. sources its water from the Colorado River, the State Water Project (SWP), Owen's Valley, and local sources, institutional arrangements and related possibilities and constraints are complex. L.A is currently attempting to increase its water self-reliance while reducing its reliance on water imports. Its long-term water management plan hinges on achieving a reduction from 80% imports down to 50% and a commensurate increase in reliance on in-basin aquifer stocks. To achieve that, however, significant groundwater clean-up needs to be achieved. Other legacies that limit the range of options and reduce fluid functionality may stem from aging infrastructure itself, e.g., when dam safety regulations restrict reservoir capacities.

4.5.4 Communication Gaps

At present, communication across lifelines dependent largely on having "friends in the right places," as one interviewee stated. Knowing someone to call in a different agency or organization, even if that person is not the right person, is better than not knowing anyone at all. Many interviewees pointed to a lack of formal communication channels and agreements as one of the most serious gaps in the interdependent lifeline system. Particularly, when decisions need to be made quickly and efficiently, unclear points of contact are potentially life threatening.

The recent experience in the December 2017 to January 2018 Santa Barbara/Ventura fires is telling: critical time passed as trained emergency response professionals had to rely on their professional judgment to determine if, when and how many communities to evacuate (St. Paul 2017).

4.5.5 Human Capital, Experience and Attitudes

When we presented the exercise scenarios at the first workshop, some participants argued over whether or not such a scenario was even plausible. With the backdrop of Hurricanes Harvey, Irma and Maria, along with the fires in Napa, Ventura, and Santa Barbara counties, followed by the catastrophic debris flows in Santa Barbara, and the preponderance of "unprecedented" types of events, with equally "unprecedented" societal teleconnection impacts, the scenario we developed may today not seem as far-fetched or as implausible as it did at the time. A fully developed scenario would need to improve the modeling of the disruptive weather events as well as of the impacted lifelines. But the response surfaced a common human response to worst-case scenarios: resistance (e.g., Yang and Kahlor 2013).

The resistance may have been fueled by the lack of experience with a serious, long-duration disaster over the last 20 years – about the extent of most study participants' professional careers. Those with relatively recent extreme event experience had a different appreciation and saw the necessity of practicing for the "worst of the worst" type of events (e.g., SCE conducts annual comprehensive exercises).

Thus, several emphasized the need for training and inculcation of skills and ways of thinking, such as accepting worst-case scenarios, calm assessment of situations, the "going the extra mile" mindset common in emergency management (but not necessarily elsewhere). A big take-away from the workshop was to build more of this capacity among more people, so that the necessary skill is available in place, and does not require moving around highly skilled people in situations when mobility may be severely restricted.

5: Conclusions and Research and Action Recommendations

5.1 Key Study Insights

Our concluding chapter mainly focuses on research needs and proposed action options. To set the stage for these recommendations, we synthesize several key high-level insights from this pilot study. The study had the following three goals:

1) to test the utility of our conceptual societal teleconnections framework as a tool to assess vulnerabilities to remote climatic events and to assist lifeline managers in preparing for climate change;
2) identify research needs and action barriers; and
3) if resolved, help other metropolitan areas and communities in California conduct similar analyses and extend their adaptation planning efforts.

To accomplish these goals, we pursued three overlapping and interdependent tasks, including:

- developing a refined understanding of lifeline system interconnections;
- delineating long-distance (teleconnected) and cascading impacts of climate impacts; and,
- exploring possible interventions, adaptive solutions, and research needs.

Here we first synthesize the key insights gained about interconnections, teleconnections and cascading impacts, emergency and adaptive interventions, and the utility of our conceptual framework before suggesting research priorities and action steps to take the important work of increasing resilience and preparedness for climate change impacts in L.A. and beyond.

5.1.1 Interconnections and Cascades

Below are the most notable insights gained from this study regarding lifeline system interconnections and cascading impacts:

- **No unified map of the interconnected lifeline system existed until this study**. At the outset of our study, we found that no unified or integrated map of the interconnected lifeline systems of the City or metropolitan area of Los Angeles existed. While each lifeline, utility or agency may have maps or digital geographic information of their respective systems, no one has attempted to integrate them into a single georeferenced information database to date. What we produced through interviews and workshop discussions with the help of the Elephant Builder thus constitutes the first attempt, albeit a mental model, not a cartographic replication of real-world systems. This mental model is already extremely complex and multi-faceted, made more complete because it integrates many people's expert system knowledge, but it also contains and reveals knowledge and awareness gaps. Several study participants wished for a secure-access, unified, integrated database to be established.
- **Functioning of the interdependent lifeline system is an emergent property without overarching control**. By contrast, as recent disasters elsewhere in the US reveal, functioning in disaster/stress situations is <u>not</u> an emergent property but must be proactively designed. Another foundational observation from this study – made with some astonishment – is the fact that no single entity is in charge of overseeing the integrated evolution of a lifeline system that consists of interrelated and interdependent sub-systems. Such an entity could, for example, formalize integrated short-term disaster preparedness and long-term adaptation planning processes, mandate joint disaster preparedness exercises, create reporting and accountability mechanisms by which modular resilience building efforts could be better coordinated, and hugely improve communication. The fact that L.A. lifelines function – under normal circumstances – as well as they do, must be understood as an emergent property of a complex system. (We make this statement fully recognizing that, in L.A., traffic congestion is infamous and well known, aging infrastructure is a pervasive problem, and the legacy of water infrastructure development connecting L.A. across the state and beyond are highly contested.) At the same time, it should be recognized that L.A. has been "lucky" in that no major region-wide disaster has stress-tested the functionality of its interdependent lifeline systems for at least 23 years (the 6.7 magnitude Northridge earthquake in

January 1994). This is longer than most utility and emergency managers have been in their current positions.

- **There are many critical interdependencies among the lifelines, and some notable gaps.** The primacy of electricity (followed closely by telecommunication) on which all other lifeline systems depend was nearly uncontested by study participants, although detailed exploration of these interdependencies revealed that not even those two could function without water or without functional transportation. A critical gap – not only in our study, but as we learned, also in other interdependent lifeline and resilience-building efforts in the region – was the difficulty of finding communication sector representatives to actively participate in our study (this was partially remedied in the second workshop). Given the significant dependence on functional communication, bringing the largely private-sector communication service providers into active engagement with other lifelines is crucial. Finally, emergency services and public health – the lifelines most immediately in charge of human safety and well-being – all depend on the proper functioning of the other lifeline systems.
- **There is an apparent overconfidence in controllability of individual (yet interconnected) lifeline systems**. While study participants much appreciated the opportunity to come together in dialogue to learn from and with each other, some participants at first exhibited a certain degree of overconfidence in the ability of their respective systems to function properly, rapidly, and effectively when faced with disruptions. They also suggested that they could take care of emerging climate adaptation needs through existing day-to-day operations over traditional (relatively short-term) planning horizons. Others thought that extensive earthquake scenario exercises already sufficiently prepared them for "the unthinkable" possibilities of climate-driven emergencies. But these attitudes seemed to shift to some degree over the course of the scenario exercises and explorations of vulnerabilities and adaptation options. Harder to influence human/social factors and governance weaknesses, as well as the rapid cascading of compound problems as multiple systems failed, shook this overconfidence to some degree. At the time, the Santa Barbara/Ventura wildfires and mudslides had not yet occurred. As headlines from other recent disasters in the US suggested, lifeline and emergency managers elsewhere had not previously been able to imagine how bad climate extremes could get. Thus, the failure to imagine the "unthinkable" and the "possible" may well be some of the most pernicious "adaptation blind spots" we actively observed.

5.1.2 Teleconnections

This study revealed the importance of teleconnections, but in general, study participants were far less aware of and concerned about them than might be warranted. This should be obvious, but was not necessarily so: somewhere else, someone else's cascading disaster (of which participants developed a serious appreciation) has become the teleconnected initiating event that could ultimately matter to L.A. because of pre-existing long-distance relationships.

- **Teleconnections have variable and overlapping geographies**. In exploring upstream, long-distance dependencies of each lifeline system and learning about the functionality of each system, we could distinguish different types of geographies:

- The *geographic extent of an entity's service area or customer base* (e.g., the transportation system serving multiple cities, the County of L.A., and even reaching into neighboring counties vs. the customer base of SCE).
- The *geographic extent of an entity's supply chain* or area from which it sources key resources, equipment, parts (e.g., conductors from China, transformers from Chile and Argentina, steel for water pipes, high-rise buildings and bridges from other US regions, water from Owen's Valley or the Colorado River watershed; sand for cement for construction from other parts of coastal California).
- The *geographic extent of its management area* (e.g., for electricity at least the Western United States, but under particular circumstances even beyond; mutual assistance agreements with others in need around the region and country).
- The *adjoining and overlapping jurisdictions involved in governance* (e.g., variably involving local, independent, regional, state, large-scale regional and federal entities)

- The teleconnections of one lifeline systems can be entirely different from those of another lifeline; however, there can also be overlaps, possibly increasing the risks to L.A. if large-scale disasters affect extensive areas in teleconnected geographies. Examples of this type of disruption include when Hurricane Katrina (2005) affected shipments in and out of Gulf ports as well as oil refining; or when the extended Midwest drought (2005, and again in 2011-12) affected shipping up and down the Mississippi River, affecting several key sectors simultaneously. Redundancies built into teleconnections can alleviate those risks, but this may be easier for some supply chains than for other teleconnections, such as layered governance systems or service areas.
- In some instances, teleconnections are already actively used and managed, such as through procurement and reliance on particular supply chains, management of electricity across a nationwide grid and associated load management technologies, or historical contracts that import water to L.A. While the teleconnection language may be unfamiliar, existing examples can help illustrate the meaning and raise awareness and interest where teleconnections are not yet seriously accounted for.
- The currently weakest parts in the teleconnections identified are the "hardware" and "software" components, i.e., the necessary and enabling components of a teleconnection. As detailed in the conceptual framework, the movement of "substances" such as food, water, infrastructure replacement parts, medical supplies, data, information, or people depend on functional "hardware" and "software." Our study revealed or re-emphasized the crucial importance of maintaining the hardware in a state of good repair (a challenge already, regardless of climate change); it also pointed to the common omission in most cases to actively coordinate priorities and procedures (the processes that would coordinate and regulate interactions) among lifelines. The exception here may be emergency management, which does this as a matter of course.

5.1.3 Climate Change Impacts, Adaptation and Preparedness for Extreme Events

The mismatch between the state of climate science and the needs of lifeline managers is not new or surprising but pronounced.

- **Climate science has made significant advances in understanding extreme events, yet aspects of greatest interest to lifeline managers are still active research frontiers.** Particularly long-duration, sequential, and concatenated or compound climate risks are least understood at this time, yet they are precisely the kinds of scenarios infrastructure managers are most concerned about and least prepared for.

- **There is a somewhat surprising lack of concern and lack of active efforts to plan for climate change impacts among those who are responsible for the basic functioning, safety, stability, and well-being of communities.** Of course, everyone has too much on their plates already. We will discuss workforce issues below. But as an overall observation, we found that while there is clearly widespread awareness of climate change, climate mitigation efforts were far more common in the electricity and transportation sectors; emergency management and electricity were almost entirely focused on preparing for and managing short-term climate variability and extreme events – an observation repeated in many other efforts at present. Where there were climate mitigation efforts, they tended to be segregated from adaptation efforts. And planning, sustainability, and resilience-focused staff of local governments were generally more concerned and advanced with adaptation thinking than lifeline managers.

5.1.4 Utility of the Conceptual Framework

Finally, our conceptual framework of societal teleconnections served us in the design and analysis phases of our study but remained a subtext of our engagement with lifeline managers. Somewhat surprisingly, the simplicity of the model stood in notable contrast to the complexity of the systems we explored.

- **The benefit of bringing lifeline managers together is to explore their multiple mutual interdependencies, and in so doing, open the imagination to complexity.** This may reflect a basic human tendency during the discovery phase of learning but proved to be a necessary first step. We surmise that subsequent work could be more structured and thus facilitated with a clear and simple framework.

- **The societal teleconnections framework** – together with the key goals and tasks of this study – **helped us focus the design and contents of interview questions and workshop exercises.** It thus proved to be an important research support aid.

- **The framework also assisted in the systematic analysis of interviews and workshop notes**. It furthermore informs, as subsequent sections will show, the research and action recommendations.

- **The teleconnection language is unfamiliar to most people, but the experience of teleconnections is not**. Moreover, the abstract language describing a teleconnection's three basic components may also limit its accessibility. Frequent translation into more familiar exemplars of teleconnections (such as a "service area" or "supply chains") and joint exploration of examples is also important. Importantly, due to existing management structures, the exploration of some teleconnections may be more fruitful with different personnel than those engaged in this study (such as procurement staff or policy liaisons).

- **The framework may have greater utility at a later stage in the assessment of teleconnected (and even cascading) risks** as it helps in balancing the uncovered – and easily overwhelming – complexity with a dialogue tool for structured inquiry.

Overall, this pilot study ended up using – as others discussed in Section 3.2.2 – predominantly participatory systems modeling tools and placing greater emphasis on cascades while spending less time with the teleconnections framework and long-distance connections. This reflects both the opportunistic shifts common in exploratory studies as much as the interest and familiarity of study participants. In the remainder of this chapter, we build on these insights and summarize the research needs and action opportunities identified by study participants.

5.2 Research Needs

A key task of this study was to identify research needs so as to inform the California Energy Commission's and other state agencies' future research priorities concerning critical lifelines and related infrastructure systems. We draw here on the literature review as well as on our in-depth interviews and workshop discussions to summarize areas in which research investment would significantly assist lifeline managers to better prepare for climate change.

5.2.1 Basic, Integrated and Applied Research Needs

5.2.1.1 Knowledge Gaps and Research Needs on Climate Science and Extreme Events Relevant to Infrastructure

Improvements in projections and understanding of singular and compound extreme events. Climate extremes expert Claudia Tebaldi (National Center for Atmospheric Research, pers. communication to authors, August 2017) suggests that while projections of climate extremes are critical for assessments of impacts on infrastructure, and capacity to do so has advanced over recent years, much work remains to improve scientific understanding[34] (see also Alexander 2016), including on:

- *climate extremes indices* (e.g., hottest day of the year, longest spell of days above a temperature threshold, number of cooling degree days) (see Tebaldi et al. 2006; Zhang et al. 2011; Sillmann et al. 2013 a, b; Sillmann et al. 2017);

- *downscaling* of global climate models to relevant decision scales, including improvements in bias correction and general increases in confidence of projections;

- *attribution* of climatic extreme events to anthropogenic climate change, which would improve forecasting capabilities (e.g., Trenberth et al. 2015; Easterling et al. 2016; NASEM 2016);

[34] Climate extremes, their causes, projections and attributions are considered a "grand challenge" within the World Climate Research Programme (WCRP) (Sillman et al. 2017).

- *concatenation* of events, i.e., events that happen simultaneously in large areas or in different but connected areas; and,

- *sequences* of events (e.g., high temperature concurrent with drought, followed by extreme runoff/flooding events and subsequent landslides).

The need for such scientific information was confirmed by study participants, including the development of probabilities of compound events, and a better understanding of geographic and temporal variability. A recent review of the relevant literature suggested that many methodologies exist to assess sequential or concatenated events occurring in a particular place or regions, but to date, "multi-risk approaches do not consider the effects of climate change and mostly rely on the analysis of static vulnerability" (Gallina et al. 2016, p.123). Thus, there is a significant need to bring climate science together with hazards and risks assessors to fill this crucial gap in infrastructure-relevant information.

Some study participants insisted, however, that a need persists to still better understand single extreme events. Study participants pointed to the crucially-important example of drought to the water sector (and, as this study shows, to all other lifelines as well). As one noted, "we have no idea how long droughts can last." Water managers need to know how far their efforts in increasing self-reliance might go in reducing their vulnerability to long-duration droughts.

Understanding of climatic events at multiple scales and across various geographic ranges. Moreover, the ability to better understand climatic events at a range of scales (from the local to the regional) would help infrastructure designers and operators to assess whether their systems – which are already designed to withstand certain disruptions – are adequately designed and prepared, and thus to assess the need for adaptive changes in placement, operation, maintenance, and emergency response procedures. Such work is underway for electric utility planners (see Joselow [2017a] reporting on Argonne National Laboratory conducting high-resolution climate modeling for utilities), but far from common or readily available to other lifeline operators. In particular, a cross-scale understanding of projections of gradual changes and extremes over the entire geographic "footprint" of infrastructure service areas (e.g., the electrical grid of a set of utilities serving one area, food sourcing areas, water supply source regions) would help to understand whether and in what ways distant climate disruptions and impacts affect a particular locale.

5.2.1.2 Knowledge Gaps and Research Needs on Teleconnections and Complex Interdependent Lifeline Systems

More research on neglected sectors. In NCA3, Corell et al. (2014) identified a number of knowledge gaps on climate change impacts, including the need to:

- Expand climate impact analyses to focus on understudied but significant economic sectors such as natural resources and energy development (for example, mining, oil, gas, and timber); manufacturing; *infrastructure*, *land development*, and *urban areas*; finance and other services; retail; and human health and well-being; and,

- Understand the *institutional and behavioral barriers to adaptation and how to overcome them,* including revisions to legal codes, building and infrastructure standards, urban planning, and policy practices.

We italicized those phrases that mirror precisely the issues unearthed by our pilot study and that remain critical information gaps if interdependent lifelines are to be better prepared for the impacts from climate change.

More transdisciplinary nexus research. More specifically, Hibbard et al. (2014, p.274) in their assessment of climate vulnerabilities at the water-energy-land nexus stated that "effective adaptation to the impacts of climate change *requires a better understanding of the interactions among the energy, water, and land resource sectors*. Whether managing for water availability and quality in the context of energy systems, or land restrictions, or both, *an improved dialog between the scientific and decision-making communities will be necessary* to evaluate tradeoffs and compromises needed to manage and understand this complex system."

Teleconnected and cascading impacts. While progress is being made, climate impacts studies to date still do not examine interdependencies as a matter of course. Few have taken systematic account of teleconnections in vulnerability assessments or adaptation planning, though awareness of the need to do so is growing (e.g., Garfin et al. 2016; authors' observations of discussions among NCA4 author teams). The role of cascading impacts due to interdependencies and a better understanding of the behavioral, ecological, and technological coupling and feedbacks were identified as critical knowledge gaps in a report informing the NCA3 (Wilbanks et al. 2012a). Wilbanks et al. (2012b), examining cascading impacts, pointed out that such cascading impacts on energy transmission and distribution systems will be amplified in urban environments due to higher concentrations of people and the spatially concentrated dependence of their activities on energy deliveries. This observation, along with recent illustrative experiences from across the US during Hurricanes Sandy, Harvey or Maria (e.g., Ferris 2017; Hester 2017; Joselow 2017b; Plumer 2017; Thomas and Kaplan 2017) or from within California itself as it experienced an extended drought, extreme rainfall events and flooding, massive wildfires, followed by landslides (e.g., Collins 2017; Downey 2017; Kahn 2017) point to the urgent need to continue exploring both teleconnected and cascading impacts of climate change.

Since Wilbanks and colleagues' call to action, a growing number of studies have explored cascading impacts (e.g., Buldyrev et al. 2010; D'Souza 2017; Yang et al. 2017). Yet experts using the telecoupling approach emphasize the need to better understand the "spill-over" effects beyond system boundaries as well as the shocks and surprises that can unfold as a result of telecouplings. Far less attention has been directed toward long-distance sources of vulnerability.

Fully integrated systems models. Repeatedly, study participants pointed out that to really assess vulnerabilities of their systems, modelling efforts would need to integrate sectoral changes currently underway and expected to expand over the coming decades. For example, both the electricity and transportation sectors are undergoing transformative (and, in fact, interconnected) changes (e.g., shift to a greater share of renewables, distributed grid, battery storage, electrification of transportation). Most studies to date are not fully integrated and do not take these policy- and market-driven changes in the affected systems into account. Similarly, full integration of land use changes into assessment models would reveal new or different vulnerabilities than climate impacts assessments that do not consider land use changes, and thus yield very different insights for infrastructure planning.

Social science contributions to disaster scenarios. In addition, workshop participants urged that "integrated" science to address the sorts of challenges listed above would explicitly need to include the social sciences. As we will discuss further below (Section 6.3.3), if lifeline managers in a particular region decide to engage in scenario exercises to better understand their mutual dependencies, physical scientists and engineers ought to develop the practice scenarios while also relying on social scientists and their understanding of institutional dynamics, governance barriers, or human behavior in normal and disaster situations in order to create more realistic scenarios. In addition, development of scenarios should consider distal initiating events and include procurement staff who are more familiar with supply chains than scientists or engineers. This is of particular concern for lifelines that depend on infrastructure components that are not locally produced (e.g., transformers in the electricity sector; pipes in the water sector, a large variety of foods). Supply chain issues were also called out in a recent National Academy study of electricity grid reliability and resilience as requiring far greater attention in improving lifeline resilience (NASEM 2017).

Economic costs and benefits across multiple sectors. Social scientists were also called to engage more fully in studies of integrated systems to assess economic costs and benefits across sectors, not just within one or two sectors, to help entities make the business case for investment in greater lifeline resilience (see also Moser et al. 2018). Workshop participants also identified the importance of governance for system resilience, particularly the governance capacity under extreme stress like a long-duration disaster, yet little was actually understood about the interrelated governance of regional lifeline systems.

Social vulnerability and resilience to complex extremes. While social, economic, health and ecological vulnerability studies for climate change and sea-level rise exist for the L.A. region (Grifman et al. 2013; Grubbs et al. 2016; Maizlish et al. 2017), they do not – to date – go into much depth on the dependence on functional lifeline systems, nor do they consider mutual interdependencies and how vulnerabilities change over time under conditions of complex interconnected sequences or multiple simultaneous extreme events. Similarly, while much is known about conditions and factors that contribute to community resilience (P2R Partners 2015; 100RC 2016; Meerow et al. 2016; Kelly et al. 2017; Reiner and McElvaney 2017; Urban Resilience Program 2018; Moser et al., in review), L.A. – to our knowledge – has not undertaken a systematic assessment of its local and regional sources of community resilience or explored how to call on them in the case of extreme or extended disasters. However, a better understanding of both the sources of social vulnerability and of social resilience under extreme circumstances would enable better planning and preparedness for what is often relegated to the "unthinkable."

5.2.1.3 Understanding the Legal and Regulatory Context

Applied research and information integration requests heard in the course of our study concerned legal issues. Workshop participants in particular wished to better understand the legal liabilities involved for upstream failures to take adequate adaptive measures. The question can be extended to the legal liability of downstream entities failing to take adaptation measures that could prevent or minimize cascades. Ultimately, such liability questions end with questions about the liability of greenhouse gas emitters for impacts and damages that have been or may be experienced in the future – a topic of growing interest and legal action – in the state, the US, and globally. This action context lends considerable urgency to research in the legal side of adaptation in a complex and teleconnected world.

A different but related information need uncovered during our study was the lack of knowledge many planners and decision-makers have of the complex world of standards, codes, regulations, and guidelines that pertain to the design, operation, and maintenance of different types of infrastructure. Workshop participants felt that compiling such information in one easily accessible place would go a long way toward helping urban and infrastructure planners and designers understand what is available, required, and possible in terms of adaptation options. At least a partial compilation of such standards is currently underway as part of the work of California's Climate-Safe Infrastructure Working Group, established through AB2800. [35]

5.2.1.4 Technical/Material Science Needs and Data Gaps

During the workshop, participants also pointed to some user-specific information and research needs. This is by no means a complete list, but points to the type of research and data portal development that could not be known without direct engagement of the subject matter experts who work in the design and management of infrastructure on a daily basis.

During discussions of current and future vulnerabilities of infrastructure, participants pointed to the need to conduct more applied science on technical/material science and the performance of infrastructure and materials under the more extreme conditions expected in the future. For example, they asked what wind speeds power lines can handle under different temperature conditions. Similar questions may be asked about the performance of pavement or batteries or different modes of telecommunication.

A different challenge, but similarly applied, is the question of the quality of Geographic Information Systems and associated data layers used by different lifeline managers, particularly (but not exclusively) IOUs: are they up-to-date? Are they complete? What information layers do or do they not contain that would improve management? In addition, workshop participants asked that such GIS databases be made sharable to create a common informational foundation for coordinated planning. Clearly, there are privacy, confidentiality, and security issues associated with creating an integrated GIS database (even a secure-access one), but study participants thought it would greatly enhance the planning and integration. Open data experts could advise the coordinating state or regional agency on how to set up such a database. At the very least, data portals like Cal-adapt could include additional non-climatic data layers. Which types of information would be most useful would need to be discussed and decided with operational/ planning staff as well as different subject matter experts so as to ensure data users understand the contents and limitations of available information.

5.2.2 Building Tools at the Right Scale

As the summary table (Table 4 in Section 3.3.2) made clear, there are important areas of work and progress in developing application-relevant information and tools, but also significant limitations in making such tools available and accessible to lifeline and utility managers at different scales of operation and at different levels of capacity and skill. In this area, we see ample room to develop improved tools to help assess vulnerabilities and adaptation options of

---

[35] For more information, see: http://resources.ca.gov/climate/climate-safe-infrastructure-working-group/.

complex interdependent lifeline systems as they coalesce in urban areas like L.A. Such tools should be developed in close collaboration with users so as to fit their needs. There is an even greater need to make these tools widely accessibly both financially and through training and tutorials so that not only high-capacity urban centers like L.A. can benefit, but smaller local governments or utility managers as well.

Once lifeline managers recognize the need to assess and manage interdependent and long-distance risks, it is likely they will develop their own in-house capacity. This may or may not obviate the need for cross-sector interaction, tools, and approaches that help experts from different sectors to come together to share and learn how their respective systems interact.

That said, the lack of tools was not a leading concern among study participants – the only tool need mentioned were cutting-edge weather forecasting tools. Moreover, we would advise against prolific development of tools. Experience in the adaptation arena to date illustrates that some tools are helpful, even necessary, but typically by themselves are insufficient. All tools require expertise, ease, and purpose to use appropriately. Often, tools in combination with training, professional development, case examples, and a peer community for learning are more effective than tools delivered without such accompanying assistance.

5.2.3 Pilot and Demonstration Projects

The last topic in this section focuses on the intersection of research (Section 5.2) and action (Section 5.3). During workshop discussions of potential adaptation options, several participants identified the need for pilot or demonstration projects to explore how a particular adaptation approach would look in practical reality and to study at a relatively small, contained neighborhood scale whether a particular approach is technically feasible, economically justifiable, environmentally beneficial, and socially acceptable. We give two specific examples below, but others may be identified by other sectors or in future conversations across lifelines.

Water cistern system. As part of improving resilience at multiple scales, a system of underground water cisterns could be established in central locations of specific L.A. neighborhoods. The best location for a pilot project (and, if successful, in other neighborhoods) would need to be identified and the cistern system designed to meet emergency needs as well as relevant drinking water standards and so on. Such a water cistern system would serve as an emergency back-up system if the main water infrastructure were disrupted. The idea is a good example of the nested approach to thinking about resilience given that DWP is already thinking about ways to increase resilience of its water pipe infrastructure overall. Moreover, it could easily be integrated with the more comprehensive idea of developing neighborhood resilience hubs (discussed below) that would serve communities not just in climatic extremes but also major seismic events, causing "imposed droughts" when major water conveyance systems are disrupted. The development of water cistern systems also offers an opportunity to learn from spatial analogues as such systems exist in hotter, drier regions of the world already.

Resilience hubs. A second suggestion for pilot and demonstration projects was to build a neighborhood "resilience hub" – a central, accessible center for the community to which people in areas affected by an emergency could be evacuated if needed. While reminiscent of shelters, workshop participants emphasized the need to build them out in ways that provide core infrastructure services when the day-to-day system is temporarily defunct. They would be centers with back-up water systems (water cistern system, see above), back-up power (a microgrid "island" off the normal grid) with solar and battery arrays; back-up food supplies, medical services in case of emergencies, and social services to help communities get back up on their feet after the crisis. Neighborhood resilience hubs could be co-located with emergency response centers, but the best design and location would need to be explored and tested, and the design should include experts as well as neighborhood representatives to ensure fit (Box 3).

Box 3: Greater Resilience though Modularity

A repeated theme during the workshop discussions on climate adaptation and increasing resilience was to need for greater *flexibility* and *modularity* (Vespignani 2010). These common resilience principles stand in tension with industry trends in some sectors (e.g., telecommunication, private electric utilities) and the frequently sought benefits of centralization (e.g., efficiency, economies of scale, profit, ease of central control).

At the same time, L.A already has a "decentralized/distributed" lifeline system at present, albeit in the sense of a fragmented landscape of siloed sectors, lifeline operators, service providers, and related governance structures. It is unrealistic, impractical, and unaffordable to centralize it. To the contrary, study participants wished for further distribution of operational and governance responsibilities in the sense of modularity. "Smart" and new technologies, big data, the integration of best practices and best available science in novel designs, and cross-sector coordination could allow for innovative solutions that increase community resilience.

The idea of "resilience districts" or "resilience hubs"† emerged independently from various break-out group discussions, illustrating the creative thinking of participants. For example, some proposed to change "water districts" (of which there are more than 400 in L.A.) to "resilience utility districts" that provide potable water and deal with waste water, but also offer other utility functions (electricity, communication, transportation, medical, etc.). Such districts should meet more than utility needs, including community safety, mutual support, and recovery services, and experimentation involving trusted community members would be required to get their design right.

In addition, establishing such resilience hubs would involve governance shifts, changes in law, codes, enforcement of regulations, and social expectations. Particularly important would be effective communication during emergencies so that the modularity does not turn into dangerous isolation. Workshop participants repeatedly argued that greater modularity can eliminate or reduce opportunities for existing back-up systems (such as being connected to a large regional electricity grid). The benefits, drawbacks and needs for redundancies would need to be carefully considered. One option is to use modular systems as secondary systems during normal operating conditions that become primary operating system only in emergencies. In this way, they become analogous to mutual aid agreements for emergencies established between communities, companies, or agencies at present. A well-designed pilot project could very well explore the pros and cons and solution options, including how to build "nested" or "fractal" resilience at micro-, meso- and mega-scales).

† See: "Resilient Los Angeles" where resilience hubs are described: https://www.lamayor.org/Resilience.

Bus bridge. Another idea suggested for a pilot project was a multi-model transportation system for emergencies. A bus bridge is a temporary public transportation system, made up of shuttle buses that can bypass disrupted trains (or even highways). Extending this idea to an emergency with prolonged fuel-shortage or to facilitate the commute of the essential lifeline and emergency workforce might be measures to increase resilience in complex lifeline emergencies. Exploration of financial models to support implementation is also needed.

Integrated adaptation/mitigation planning in the electricity sector. Study participants noted that with electric utilities there is greater recognition of the need for mitigation than for adaptation at this point. Particularly privately-owned IOUs are not in the same way obliged as POUs at this point to undertake both. While CPUC has released a White Paper to encourage utilities to begin adaptation planning by conducting vulnerability assessments of their assets (Ralph-Douglas 2016), the next step of adaptation planning that is commensurate and coherent with utilities' mitigation efforts have by and large not yet been undertaken. Study participants suggests that CalISO, CPUC, and CEC could help move utilities along through pilot projects that explore such integrated planning within and beyond common planning horizons (10 years).

5.3 Action Opportunities

A second major task of this study was to compile a list of action opportunities that CEC, other state agencies, the state legislature, metropolitan governments and/or utility/lifeline operators could take to improve their resilience and preparedness in light of current and increasing threats from climate change. We organize these here from the state to the local and utility level, fully recognizing that:

- in some lifeline sectors, federal rules and agencies must be involved as well in advancing adaptation; and,
- the greatest advance on resilience will be made if there is cross-scale coordination and collaboration (see Section 3.2.1).

We thus begin this section with a compilation of insights on how to close cross-sectoral and cross-scale governance gaps to improve policy and action coherence because they should be regarded as overarching principles or best practices that apply to the most specific suggestions that emerged from workshop discussions (Table 6).

Table 6: Closing Governance Gaps and Improving Policy Coherence

Conditions for increasing the likelihood of cross-sector coordination and collaboration • Knowledge and knowledge exchange (new insights, new ideas, new information) • Political commitments by one entity affecting the interests of other entities • Behavioral changes in one entity become relevant to other entities • Mutual need for goods or services provided by the respective other party • Interdependence of institutions governance objectives on one another • Having the power over another party to make them interact • Relatively low cost or ease of interaction and dedicated resources to support coordination
Ways to increase (the effectiveness of) coordination and collaboration • Clarify the coordination challenge (redundancy/duplication/overlap vs. lacunae/gaps vs. incoherence/contradictions vs. competition) • Clearly identify whose collaboration needs to be enhanced, when, and who the key actors are (issue dependent; cross-sector, cross-scale) • Clarify each party's rights and responsibilities • Identify available coordination approaches, e.g.: o regulatory instruments (e.g., changing rules, standards, guidelines, procurement requirements, triple bottom line, etc.; self-regulation, co-regulation) o market-based instruments (e.g., incentives, differential pay rates, taxation) o soft/voluntary arrangements (e.g., network building, trainings, labels, voluntary standards) • Use motivational/informational instruments and organizational measures (e.g., building capacity and competence, establishing mandates, increasing resources, addressing communication challenges and power imbalances, establishing inter-departmental and cross-sectoral working groups) • Jointly contribute to agenda-setting, problem definition and decision-making • Sequence the introduction of coordinating approaches to avoid challenges with implementation • Identify shared vision and "nexus" objectives as well as clear prioritization of objectives • Track acceptance of shared objectives (mention in policy documents, shared understanding, evidence in weighting of options in decisions • Establish shared guiding principles to help negotiate divergent interests/values • Establish meta-governance principles (e.g., inclusivity, transparency, accountability, empowerment of weaker actors, providing access to information/knowledge sharing, institutional learning, use of performance-based indicators) • Actively coordinate on policies and projects • Create a coordinating entity or agency with different types of tasks and varying degrees of power over the independent entities that need to be coordinated (e.g., knowledge exchange, learning, creation of standards, conflict resolution, promotion of common interests, policy advocacy, provision of neutral spaces for exchange and exploration, assistance with scaling up good practices)

Ways to improve dynamics among stakeholders beyond the defined interdependent multi-sectoral lifeline system • Always consider and explore horizontal and vertical dependencies beyond the defined system • Ensure communication, opportunities for input, and transparency to parties/stakeholders beyond the multi-sector/multi-party system in focus • Jointly explore rules and policies established at higher levels to ensure consistent or compatible interpretation • Recognize local/stakeholder rights and interest, especially where power relationships are asymmetrical • Explore implications of policy changes at all stages of the policy process (from front-end negotiation to final implementation); may require involvement of different actors • Expect and respect the messiness of unclear system boundaries as different sectors depend on different actor networks • Monitor for spill-over expect/unintended consequences
Ways to better account for the political and cognitive factors that determine change • Recognize that cross-sector interactions are never apolitical; ideological and cognitive factors also always play a part in shaping interactions • Build trust through freely sharing information, openness, mutuality, timely delivery of high-quality inputs etc. • Engage in joint problem definition and revisit problem definition if it unduly limits the range of possible solutions • Clarify principles underlying policies to surface interests and values and negotiate adjusted/shared principles • Recognize that there may be multiple paths to achieving desirable outcomes (with different implications for stakeholders) • Encourage and share ownership of both the challenge and the solution • Engage in joint strategic thinking and planning • Support open and collaborative processes of learning, internally and among partners, to build shared understanding • Build competence and capacity through training and appropriate professional development opportunities • Explore participating parties' risk aversion and openness to risk-taking and potential consequences of "failures" • Ensure that all key actors (not just some) benefit from these types of processes (technical staff, financial/procurement staff, policy- or decision-makers, stakeholders, elected officials etc.) • Extend the range of actors involved to increase legitimacy • Include actors with strong leadership skills and discursive power to improve processes, and increase efficiency, visibility and political influence • Involve neutral intermediaries if there is a history of distrust or conflict • Make space for autonomy (e.g., platforms for free sharing of alternative views, permission of multiple legitimate solutions) if it increases overall buy-in and participation • Clearly articulate, assign and agree on respective responsibilities and powers of interacting entities

Source: The Authors, derived from an extensive review of the governance literature undertaken by Weitz et al. (2017)

5.3.1 Motivating Integrated Adaptation Planning through State-Level Policy

Study participants made a variety of suggestions on how to stimulate adaptation planning and measures from the top down (Table 7). These suggestions are related to the State's own functions and responsibilities, but also its power to mandate, regulate, set standards or provide guidance and oversight over private entities and local government. They also build on the precedence provided by California's powerful role in setting climate mitigation policy.

Table 7: State-Level Policy Actions to Encourage Adaptation and Cross-Sector Coordination

Sector	Policy actor	Proposed policy action
Energy	CPUC	Encourage or demand (as part of relicensing or other scheduled oversight opportunities) that all utilities assess current and future climate risks and initiate adaptation planning; emphasize integration and coordination with mitigation activities (AB32 etc.) as well as consideration of complex risks; mandate should not micro-manage approach to doing so, but mandate that it is done. At present mitigation and adaptation are not on the same level in terms of state mandate, allowing adaptation to be neglected.
	Legislature	Request that CPUC Commissioners explore adaptation to raise awareness of its importance among Commissioners.
Communication	Legislature/CPUC	Establish an open data policy that considers private sector needs while facilitating easier coordination with and beyond the communication sector in emergencies.
Water	Legislature	Maintain drought water restrictions at all times.
	DWR	Review, and if necessary, adjust policies to enable water capture and storage at household level, promote stormwater capture.
Water & Transportation	DWR & Caltrans	Provide guidance to state and local transportation and land use agencies on preferential use of absorptive pavement; provide incentives to decrease surface sealing.
Emergency Management	CalOEM (possibly via legislative mandate)	Demand that all utilities participate regularly in major extreme climate emergency scenario exercises, similar to those undertaken for earthquake preparedness.
All sectors	Office of Planning and Research (OPR)	Provide guidance and oversee strategic planning in all state and local government departments, including consideration of extended time horizons to assess potential climate risks from complex extreme events, so as to increase the likelihood of effective governance performance even under duress.
	Insurance Commissioner	Explore insurance options for public and private sector utilities (electricity, water, telecommunication) for when weather/climate-driven service outages occur.
	OPR & OPC	Amend local planning guidance for Local Hazard Mitigation Plans, General Plans, Local Coastal Programs, and Adaptation Plans to explicitly require (or incentivize) consideration of cross-sector dependencies and vulnerabilities related to long-distance climate change impacts.

Source: The Authors

The additional recommendation made by study participants that the State revisit its infrastructure codes and standards is not listed because AB2800 (Quirk), Climate-Safe Infrastructure (passed in 2016) already demands just that.

5.3.2 Addressing Institutional Barriers Within and Between Lifeline Sectors

Institutional barriers identified by study participants can sometimes be addressed though state action, but other times can or should be addressed at regional or local levels or within utility companies (whose reach may span various geographic scales). Moreover, institutional barriers can be substantial, thus also warranting a high priority for relevant actors. We thus list it at this high organizational level in our report.

Table 8 synthesizes the barriers we learned about in the course of interviews and workshop discussions, including potential solutions (some were suggested by study participants).

Table 8: Within and Cross-Sector Barriers and Potential Ways to Overcome Them

Sector	Barrier	Potential Way to Overcome Barrier
Energy (utilities)	Siloed approach to thinking about climate change (mitigation separate from disaster preparedness and from infrastructure/equipment).	In addition to mandate to conduct integrated assessments and planning (see Table 7), utility level leadership demanding integration.
	Planning for energy needs before/during/after emergencies insufficiently integrates human behavior component due to lack of social science expertise.	Work with behavioral scientists to improve energy planning.
	Rapid technological change in energy sector (grid changes, energy storage changes, renewables) renders adaptation planning more difficult.	Think more creatively to explore all options for stabilizing grid; engage multiple subject matter experts to gain wide range of perspectives.
	Liability and competition issues can inhibit or entirely beyond-sector communication.	Review liability policies at appropriate levels (state, federal, insurance). See also policy action on open data policy proposed in Table 7 and the need for a secure central information repository.
Communication	Lack of clarity on how communication providers prepare for and respond to emergencies (state looks to federal guidance, federal agencies punt to state, resulting in no action).	Lobby legislature to demand rules and standards for how telecommunication providers should prepare for disasters/disruptions.
	Currently no state mandate to explore climate risk in communications sector.	CPUC or other relevant state or federal entity should mandate that telecommunications providers conduct vulnerability assessments of climate risks (over various timescales and considering complex coupled upstream and downstream risks) and undertake adaptation planning/action accordingly.

	Lack of public communication to shape public expectations of communication services during emergencies; insufficiently understood linguistic/cultural diversity; public climate change disinterest, avoidance or denial.	Work with climate change communication experts to improve emergency and long-term risk communication.
Water	Cost to homeowners to use rain barrels and increase stormwater capture.	Use utility incentives coupled with local and state policy to continue to mandate drought water restrictions (see Table 7).
Transportation	Lack of adequately trained personnel for use of different aspects of the multi-model transportation system.	Generate funds (fees, grants etc.) to provide for adequate training in more than one transportation modality.
Emergency Management	Lower standing than Policy and Fire Departments (except in disasters); resulting politics result in budget constraints and insufficient staff.	Recognition of importance of EM at the mayoral level; otherwise continued dependence on grant funding (which is inadequate).
	Rapid change of technologies EM depends on (communication, energy)	Ongoing monitoring; task force to explore options for rapid uptake and updating of procedures; constant updating of EM response plans; frequent EM response practices, particularly with volunteer forces (e.g., reverse 911).
All sectors /Cross-cutting	Lack of incentives to plan proactively for disasters.	Guidance from OPR (see Table 7); mandate from State, local and agency leaders to proactively plan for disaster, to do vulnerability assessments and adaptation planning.
	Reactive mindset (in part due to too many demands at present).	Combination of sufficient staff capacity, mandates to prioritize proactive planning, leadership.
	Standards and codes prevent building back better after disaster.	Review and revise at state and local levels (see work related to AB2800).
	Lack of institutional mandates or incentives to coordinate with other lifelines.	Scale up, increase frequency and expand the work of the Southern California Critical Lifelines Working Group (see Section 6.3.3), especially to include climate change risks; leadership in each agency should demand staff participation; high-level leader forum to generate visibility and political will.
	Workforce issues (e.g., retirements, staffing shortage, inadequate training).	All sectors face workforce issues, albeit with unique staffing and workforce development needs. Top-level leadership should address and pursue solutions with long-term commitment.

Source: The Authors

5.3.3 Participating in Regional Lifeline Scenario Planning Exercises

As already mentioned in Table 8, workshop participants repeatedly commented on the need for continued interactions and even more structured exercises and exchanges than this pilot study provided. In particular, they called out the need for regional extreme climate event scenario exercises, similar to the seismic emergency scenario exercises with which lifeline managers are already familiar.

The Southern California Critical Lifelines Workgroup – led since 2015 by Dan Stevens (SCE) and Leslie Luke (L.A. County OEM) – may serve as a critical point of contact or partner to initiate, plan, and coordinate such scenario exercises, involving a variety of experts in developing the exercise scenarios (see discussion in Section 5.2.1.2 and Box 4).[36]

Source: The Authors

Box 4: The Southern California Critical Lifelines Workgroup

Mission: Coordinate critical lifeline utility resilience efforts between public, private sector, and independent stakeholders in the California Office of Emergency Services (Cal OES) Southern Region.

Its objectives are to: (1) Identify interdependencies across the critical lifeline providers and the public-sector emergency management community; (2) Align and support stakeholder plans, training, and exercise initiatives; (3) Build peer-to-peer networks; (4) Implement shared best practices on operational response, incident management, and restoration strategies; and (5) Build upon available Mutual Aid and Mutual Assistance opportunities that address personnel, equipment, and commodities to help post-disaster utility relief efforts (Stevens and Luke 2016).

As the list of objectives suggests, the Workgroup to date is not solely focused on weather extrems but takes an all-hazard portfolio approach. At the same time, there is no explicit recognition or goal to assess readiness for more frequent and/or more extreme climatic and derivative hazards. While it explicitly focuses on interdependencies and thus on potential cascading effects, so far it does not include explicit awareness or assessment of distal origins of risks. Thus, an action recommendation for the SCCLWG is to expand its mission and objectives accordingly.

Well-constructed scenarios developed for training purposes serve as "boundary objects" (e.g., Star and Griesemer 1989; Star 2010) around which otherwise siloed managers come together. Their central purpose is to stress-test existing emergency procedures and – as necessary – revise and refine them. Importantly, regular scenario exercises also bring relevant actors together,

---

[36] Their work may usefully be integrated with that of the Southern California Disaster Risk Reduction Initiative, although at present it also fails to look at climate change (see: USC Bedrosian Center on Governance 2016).

maintain social and professional networks and institutional memory, build trust, and simply allow actors to practice what is not needed in day-to-day operations.

Interestingly, while some workshop participants exhibited (common human) resistance to considering truly nightmarish scenarios, others emphasized that it is precisely these "Dark City"[37], "Maximum Maximum", or worst-case exercises which confront people with "the unthinkable issues" that need to be practiced and thought through. Inevitably, such exercises surface:

- *workforce challenges* (e.g., all lifeline functioning in normal times and response activities and repairs in emergency situations depend on the availability of the workforce. This emerged as one of the most central issues through the Elephant Builder exercise. But chronic staff shortages, lack of sufficient trained personnel, inability of workers to come to work for transportation, personal safety, family, or other reasons can severely curtail the availability of workers)
- *mental blind spots* (e.g., Southern California is very earthquake and fire-focused, but far less concerned with climate extremes; consequently, few are thinking about how bad climate extremes may actually become; and few extend beyond the familiar hazards and responses, failing to imagine – for example – how to fight fires in a very long drought when there is no water left in reservoirs);
- *institutional gaps* (e.g., not all impacted assets or resources are owned by the same entity, hence control, access to information, operating rules vary);
- *institutional/regulatory barriers* and the public health consequences of emergency deviations (e.g., air quality standards may limit the use of back-up generators over extended heat-extreme periods; toxic substance release regulations may be exceeded during flooding events);
- *material/resource gaps* (e.g., inadequate preparedness for the fuel needs in a post-disaster situation); and
- *communication challenges or failures* (e.g., the tremendous public relations problems that can ensue when disaster preparedness is foregone but then surfaces in the form of failed disaster response. Such challenges usually result in media investigations and loss of trust and public confidence in lifeline providers).

Workshop participants urged that such scenario exercises be written up in after-action reports and participants need be required to use them to improve operations. At the same time, they urged to be careful not to let exercises drain capacity, not to create scenarios that are "dull and uninteresting," but to create detailed, believable scenarios to engage people with more vigor. If done well, they can be used repeatedly with different groups or to see how interventions have improved over time (e.g., ShakeOut earthquake scenario from 2008 is still in use today).

---

[37] "Dark City" is a 1998 movie whose tagline was: A world where the night never ends. Where man has no past. And humanity has no future.

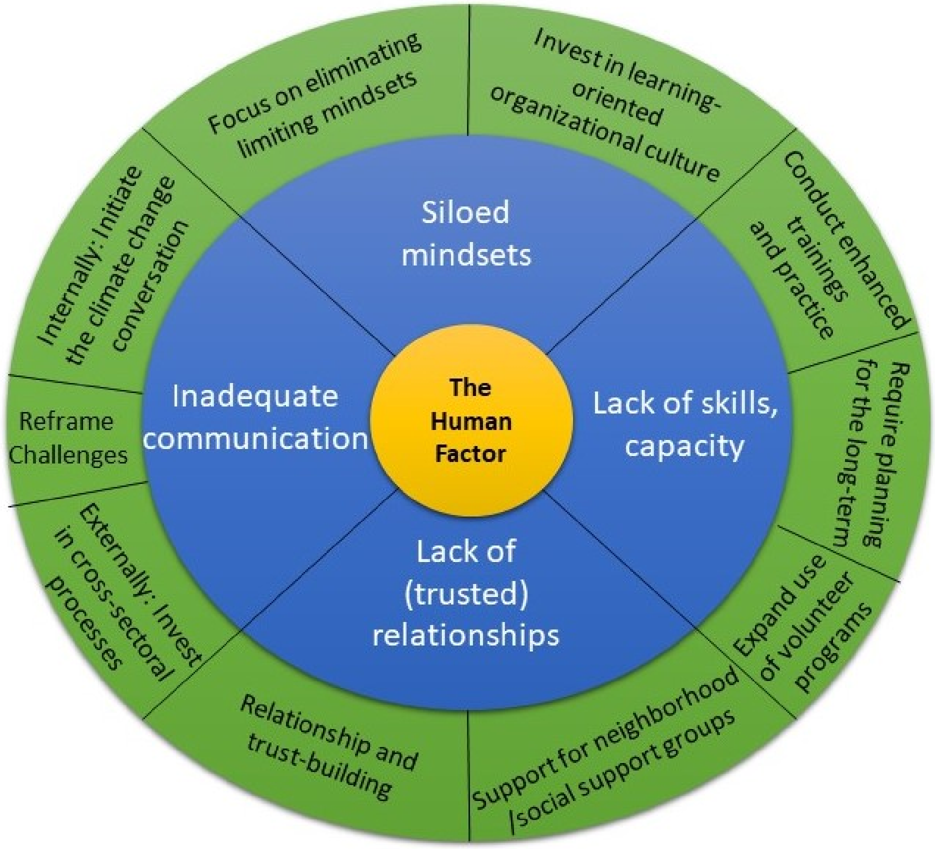
Scenario materials should include factsheets, web contents, videos, story maps, circulars and visualizations.

5.3.4 Taking Preparedness Measures at the Utility and Agency-Level

Over the course of our interviews, workshops and teleconferences with the TAG, study participants acknowledged that each public-sector agency and department and all private-sector organizations can do more to improve not just emergency preparedness for truly extraordinary disasters, but to expand that preparedness to climate adaptation. As indicated above, while there is general awareness of climate change and acceptance of the need for adaptation varies across sectors, active assessment of climate risks and adaptation planning is notably limited still. Where it occurs, it typically has been driven by top-level leadership and mandates or by staff-level policy entrepreneurship coupled with a growing sense of urgency.[38]

Here we summarize some of the repeatedly-mentioned and cross-cutting strategies that were suggested that may vary in the specific sectoral adoption, but that would help significantly to advance climate risk awareness, coherence within agencies and entities to improve internal consistency, and coordination among agencies to address the interdependent risks. A theme running across all of these recommended steps is the importance of the "human factor" in lifeline management (Source: The Authors **Figure *10*** and Box).

[38] Several participants noted that their agencies are actively working on climate change mitigation, but these efforts appeared to occur entirely segregated from emerging adaptation thinking (where it occurred at all). Thus, there was little awareness of potential synergies, trade-offs, or potential competition between the two.



Source: The Authors

Figure 10: "Human factors" (blue) and potential strategies to address related problems (green)
(details in text)

Box 5: The Overarching Importance of the "Human Element" in Lifeline Resilience

Lifeline managers are accustomed to dealing with physical infrastructure, computer-aided decision-making, smart technologies and so on, but study participants emphasized again and again that nothing ultimately works without ongoing and strengthened attention to the "human component" of integrated lifeline systems. Often humans are the sources of system disruptions or inadequate responses. By the same token, they are also the source of increased resilience of the complex, interdependent aspects of the lifeline system. Key foci are shown in Figure 12, and should be explored how they can be addressed specifically in each lifeline sector/agency:

- *People as back-up of automated systems*. Workshop participants applauded a healthy degree of distrust in automated systems and emphasized that excitement and focus on new technologies should never sideline the needs and capacities of operational staff;
- *Much-enhanced training and practice* of existing and new/expanded staff in (a) dealing with known/expected extreme events and disasters so as to increase likelihood of effective response; (b) constantly changing technologies; (c) climate change, adaptation and comprehensive resilience building because it has present-day and future benefits;
- *Reframing the problems and solutions* can be essential in transcending common barriers referred to as "politics;"
- *Investing in cross-sectoral processes now* as they take time to establish, test, and get right, but are essential to function properly in case of lifeline disruptions. This likely requires a dedicated convener;
- *Relationship- and trust-building* among relevant staff at all levels (from leadership to "the right people" at the operational level); efforts should not only be directed at relationships between first responders and the public but also between other city/county staff and the public and among lifeline experts. In many instances this will involve overtly dealing with legacies of distrustful past relationships;
- *Assessing and addressing the differential social vulnerabilities* of different populations to different and complex risks, including *differential coping- and adaptive capacity* of individuals, households, organizations, businesses, and government agencies;
- *Supporting social/neighborhood support groups*. While investing in neighborhood relations, donating volunteer time, money, or offering educational materials and information can help build relationships between public and lifeline managers;
- *Expanding use of Community Emergency Response Teams (CERT) and other volunteer programs* to increase neighborhood-level preparedness and resilience as an extended workforce;
- *Focusing on eliminating limiting mindsets* (e.g., siloed perspectives, lack of appreciation of system interactions, overconfidence without relevant experience, lack of imagination of both the scope of the problem and the possibilities of alternative solutions.

Source: The Authors

5.3.4.1 Communication

Initiate the "climate change conversation" within each lifeline sector and organization. This can be done in a variety of ways, e.g., by conducting surveys of attitudes among staff and leadership, mandating detailed vulnerability and adaptation barrier assessments, assigning staff-level responsibility for cross-departmental coordination of dialogue and assessments, high-level/leadership forums, and exchange among similar entities across the state or nation. Importantly, such conversations need to strike the difficult balance between oversimplification and overwhelming with the complexities of climate change and interdependent lifelines. Storytelling might be a useful technique as it makes space for substantive content and emotion.

Change information flows throughout the disaster cycle within and across lifeline organizations. Different lifeline sectors vary in the quality, frequency and effectiveness of information sharing within and beyond the sector. Typically, it is better during an emergency than in the preparation or recovery phase. CalOES, for example, was praised for its information flow and information clearinghouse as well as the clarity of expectations on procedures (e.g., NIMS and SEMS). All lifelines should review, practice, and improve their emergency communication procedures (not only internally, but particularly across lifeline sectors and with the public). Cross-sector development of communication plans can help to identify which information is relevant and accurate, and how it can be validated before distribution. Awareness of the growing prevalence of social media (which works fast, but not necessarily accurately) must enter modern communication planning. Developing appropriate and helpful uses of social media (e.g., setting up a "I'm safe" Facebook page or building "Check on your neighbors" apps) should be a focus. Special attention to socially vulnerable groups (e.g., elderly, sick, those dependent on medical devices, linguistically easily isolated groups) is critical.

5.3.4.2 Workforce Development

Invest in workforce development and organizational culture. Hiring open-minded, agile, systems-oriented staff; encouraging experimentation, creative thinking and constant openness to learning; and training up existing staff in climate change and adaptation literacy sets organizational norms and expectations as to the values, qualifications, and capacities that a 21st century lifeline organization should have. These may act more slowly but affect organizations at the deepest and most enduring level. Due to retirements and other staff turn-over, trainings should be offered frequently, repeatedly, and be mandated to increase professional capacity.

Encourage or require that staff in all lifeline sectors think about long-term issues. Typical planning horizons in many of the lifeline sectors only go out 10 years (transportation and water have longer time horizons given the lifetime of some infrastructure); staff do not usually make the connection between short-term and long-term needs, and time pressures, job specialization, and siloed responsibilities predicate people to not see the whole picture.

5.3.4.3 Approaches to Resilience Building and Adaptation

Examine which lessons from emergency management can be transferred to adaptation (and which cannot). Because of the relatively stronger tradition and greater familiarity in lifeline systems with disaster preparedness and response, there may be a useful reservoir of lessons and procedures that can be transferred to adaptation planning, but it should not be assumed that preparedness for disasters is an adequate replacement for adaptation planning. For instance, typical emergency planning is focused on preparedness for a 3-4 days-long event. To what extent this experienced can be leveraged for longer-term challenges should be explored.

Similarly, available risk maps may be a helpful asset for adaptation, but these are generally not using forward-looking climate science (e.g., FEMA Flood Insurance Rate Maps do not account for sea-level rise). Emergency managers should explore how present-day emergency management risk maps can be used in tandem with climate projections to provide a longer-term view of current and future risks to lifelines.

Approach lifeline resilience building through a multi-hazard approach, emphasizing interdependencies. While not a novel concept in theory, practice is still far from implementing approaches where systems work for multiple types of hazards and are tested to be robust under complex circumstances (e.g., multiple lifeline failures and/or a simultaneous cyberattack). Even where multiple sectors are asked to assess their risks to climate change, they do not typically account for failures of systems in other sectors on which they depend.

Coordinate priorities across sectors through trained, calm people. Improved knowledge of the urban landscape and of the specific needs of different types of facilities (hospitals vs. gas stations vs. prisons).

Invest in resilience that has benefits year-round. For cost-effectiveness, resilience-building efforts should work not just in the rare occasion when they are most needed. Examples include investment in workforce development, building community social capital, exploring green infrastructure, reducing environmental stresses to improve public health overall, and so on. Aiming for such multi-benefits resilience-building will be aided by active engagement of the communities to be served, so as to tap into local needs, knowledge, and strengths

Enhance the frequency and depth of collaboration with planners for pre-disaster and recovery planning to ensure people build back better after a disaster so that infrastructure, communities and facilities are less vulnerable to future events and to ensure that long-term planning does not undermine the ability of emergency services to respond effectively to critical needs. Given institutional barriers, this will require coordinated action with local, state and federal agencies.

5.3.4.4 Concrete Near-Term Actions

Commit to addressing "low-hanging fruit." The first is to reduce the vulnerabilities of each lifeline sector (see Tables 5a-d). In addition there are many cross-sector examples, including using dialogue or simple multi-sector modeling to identify subsystems that are vulnerable to the same upstream risk factors; encouraging creative problem solving by multi-entity or multi-sector workgroups, e.g., on how to align budgets, or how to jointly address an upstream issue than trying to protect against hazards in every subsystem separately; and building relationships now because complexity is unpredictable and disasters will come, but well-established connections and trust are crucial assets in completely unfamiliar situations.

5.4 Concluding Thoughts

This pilot study has yielded a rich set of initial insights and a wide-ranging and actionable research and action agenda. It is *by no means* the final word on teleconnected and cascading climate change impacts on lifeline systems. But it does open up a next generation of research for California's future assessments. What is needed is research that recognizes the interconnectedness between electricity and lifeline systems and places growing emphasis on:

- transdisciplinary, stakeholder-engaged research;

- interdisciplinary research with increased participation of the social, economic and behavioral sciences in application-oriented projects;
- solution-oriented research that is focused on the experienced or anticipated problems of practitioners; and,
- advancing understanding of the complex interdependent systems in which we actually live and on whose ability to function communities and economies depend.

6: References

100 Resilient Cities (100RC). 2016. Resilience in Action: Early Insights into How Cities are Institutionalizing Resilience. New York: The Rockefeller Foundation.

Adger, W. N., Eakin, H., and Winkels, A. 2009. Nested and teleconnected vulnerabilities to environmental change. Frontiers in Ecology and the Environment 7(3): 150–157.

Alexander, L. V. 2016. Global observed long-term changes in temperature and precipitation extremes: A review of progress and limitations in IPCC assessments and beyond. Weather and Climate Extremes 11: 4-16.

American Meteorological Society. 2012. Meteorology Glossary. Retrieved from: http://glossary.ametsoc.org/wiki/Teleconnection; last accessed on June 15, 2018.

American Society for Civil Engineers (ASCE) 2017. 2017 Infrastructure Report Card. Washington, DC: ASCE.

Arent, D. J., R. S. J. Tol, E. Faust, J. P. Hella, S. Kumar, K. M. Strzepek, F. L. Tóth, and D. Yan. 2014. Key economic sectors and services. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 659-708, C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds). Cambridge, UK and New York, NY: Cambridge University Press.

Aronson, D., and D. Angelakis. No date. Step-by-step stocks and flows: Converting from causal loop diagrams. The Systems Thinker 10; available at: https://thesystemsthinker.com/step-by-step-stocks-and-flows-converting-from-causal-loop-diagrams/.

Ayyub, B. M. 2015. Risk and uncertainty in engineering systems: Editor's introduction to the aims and scope of the ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems. Journal of Risk and Uncertainty in Engineering Systems Part B: Mechanical Engineering 1(1): 010201-1 - 010201-5.

Ballard, G., Barnard, P.L., Erikson, L., Fitzgibbon, M., Moody, D., Higgason, K., Psaros, M., Veloz, S., Wood, J. 2016. Our Coast Our Future (OCOF). Petaluma, California. Available at: www.ourcoastourfuture.org.

Bartos, M. D., and M. V. Chester. 2015. Impacts of climate change on electric power supply in the Western United States. Nature Climate Change 5: 748-752.

Bartos, M., M. Chester, N. Johnson, B. Gorman, D. Eisenberg, I. Linkov, and M. Bates. 2016. Impacts of rising air temperatures on electric transmission ampacity and peak electricity load in the United States. Environmental Research Letters 11(11): 114008.

Berry, B. 2011. SCADA Tutorial: A Fast Introduction to SCADA Fundamentals and Implementation. Fresno, CA: DPS Telecom.

Biehl, E., S. Buzogany, A. Huang, G. Chodur, and R. Neff. 2017. Baltimore Food System Resilience Advisory Report. Baltimore, MD: Johns Hopkins Center for a Livable Future and Baltimore Office of Sustainability.

Bijl, D. L., P. W. Bogaart, S. C. Dekker, and D. P. van Vuuren. 2018. Unpacking the nexus: Different spatial scales for water, food and energy. Global Environmental Change 48: 22-31.

Bruckner, M., G. Fischer, S. Tramberend, and S. Giljum. 2015. Measuring telecouplings in the global land system: A review and comparative evaluation of land footprint accounting methods. Ecological Economics 114: 11-21.

Buldyrev, S. V., R. Parshani, G. Paul, H. E. Stanley, and S. Havlin. 2010. Catastrophic cascade of failures in interdependent networks. Nature 464(7291): 1025-1028.

Burillo, Daniel, Mikhail Chester, Stephanie Pincetl, Eric Fournier, Katharine Reich, Alex Hall. (University of California Los Angeles). 2018. ***Climate Change in Los Angeles County: Grid Vulnerability to Extreme Heat.*** California's Fourth Climate Change Assessment, California Energy Commission. Publication number: CCCA4-CEC-2018-013.

Camargo, S. J., and S. Anji. 2016. Hottest summers the new normal. Environmental Research Letters 11(8): 081001.

City of Los Angeles. 2015. pLAn: Transforming Los Angeles. Los Angeles: Mayor's Office of Sustainability.

Collins, R. 2017. Calif. dam crisis scrambles power market. E&E News, February 14, 2017.

Corell, R. W., D. Liverman, K. Dow, K. L. Ebi, K. Kunkel, L. O. Mearns, and J. Melillo. 2014. Ch. 29: Research Needs for Climate and Global Change Assessments. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 707-718, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Cutter, S. L., W. Solecki, N. Bragado, J. Carmin, M. Fragkias, M. Ruth, and T. J. Wilbanks. 2014. Ch. 11: Urban Systems, Infrastructure, and Vulnerability. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 282-296, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Dasgupta, P., J. F. Morton, D. Dodman, B. Karapinar, F. Meza, M. G. Rivera-Ferre, A. T. Sarr, and K. E. Vincent. 2014. Rural areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 613-657. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.). Cambridge, UK and New York, NY: Cambridge University Press

Dell, J., S. Tierney, G. Franco, R. G. Newell, R. Richels, J. Weyant, and T. J. Wilbanks. 2014. Ch. 4: Energy Supply and Use. In: Climate Change Impacts in the United States: The Third

National Climate Assessment, 113-129, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Department of Energy (DOE). 2013. U.S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather. Available at: https://www.energy.gov/sites/prod/files/2013/07/f2/20130716-Energy%20Sector%20Vulnerabilities%20Report.pdf.

DOE. 2016. Climate Change and the Electricity Sector: Guide for Assessing Vulnerabilities and Developing Resilience Solutions to Sea Level Rise. Washington, DC: DOE Office of Energy Policy and Systems Analysis.

Department of Homeland Security (DHS). 2013. NIPP 2013: Partnering for Critical Infrastructure Security and Resilience. Washington, DC: Department of Homeland Security.

Downey, D. 2017. The 'extraordinary situation' that led Edison to cut power to thousands as wildfire-prevention strategy. The Orange County Register, December 11, 2017.

D'Souza, R. M. 2017. Curtailing cascading failures. Science 358(6365): 860-861.

Eakin, H., X. Rueda, and A. Mahanti. 2017. Transforming governance in telecoupled food systems. Ecology and Society 22(4): [32].

Easterling, D. R., K. E. Kunkel, M. F. Wehner, and L. Sun. 2016. Detection and attribution of climate extremes in the observed record. Weather and Climate Extremes 11:17-27.

Ernst, K. M., and B. L. Preston. 2017. Adaptation opportunities and constraints in coupled systems: Evidence from the U.S. energy-water nexus. Environmental Science & Policy 70: 38-45.

Evans, P., and P. Fox-Penner. 2014. Resilient and sustainable infrastructure for urban energy systems. Solutions 5(5): 48-54.

Fang, A. J., P. N. Joshua, and J. C. Joshua. 2015. The energy and emissions footprint of water supply for Southern California. Environmental Research Letters 10(11): [114002].

Fang, B. L., Y. Tan, C. B. Li, Y. J. Cao, J. G. Liu, P. J. Schweizer, H. Q. Shi, B. Zhou, H. Chen, and Z. L. Hu. 2016. Energy sustainability under the framework of telecoupling. Energy 106: 253-259.

Federal Energy Regulatory Commission (FERC). 2016. Reliability Primer. Washington, DC: FERC.

Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation. 2012. Arizona-Southern California Outages on September 8, 2011: Causes and Recommendations. Staff Report, April 2012, Washington, DC: NERC. Available at: https://www.nerc.com/pa/rrm/ea/September%202011%20Southwest%20Blackout%20Event%20Document%20L/AZOutage_Report_01MAY12.pdf.

Ferris, D. 2017. In Puerto Rico, the blackout never ends. E&E News, October 19, 2017.

Forzieri, G., A. Bianchi, F. B. e. Silva, M. A. Marin Herrera, A. Leblois, C. Lavalle, J. C. J. H. Aerts, and L. Feyen. 2018. Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environmental Change 48: 97-107.

Friis, C., J. O. Nielsen, I. Otero, H. Haberl, J. Niewohner, and P. Hostert. 2016. From teleconnection to telecoupling: Taking stock of an emerging framework in land system science. Journal of Land Use Science 11(2): 131-153.

Gallagher, L., J. Dalton, C. Bréthaut, T. Allan, H. Bellfield, D. Crilly, K. Cross, D. Gyawali, D. Klein, S. Laine, X. LeFlaive, L. Li, A. Lipponen, N. Matthews, S. Orr, J. Pittock, C. Ringler, M. Smith, D. Tickner, U. von Schlippenbach, and F. Vuille. 2016. The critical role of risk in setting directions for water, food and energy policy and research. Current Opinion in Environmental Sustainability 23: 12-16.

Gallina, V., S. Torresan, A. Critto, A. Sperotto, T. Glade, and A. Marcomini. 2016. A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. Journal of Environmental Management 168: 123-132.

Galston, W. A. 2018. Trump's infrastructure plan: The good, the bad, and the biblical. Washington, DC: The Brookings Institute. Available at: https://www.brookings.edu/blog/fixgov/2018/02/12/trumps-infrastructure-plan-the-good-the-bad-and-the-biblical/; last accessed 6/15/18.

Garfin, G., G. Franco, H. Blanco, A. Comrie, P. Gonzalez, T. Piechota, R. Smyth, and R. Waskom. 2014. Ch. 20: Southwest. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 462-486. J. M. Melillo, T. T. C. Richmond and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Garfin, G., S. LeRoy, B. McMahan, M. Black, and B. Roh. 2016. Preparing for High Consequence, Low Probability Events: Heat, Water & Energy in the Southwest. Report to the U.S. Bureau of Reclamation, from the project Enhancing Water Supply Reliability. Tucson, AZ: University of Arizona, Institute of the Environment.

Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates. 2014. Ch. 3: Water Resources. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 69-112, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Gershunov, A. and K. Guirguis. 2012. California heat waves in the present and future. Geophysical Research Letters 39(18): L18710.

Greater Los Angeles County Integrated Water Management Region (GLAC Region) Leadership Committee. 2014. The Greater Los Angeles County Integrated Regional Water Management Plan. 2014 Update. Los Angeles, CA: GLAIWM.

Grifman, P., J. Hart, J. Ladwig, and M. Schulhof. 2013. Sea Level Rise Vulnerability Study for the City of Los Angeles: A Report for the Mayor of Los Angeles. Los Angeles: University of Southern California Sea Grant Program, USCSG-TR-05-2013.

Griggs, G, Árvai, J, Cayan, D, DeConto, R, Fox, J, Fricker, HA, Kopp, RE, Tebaldi, C, Whiteman, EA (California Ocean Protection Council Science Advisory Team Working Group). 2017. Rising Seas in California: An Update on Sea-Level Rise Science. Oakland, CA: California Ocean Science Trust.

Grubbs, M. W., K. K. Johnston, G. Wang, and T. Ford. 2016. Climate Change Vulnerability Assessment of the Santa Monica Bay National Estuary Program's Bay Restoration Plan. Final Report prepared by the Santa Monica Bay National Estuary Program for the United States Environmental Protection Agency. Santa Monica, CA: Santa Monica Bay National Estuary Program.

Güneralp, B., K. C. Seto, and M. Ramachandran. 2013. Evidence of urban land teleconnections and impacts on hinterlands. Current Opinion in Environmental Sustainability 5(5): 445-51.

Guidotti, R., H. Chmielewski, V. Unnikrishnan, P. Gardoni, T. McAllister, and J. van de Lindt. 2016. Modeling the resilience of critical infrastructure: The role of network dependencies. Sustainable and Resilient Infrastructure 1(3-4): 153-168.

Guirguis, K., et al. 2018. Heat wave probability in the changing climate of the Southwest US. Climate Dynamics 50(9): 3853-3864.

Guzman-Morales, J., A. Gershunov, J. Theiss, H. Li, and D. Cayan. 2016. Santa Ana winds of Southern California: Their climatology, extremes, and behavior spanning six and a half decades. Geophysical Research Letters 43(6): 2827-2834.

Hay, J. E., D. Easterling, K. L. Ebi, A. Kitoh, and M. Parry. 2016. Conclusion to the special issue: Observed and projected changes in weather and climate extremes. Weather and Climate Extremes 11: 103-105.

Helmuth, M., P. Schultz, J. Bruzgul, D. Spindler, H. Pacini. 2014. Assessment of Climate Change Risks to Energy Reliability in the WECC Region. Report Prepared for WECC by ICF International. Available at: https://www.wecc.biz/Reliability/Assessment-of-Climate-Change-Risks-to-Reliability-ICF-Dec-2014.pdf.

Hester, J. L. 2017. Harvey is changing the way we feed people during disaster. Grist Magazine, September 1, 2017.

Hibbard, K., T. Wilson, K. Averyt, R. Harriss, R. Newmark, S. Rose, E. Shevliakova, and V. Tidwell. 2014. Ch. 10: Energy, Water, and Land Use. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 257-281, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, Dc: U.S. Global Change Research Program.

Howarth, C., and I. Monasterolo. 2017. Opportunities for knowledge co-production across the energy-food-water nexus: Making interdisciplinary approaches work for better climate decision making. Environmental Science & Policy 75: 103-110.

Howells, M., et al. 2013. Integrated analysis of climate change, land-use, energy and water strategies. Nature Climate Change 3: 621-626.

Hughes, M., A. Hall, and J. Kim. 2009. Anthropogenic Reduction of Santa Ana Winds. Sacramento, CA: California Energy Commission.

IFAD. 2009. Good Practices in Participatory Mapping. A Review Prepared for the International Fund for Agricultural Development (IFAD). Rome, Italy: IFAD.

Joselow, M. 2017a. National lab helps utilities plan for a warmer climate. E&E News, June 12, 2017.

Joselow, M. 2017b. Superstorm Sandy a 'wake-up call' for microgrid supporters. E&E News, July 11, 2017.

Jurardo, J. 2017. Critical Infrastructure and Future Flood Risk in Broward County. Presentation to the Technical Advisory Committee to the Broward Water Advisory Board on February 17, 2017. Available at: https://broward.org/NaturalResources/AboutUs/Documents/tacpres021717_cifre.pdf.

Kahn, D. 2017. PG&E stock drops as regulators probe link to Calif. wildfires. E&E News, October 17, 2017.

Kelly, C., C. Martinez, and W. Hathaway-Williams. 2017. A Framework for Local Action on Climate Change: 9 Ways Mayors Can Build Resilient and Just Cities. Washington, DC: Center for American Progress.

Kim, D. H. 2016. Introduction to systems thinking. The Systems Thinker 3; available online at: https://thesystemsthinker.com/wp-content/uploads/2016/03/Introduction-to-Systems-Thinking-IMS013Epk.pdf.

Kim, D. H. 1992. System Archetypes I: Diagnosing Systemic Issues and Designing High-leverage Interventions. Waltham, MA: Pegasus Communications Inc.

Krishnamurthy, V., and A. Kwasinski. 2016. Modeling of communication systems dependency on electric power during nuclear attacks. Paper read at 2016 IEEE International Telecommunications Energy Conference (INTELEC), 23-27 Oct. 2016.

Lannon, C. P. No date. Causal loop construction: The basics. The Systems Thinker 23(7); available online at: https://thesystemsthinker.com/causal-loop-construction-the-basics/.

Lenschow, A., J. Newig, and E. Challies. 2016. Globalization's limits to the environmental state? Integrating telecoupling into global environmental governance. Environmental Politics 25(1): 136-159.

Lifelines Council of the City and County of San Francisco (Lifelines Council). 2014. Lifelines Interdependency Study. San Francisco, CA: City of San Francisco, Mayor's Office.

Liu, J. G., V. Hull, M. Batistella, R. DeFries, T. Dietz, F. Fu, T. W. Hertel, R. C. Izaurralde, E. F. Lambin, S. X. Li, L. A. Martinelli, W. J. McConnell, E. F. Moran, R. Naylor, Z. Y. Ouyang, K. R. Polenske, A. Reenberg, G. D. Rocha, C. S. Simmons, P. H. Verburg, P. M. Vitousek, F. S. Zhang, and C. Q. Zhu. 2013. Framing sustainability in a telecoupled world. Ecology and Society 18(2): [26].

Liu, J. G., V. Hull, J. Y. Luo, W. Yang, W. Liu, A. Vina, C. Vogt, Z. C. Xu, H. B. Yang, J. D. Zhang, L. An, X. D. Chen, S. X. Li, Z. Y. Ouyang, W. H. Xu, and H. M. Zhang. 2015a. Multiple telecouplings and their complex interrelationships. Ecology and Society 20(3): [44].

Liu, J. G., H. Mooney, V. Hull, S. J. Davis, J. Gaskell, T. Hertel, J. Lubchenco, K. C. Seto, P. Gleick, C. Kremen, and S. X. Li. 2015b. Systems integration for global sustainability. Science 347(6225): 963 and 1258832-1–1258832-9.

Liu, J. G., W. Yang, and S. X. Li. 2016. Framing ecosystem services in the telecoupled Anthropocene. Frontiers in Ecology and the Environment 14(1): 27-36.

Liu, J. G. 2017. Integration across a metacoupled world. Ecology and Society 22(4): [29].

Lopez, H., R. West, S. Dong, G. Goni, B. Kirtman, S.-K. Lee, and R. Atlas. 2018. Early emergence of anthropogenically forced heat waves in the western United States and Great Lakes. Nature Climate Change, online first, doi:10.1038/s41558-018-0116-y.

Macknick, J., E. Zhou, M. O'Connell, G. Brinkman, A. Miara, E. Ibanez, and M. Hummon. 2016. Water and Climate Impacts on Power System Operations: The Importance of Cooling Systems and Demand Response Measures. NREL Technical Report NREL/TP-6A20-66714. Golden, CO: NREL.

Maizlish, N., D. English, J. Chan, K. Dervin, and P. English. 2017. Climate Change and Health Profile Report: Los Angeles County. Sacramento, CA: Office of Health Equity, California Department of Public Health.

McMahon, J. E., and S. K. Price. 2011. Water and energy interactions. Annual Review of Environment and Resources 36(1):163-191.

McNichol, E. 2017. It's Time for States to Invest in Infrastructure. Washington, DC: Center for Budget and Policy Priorities.

Meerow, S., J. P. Newell, and M. Stults. 2016. Defining urban resilience: A review. Landscape and Urban Planning 147: 38-49.

Melillo, J. M., T. C. Richmond & G. W. Yohe. 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. Washington, DC: U.S. Global Change Research Program.

Miara, A., J. E. Macknick, C. J. Vörösmarty, V. C. Tidwell, R. Newmark, and B. Fekete. 2017. Climate and water resource change impacts and adaptation potential for US power supply. Nature Climate Change 7: 793.

Miller, N. and N. Schlegel. 2006. Climate-Change Projected Santa Ana Fire Weather Occurrence. White Paper, CEC-500-2005-204-SF. Sacramento, CA: California Energy Commission.

Moftakhari, R.H., G. Salvadori, A. AghaKouchak, B. Sanders, and R. Matthew. 2017. Compounding effects of sea level rise and fluvial flooding. Proceedings of the National Academy of Sciences of the United States of America 114(37): 201620325.

Moser, S. C., and J. A. Ekstrom. 2010. A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences of the United States of America 107(51): 22026-22031.

Moser, S. C., M. A. Davidson, P. Kirshen, P. Mulvaney, J. F. Murley, J. E. Neumann, L. Petes, and D. Reed. 2014. Ch. 25: Coastal Zone Development and Ecosystems. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 579-618, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Moser, S. C., and J. A. F. Hart. 2015. The long arm of climate change: Societal teleconnections and the future of climate change impacts studies. Climatic Change 129(1-2): 13-26.

Moser, Susanne C., J.A. Ekstrom, J. Kim, S. Heitsch. (Susanne Moser Research & Consulting, Department of Water Resources, Local Government Commission and ICF). 2018. ***Adaptation Finance Challenges: Characteristic Patterns Facing California Local Governments and Ways to Overcome Them***. California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CCCA4-CNRA-2018-007.

Moser, S. C., S. A. Meerow, J. C. Arnott, and E. Jack-Scott. forthcoming. The turbulent world of resilience: Signals rising above the noise in cross- and transdisciplinary communication. Climatic Change, in review.

National Academies of Sciences, Engineering, and Medicine (NASEM). 2016. Attribution of Extreme Weather Events in the Context of Climate Change. Washington, DC: The National Academies Press.

NASEM. 2017. Enhancing the Resilience of the Nation's Electricity System. Washington, DC: The National Academies Press.

National Coordinating Centre for Public Engagement (NCCPE). No date. Participatory mapping. NCCPE; available online at: http://www.publicengagement.ac.uk/do-it/techniquesapproaches/participatorymapping.

North American Electric Reliability Council (NERC). 2016. 2016 Long-Term Reliability Assessment. Atlanta, CA: NERC.

Oberlack, C., S. Boillat, S. Brönnimann, J.-D. Gerber, A. Heinimann, C. Ifejika Speranza, P. Messerli, S. Rist, and U. Wiesmann. 2018. Polycentric governance in telecoupled resource systems. Ecology and Society 23(1): [16].

Ocean Protection Council (OPC). 2018. State of California Sea-Level Rise Guidance: 2018 Update. Sacramento, CA: OPC/CNRA.

Office of the President. 2018. Legislative Outline for Rebuilding Infrastructure in America. Washington, Dc: The White House. Available at: https://www.whitehouse.gov/wp-content/uploads/2018/02/INFRASTRUCTURE-211.pdf.

Pathways to Resilience (P2R) Partners. 2015. Pathways to Resilience: Transforming Cities in a Changing Climate. Oakland CA: P2R Partners (Movement Strategy Center, Movement Generation, The Praxis Project, Reimagine! RP&E and the Kresge Foundation).

Pescaroli, G., and D. Alexander. 2015. A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. Planet@Risk, Global Risk Forum (GRF) Davos 3(1): 58-67.

Platt, R. H. 1991. Lifelines: An emergency management priority for the United States in the 1990s. Disasters 15(2): 172-176.

Plumer, B. 2017. Why getting the power back on in Florida could take weeks. The New York Times, September 12, 2017.

Ralff-Douglas, K. 2016. Climate Adaptation in the Electric Sector: Vulnerability Assessments & Resiliency Plans. Sacramento, CA: California Public Utilities Commission (CPUC).

Ramaswami, A., C. Weible, D. Main, T. Heikkila, S. Siddiki, A. Duvall, A. Pattison, and M. Bernard. 2012. A social-ecological-infrastructural systems framework for interdisciplinary study of sustainable city systems. Journal of Industrial Ecology 16(6): 801-813.

Rao, P., R. Kostecki, L. Dale, and A. Gadgil. 2017. Technology and engineering of the water-energy nexus. Annual Review of Environment and Resources 42(1): 407-437.

Reiner, M., and L. McElvaney. 2017. Foundational infrastructure framework for city resilience. Sustainable and Resilient Infrastructure 2(1): 1-7.

Revi, A., D. E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R. B. R. Kiunsi, M. Pelling, D. C. Roberts, and W. Solecki. 2014. Urban areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 535-612, C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.). Cambridge, UK and New York, NY: Cambridge University Press.

Romero-Lankao, P., J. B. Smith, D. J. Davidson, N. S. Diffenbaugh, P. L. Kinney, P. Kirshen, P. Kovacs, and L. V. Ruiz. 2014. North America. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1439-1498, C. B. Field, V. R. Barros, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea and L. L. White (eds.). Cambridge, UK and New York, NY Cambridge University Press.

Romero-Lankao, P., T. McPhearson, and D. J. Davidson. 2017. The food-energy-water nexus and urban complexity. Nature Climate Change 7(4): 233-235.

Schoof, J. T., and S. M. Robeson. 2016. Projecting changes in regional temperature and precipitation extremes in the United States. Weather and Climate Extremes 11: 28-40.

Schwartz, H. G., M. Meyer, C. J. Burbank, M. Kuby, C. Oster, J. Posey, E. J. Russo, and A. Rypinski, 2014: Ch. 5: Transportation. In: Climate Change Impacts in the United States: The Third National Climate Assessment, 130-149, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe (eds.). Washington, DC: U.S. Global Change Research Program.

Seto, K. C., Reenberg, A., Boone, C. G., Fragkias, M., Haase, D., Langanke, T., and Simon, D. 2012. Urban land teleconnections and sustainability. Proceedings of the National Academy of Sciences 109(20): 7687–7692

Sillmann, J., V. V. Kharin, X. Zhang, F. W. Zwiers, and D. Bronaugh. 2013a. Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate. Journal of Geophysical Research: Atmospheres 118(4): 1716-1733.

Sillmann, J., V. V. Kharin, F. W. Zwiers, X. Zhang, and D. Bronaugh. 2013b. Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. Journal of Geophysical Research: Atmospheres 118(4): 2473–2493.

Sillmann, J., T. Thorarinsdottir, N. Keenlyside, N. Schaller, L. V. Alexander, G. Hegerl, S. I. Seneviratne, R. Vautard, X. Zhang, and F. W. Zwiers. 2017. Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities. Weather and Climate Extremes 18: 65-74.

Sobczak, B. 2017. GAO clears the air around overlapping resiliency efforts. E&E News, February 28, 2017.

Sonter, L. J., J. A. Johnson, C. C. Nicholson, L. L. Richardson, K. B. Watson, and T. H. Ricketts. 2017. Multi-site interactions: Understanding the offsite impacts of land use change on the use and supply of ecosystem services. Ecosystem Services 23: 158-164.

Star, S. L. 2010. This is not a boundary object: Reflections on the origin of a concept. Science Technology Human Values 35: 601-617.

Star, S. L. and J. R. Griesemer. 1989. Institutional ecology, 'translations,' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social Studies of Science 19: 387-420.

St. John, P. 2017. Alarming failures left many in path of California wildfires vulnerable and without warning. Los Angeles Times, December 29, 2017.

Stevens, D., and L. Luke. 2016. Southern California Critical Lifelines Workgroup. Introductory presentation to the Workgroup. Available at: http://cms.capitoltechsolutions.com/ClientData/CUEA/documents/Stevens_CUEAslidesJune2016.pdf

Tebaldi, C., K. Hayhoe, J. M. Arblaster, and G. A. Meehl. 2006. Going to the Extremes. Climatic Change 79(3): 185-211

Thomas, K., and S. Kaplan. 2017. Hurricane damage in Puerto Rico leads to fears of drug shortage nationwide. The New York Times, October 4 2017, p.A1.

Tonini, F., and J. Liu. 2017. Telecoupling toolbox: Spatially explicit tools for studying telecoupled human and natural systems. Ecology and Society 22(4): [11].

Trenberth, K. E., J. T. Fasullo, and T. G. Shepherd. 2015. Attribution of climate extreme events. Nature Climate Change 5: 725.

Turoff, M., V. A. Bañuls, L. Plotnick, S. R. Hiltz, and M. Ramírez de la Huerga. 2016. A collaborative dynamic scenario model for the interaction of critical infrastructures. Futures 84(Part A): 23-42.

Urban Resilience Program. 2018. Ten Principles for Building Resilience. Washington, DC: Urban Land Institute.

USC Bedrosian Center on Governance. 2016. Strengthening SoCal: Southern California Disaster Risk Reduction Initiative. Los Angeles: USC Bedrosian Center on Governance; available at: https://bedrosian.usc.edu/files/2016/06/SCDRRIReport.pdf.

Vaidya, S., and M. Hounjet. 2017. Enabling early action by focusing on partnerships among Critical Infrastructure Networks. Delft, Netherlands: Deltares.

Vespignani, A. 2010. The fragility of interdependency. Nature 464: 984.

Western Electricity Coordinating Council (WECC), and North American Electric Reliability Corporation (NERC). 2016. Reliability Assurance Project of the Western Interconnection Findings. Salt Lake City, UT: WECC.

Weitz, N., C. Strambo, E. Kemp-Benedict, and M. Nilsson. 2017. Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. Global Environmental Change 45: 165-173.

Wilby, R. L., and S. Dessai. 2010. Robust adaptation to climate change. Weather 65(7): 180-185.

Yang, Y., T. Nishikawa, and A. E. Motter. 2017. Small vulnerable sets determine large network cascades in power grids. Science 358(6365): 886 and eaan3184 (7 pp.).

Yang, Z. J., and L. Kahlor. 2013. What, me worry? The Rrle of affect in information seeking and avoidance. Science Communication 35(2): 189-212.

Zhang, X., L. Alexander, G. C. Hegerl, P. Jones, A. K. Tank, T. C. Peterson, B. Trewin, and F. W. Zwiers. 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. Wiley Interdisciplinary Reviews: Climate Change 2(6): 851-870.

APPENDIX A: List of Interviewees and Workshop Participants

Workshop participants and interviewees are listed in alphabetical order. Those who also served on the study's Technical Advisory Group (TAG) are indicated as such.

Marissa Aho (City of L.A., Mayor's Office, TAG member)
Margaret Ayalla (L.A. County Emergency Management)
Tim Ayers (ExteNet)
Lindsay Barker (City of Santa Monica, Office of Emergency Management)
Kit Batten (PG&E)
Lawrence Beer (ExteNet)
Neil Berg (UCLA)
Sabrina Bornstein (City of L.A., Mayor's Office, TAG member)
Daniel Burillo (Arizona State University)
Rita Burke (Children's Hospital L.A.)
Anna Burton (then with L.A. Emergency Management, TAG member)
John Bwarie (Stratiscop)
Dale Cox (USGS, TAG member)
Don Daigler (Southern California Edison/SCE)
Geoffrey Danker (Southern California Gas Company)
Craig Davis (DWP)
Karen Eckersley (CPUC)
Zoe Elizabeth (then with the L.A. Regional Collaborative/LARC)
Lauren Faber O'Conner (City of L.A., Mayor's Office, TAG member)
David Fink (then with Climate Resolve)
Keith Garcia (L.A. Department of Power and Water/DWP, TAG member)
Phyllis Grifman (USC Sea Grant)
Alex Hall (UCLA)
Lisa Hayes (DWP)
Emily Helder (City of L.A. Emergency Management Department)
Yu Ho (California Energy Commission)
Patrick Horton (DWP, TAG member)
Kenneth Hudnut (USGS)
Michelle Hummel (UC-Berkeley)
Laurel Hunt (LARC)
Andrew Jones (Lawrence Berkeley National Laboratory)
Rob Lempert (Rand Corp.)
Cris Liban, Ph.D. (L.A. Metro, TAG member)
Kristine Lloyd (then with Southern California Gas Company)
Leslie Luke (L.A. County Office of Emergency Management, TAG member)
Emily Montanez (L.A. County Office of Emergency Management)

Jay Noceta (ExteNet)
Shannon Parry (City of Santa Monica, Office of Sustainability and the Environment)
Kristin Ralff Douglas (CPUC, TAG member)
Michelle Riebeling (City of L.A. Emergency Management Department)
Elizabeth Rhoades (L.A. Department of Public Health, TAG member)
Jamesine Rogers Gibson (Union of Concerned Scientists)
Nick Sadrpour (USC Sea Grant)
Jack Sahl, Ph.D. (SCE, TAG member)
Iesha Siler (Good Food L.A.)
Mark Stacey (UC-Berkeley)
Dan Stevens (SCE, TAG member)
Roger Wang (UC-Berkeley)

APPENDIX B: Interview Protocol

B.1 Interview Protocol for Interviewees in the Energy Sector:

Opening/prior to interview: inform interviewee of study, expected length of interview, and request consent to be interviewed (signing of consent form)

1. Before we get started, do you have any question to us on the study, from the webinar (if applicable), or about the interview?

Background information on interviewee:

2. Please describe your current responsibilities in your organization.
   Follow-up (FUP): How long have you held this position?
   FUP: How long have you been at this agency?
   FUP: Where were you previously employed (if relevant to the study)?

Background questions on the organization:

3. Can you describe the range of services your organization provides to the Greater L.A. region?
4. What is the exact geographic extent over which your organization provides [electricity, water, telecommunication, emergency etc.] services?
   FUP: Is there a map we can look at together to get a better sense of what area you cover?
5. In order for your organization to provide these services, are you dependent on other's supplies, resources or services?
   FUP: And what is the geographic extent of your upstream service providers?

Disruption-related questions:

6. In your day-to day work, what kind of service disruptions do you expect and plan for?
   FUP: Are there specific extreme events that you are most concerned about?

7. What procedures are in place to get disrupted systems back up and running?
   FUP: Can you say more?

8. Can you describe a "good day", i.e., a day when maybe a disruption occurred and your plans for these types of events worked exactly as intended and you had your system back up and running as quickly as possible, with minimal damage or losses?
   FUP: What was the origin of the disruption?
   FUP: How long did the disruption last (from first interruption to full system reestablishment)?
   FUP: What impacts did this event have on your system?
   FUP: What impacts did it have on the clients of your services?
   FUP: What do you think made this a "good day"? What worked well?

9. Now can you describe a "not so good day" i.e., a day when a disruption occurred and your plans did not work as intended, your system was down longer and the impacts were far more significant?
   FUP: What was the origin of that disruption?
   FUP: How long did this disruption last (from first interruption to full system reestablishment)?
   FUP: What impacts did this event have on your system?
   FUP: What impacts did it have on the clients of your services?
   FUP: What do you think made this a "bad day"? Where did things go wrong?
   FUP: Probe further as necessary.

Questions about system interconnectivity:

10. In order for your system to operate at its most effective and efficient together with your upstream providers:
    a. What is the standard operating procedure (SOP)?
    b. Who are you mandated to communicate with?
    c. Who else do you reach out to?

11. How does your organization coordinate with downstream clients/ sectors/ operators?
    a. What is the SOP?
    b. Who are you mandated to communicate with?
    c. Who else do you reach out to?

12. What is working well, in your opinion, in these up- and downstream connections?
    FUP: Why do you think this is working as well as it does?

13. Is there any aspect in this upstream and downstream interaction you would like to see improved?
    FUP: If yes, what is it and how should it be improved in your opinion?

Questions about climate preparedness and adaptation:

14. What kind of service disruptions do you anticipate from climate variability & change?
    FUP: Are the interruptions dependent on the type of climate impact (e.g. heat vs. flood vs. fire?

15. To what extent does your organization consider climate adaptations to date?
    FUP: Are there any official procedures (or adaptation strategies) in place to address these?

    FUP: are there documents you can share?

16. What is your particular role in all that?

17. Is there anything regarding climate change that worries you in terms of your continued ability to provide the services you provide?

18. Do you have any other thoughts regarding the long-distance/upstream and potential downstream impacts of climate change?

Questions to advance project:

19. Who do you recommend we speak to in [name relevant other connected sectors or organizations]?
20. Did our conversation raise any issues for you that you would like to see addressed by this project?

B.2 Interview Protocol for Iinterviewees in Other Sectors

Opening/prior to interview: inform interviewee of study, expected length of interview, and request consent to be interviewed (signing of consent form)

1. Before we get started, do you have any question to us on the study, from the webinar (if applicable), or about the interview?

Background information on interviewee:

2. Please describe your current responsibilities in your organization.
   Follow-up (FUP): How long have you held this position?
   FUP: How long have you been at this agency?
   FUP: Where were you previously employed (if relevant to the study)?

Background questions on the organization:

3. Can you describe the range of services your organization provides to the Greater L.A. region?
4. What is the exact geographic extent over which your organization provides [electricity, water, telecommunication, emergency etc.] services?
   FUP: Is there a map we can look at together to get a better sense of what area you cover?
5. In order for your organization to provide these services, are you dependent on other's supplies, resources or services?
   FUP: And what is the geographic extent of your upstream service providers?

Disruption-related questions:

6. In your day-to day work, what kind of service disruptions do you expect and plan for?
   FUP: Are there specific extreme events that you are most concerned about?
7. What procedures are in place to get disrupted systems back up and running?
   FUP: Can you say more?

8. Can you describe a "good day", i.e., a day when maybe a disruption occurred and your plans for these types of events worked exactly as intended and you had your system back up and running as quickly as possible, with minimal damage or losses?
   FUP: What was the origin of the disruption?
   FUP: How long did the disruption last (from first interruption to full system reestablishment)?
   FUP: What impacts did this event have on your system?
   FUP: What impacts did it have on the clients of your services?
   FUP: What do you think made this a "good day"? What worked well?

9. Now can you describe a "not so good day" i.e., a day when a disruption occurred and your plans did not work as intended, your system was down longer and the impacts were far more significant?
   FUP: What was the origin of that disruption?
   FUP: How long did this disruption last (from first interruption to full system reestablishment)?
   FUP: What impacts did this event have on your system?
   FUP: What impacts did it have on the clients of your services?
   FUP: What do you think made this a "bad day"? Where did things go wrong?
   FUP: Probe further as necessary.

Questions about system interconnectivity:

10. In order for your system to operate at its most effective and efficient together with your upstream providers:
    a. What is the standard operating procedure (SOP)?
    b. Who are you mandated to communicate with?
    c. Who else do you reach out to?

11. How does your organization coordinate with downstream clients/ sectors/ operators?
    a. What is the SOP?
    b. Who are you mandated to communicate with?
    c. Who else do you reach out to?

12. What is working well, in your opinion, in these up- and downstream connections?
    FUP: Why do you think this is working as well as it does?

13. Is there any aspect in this upstream and downstream interaction you would like to see improved?
    FUP: If yes, what is it and how should it be improved in your opinion?

Questions about climate preparedness and adaptation:

14. What kind of service disruptions do you anticipate from climate variability & change?
    FUP: Are the interruptions dependent on the type of climate impact (e.g. heat vs. flood vs. fire?

15. To what extent does your organization consider climate adaptations to date?
    FUP: Are there any official procedures (or adaptation strategies) in place to address these?

FUP: Are there documents you can share?

16. What is your particular role in all that?
17. Is there anything regarding climate change that worries you in terms of your continued ability to provide the services you provide?
18. Do you have any other thoughts regarding the long-distance/upstream and potential downstream impacts of climate change?

Questions to advance project:

19. Who do you recommend we speak to in [name relevant other connected sectors or organizations]?
20. Did our conversation raise any issues for you that you would like to see addressed by this project?

APPENDIX C: Critical Nodes of Interconnection in L.A.'s Lifeline System

Appendix C: List of Nodes Incorporated in the Elephant Builder

Table C-1: List of Nodes Crossed by their Associated Lifeline

Lifeline	List of Related Nodes	Lifeline	List of Related Nodes
Telecommunication	comms maintenance comms switch function comms transmission - wired comms transoceanic landing communications reliability firstnet function internet access phone function radio function satellite phone function scada function	Emergency Management	civil unrest community stability emerg basic needs emerg training and exercises emergency food availability emergency services provision emergency shelter eoc activation/coord of srvcs firefighting water supply first responder availability food safety law enforcement pod function ppe availability property damage public safety
Health Services	health services provision hospital datacenter function onsite disaster management preventive maintenance	Public Health	environmental risk assessment health facility function heat-related illness interagency coordination mental health mobile command post function morbidity and death public health public health advisories public health srvc provision

Source: The Authors

Lifeline	List of Related Nodes	Lifeline	List of Related Nodes
Energy	backup generator function diesel supply discrepancy supply-demand distributed energy resources distribution equipment functio distribution switching electrical buffering capacity electrical power generation	Transportation	accessibility air transpo reliability bus reliability connectivity of communities distribution of supplies engineering standards fueling of buses gasoline availability

	electrical power provision hydropower generation isolation of distrib equipment isolation of transm equipment load shedding local electricity demand local load balance natural gas availability natural gas compression natural gas pipeline integrity natural gas storage capacity peaker plant function refinery function regional discrep supply-demand regional electricity demand regional load balance solar power generation transmission equipment functio transmission switching vegetation management wind power generation steam power generation		goods movement heavy equipment availability heavy equipment function highway system reliability light rail reliability mobility private vehicle function rail reliability road age road i.t. system function road maintenance road material availability shipping transpo reliability state of good repair street services subway reliability
Water	aqueduct volume bottled water availability colorado river flow dwp reservoir stock dwr reservoir stock eastern sierra snowpack in-basin aquifer stock irrigation mwd reservoir stock potable water supply rainwater harvesting San Joaquin delta function stormwater capture wastewater pump function wastewater treatment wastewater volume water availability water conservation water pump function water recycling water system maintenance water treatment function water use	No lifeline assigned	air quality backup battery function commerce decomposition evaporative cooling generator function heating household function hvac function refrigeration sanitation stormwater management workforce availability workforce development

Source: The Authors