Built to Last

Challenges and Opportunities for Climate-Smart Infrastructure in California

Jamesine Rogers Gibson

November 2017

Union of Concerned Scientists

© 2017 Union of Concerned Scientists
All Rights Reserved

Jamesine Rogers Gibson is the Western States senior climate analyst in the UCS Climate and Energy Program.

The Union of Concerned Scientists puts rigorous, independent science to work to solve our planet's most pressing problems. Joining with people across the country, we combine technical analysis and effective advocacy to create innovative, practical solutions for a healthy, safe, and sustainable future.

More information about UCS and the Climate and Energy Program is available on the UCS websites: *www.ucsusa.org/global_warming* and *www.ucsusa.org/global_warming/regional_information/ca-and-western-states.html.*

This report is available online (in PDF format) at *www.ucsusa.org/climate-smart-infrastructure.*

NATIONAL HEADQUARTERS
Two Brattle Square
Cambridge, MA 02138-3780
t 617.547.5552
f 617.864.9405

WASHINGTON, DC, OFFICE
1825 K St. NW, Ste. 800
Washington, DC 20006-1232
t 202.223.6133
f 202.223.6162

WEST COAST OFFICE
500 12th St., Suite 340
Oakland, CA 94607-4087
t 510.843.1872
f 510.451.3785

MIDWEST OFFICE
One N. LaSalle St., Ste. 1904
Chicago, IL 60602-4064
t 312.578.1750
f 312.578.1751

[CONTENTS]

[FIGURES, TABLE, AND BOXES]

FIGURES

TABLE

BOXES

[ACKNOWLEDGMENTS]

This work was made possible by the generous support of the Energy Foundation and members of the Union of Concerned Scientists. It was informed and shaped by the expertise and deliberations of participants at the UCS "Climate Risk and Infrastructure" convening held in April 2017 and expert interviews.

The paper was improved by valuable feedback from a number of reviewers: Anisha Anantapadmanabhan and Karen Yacos (Ceres), David Behar (San Francisco Public Utilities Commission), Josiah Cain (Sherwood Design Engineers), Laura Engeman (San Diego Regional Climate Collaborative), Chione Flegal (PolicyLink), Dr. Cris Liban, PE (American Society of Civil Engineers (Fellow) and Los Angeles Metropolitan Transportation Authority), Sona Mohnot (Greenlining Institute), Bruce Riordan (Climate Readiness Institute), and Dr. Kif Scheuer (Local Government Commission).

The author would also like to acknowledge the many UCS staff who supported this work and final product. This paper would not have been possible without the partnership of the following people. Adrienne Alvord provided invaluable strategic direction and review of the document. Deborah Moore planned and facilitated the convening, assisted with the expert interviews, and gave insightful recommendations and feedback on the document. Katherine Cullen helped organize the convening and provided excellent research support, especially for the graphics and table. For their thoughtful review and input into the document, I thank Angela Anderson, Astrid Caldas, Rachel Cleetus, Abby Figueroa, Erika Spanger-Siegfried, and Shana Udvardy. The author would also like to thank Heather Tuttle for shepherding the paper through the graphics process and Maria Vidart for her assistance with the web features that accompany this document.

I am also grateful to Leslie Brunetta for her invaluable assistance as copy editor of this paper and to Tyler Kemp-Benedict for translating our vision into a compelling graphic.

Organizational affiliations are listed for identification purposes only. The opinions expressed herein do not necessarily reflect those of the organizations that funded the work or the individuals who reviewed it. The Union of Concerned Scientists bears sole responsibility for the report's contents.

[EXECUTIVE SUMMARY]

A reliable and safe infrastructure system is the backbone of a healthy economy, public safety, and quality of life in California. It provides essential services and access to opportunity, from jobs to education to healthcare. The consequences of infrastructure disruptions on communities and the economy can therefore be devastating, with serious implications for their well-being and resilience in the face of hazards.

In California as elsewhere, global warming and climate change together represent one of the greatest threats to communities and the infrastructure on which they depend. With a “new normal” of ever-increasing variability and extremes in climate conditions, we expect to see more extreme heat and precipitation, more extensive and longer-lasting droughts, more frequent and intense wildfires, and sea level rise. We are already experiencing some of these events today, including this year’s devastating wildfire season in the West, an historic extreme rainfall following a five-year drought, and a deadly heat wave in California. Extreme climate conditions affect other parts of the country as well, the most recent example being the horrible human suffering, lives lost, property-related damage, and humanitarian crises in the places impacted by Hurricanes Harvey, Irma, and Maria. These changing conditions threaten an already deteriorating infrastructure system, which traditionally has been planned, designed, and engineered based on historical climate and weather data and trends on the assumption that the past is a good predictor of the future.

We must take future weather and climate conditions into account as we plan, build, and retrofit our long-lived critical public infrastructure[1] so that it can remain safe, reliable, and functional despite these impacts. Just as California considers seismic risks as we build and retrofit our infrastructure even though we do not know exactly when, where, or how the next big earthquake will happen, we need to consider climate risks.[2] The state plans to invest billions of dollars over the next few years in new and existing infrastructure, including long-lived assets that will experience more severe climate conditions over their life spans. This significant level of taxpayer investment increases the urgency with which we need to incorporate climate-risk management into these and other infrastructure projects, so that they can continue to deliver services essential to the public’s health, safety, and welfare over their planned lifetimes. These projects must be resilient: able to withstand these climate-related risks, and other hazards, in order to maintain essential services with minimal disruptions, to recover quickly when damage does occur, and to adapt to changing conditions in ways that benefit all people. Otherwise, we risk building costly infrastructure that may fail well before its intended life span, to the serious detriment of community well-being, public health and safety, the economy, and limited recovery resources.

While it is not possible or practical to avoid every negative effect of climate change on infrastructure and the services it provides, we can minimize risk by designing our infrastructure to be “climate-smart.” In this white paper, we present and elaborate key principles for achieving climate-smart infrastructure: applying rigorous science; prioritizing equitable outcomes; spending limited resources wisely; and planning proactively, holistically, and transparently. By building climate-smart infrastructure, California can also reap multiple social, economic, health, and environmental benefits and take advantage of opportunities to reduce heat-trapping emissions and encourage innovative infrastructure solutions for the 21st century.

---

[1] This white paper examines public infrastructure only, not private infrastructure. It employs a modified definition of public infrastructure taken from Poole, Toohey, and Harris (2014): an “investment where the government has the primary role in, and responsibility for, deciding on whether and how the infrastructure is provided in the interests of the broader community and on the source of the revenue streams to pay for the infrastructure over its life.” It therefore includes “infrastructure that is owned or directly funded by the public sector” but also some “infrastructure assets and services owned and operated by the private sector, but where the government has created the overarching policy and regulatory framework or possibly retains a contingent liability for the infrastructure assets and continued service provision.” We acknowledge that public–private partnerships are becoming more common financing mechanisms, and a portion of California’s infrastructure is privately owned. The private infrastructure is interconnected to the overall infrastructure system, so its degree of resilience to extreme weather and climate change is important as well.

[2] This paper also focuses on climate risks related to climate variability and change. There are other important risks associated with climate change that may affect infrastructure—such as a price on carbon or other policies designed to reduce heat-trapping emissions, divestment and stranded assets, etc.—but we do not address them in this white paper.

California recently adopted policies requiring state agencies to take climate change into account in planning and investment.[3] These efforts are at an early stage and are not yet systematically implemented, especially at the project level. The next few years present critical opportunities to help shape implementation and ensure that the billions of dollars the state is planning to invest in new infrastructure and the maintenance and retrofits of existing infrastructure bolster the climate resilience of the overall system so that it can continue to deliver key services for many decades to come. It is also critical that climate-resilient infrastructure decisions take into account the needs of underserved communities, including low-income communities and communities of color who frequently bear the worst brunt of both infrastructure failures and climate impacts.

To better understand how to improve and accelerate integration of climate-smart principles into public infrastructure decisions, the Union of Concerned Scientists (UCS) conducted a series of interviews, performed a selective literature review, and in early 2017 convened experts from a wide variety of domains involved in the planning, development, building, and financing of infrastructure as well as experts involved in climate science, emergency management, and equity and social justice. (See the appendix for a list of attendees.) We present our research results in this paper. We found several barriers to progress and make recommendations for overcoming them that generally fall into three categories: (1) data, tools, and standards; (2) financial and economic assessments and investments; and (3) institutional capacity and good governance. We highlight equity issues throughout.

Our policy recommendations are intentionally high level so that they can be applied and tailored to various contexts across different sectors and regions of the state. They are summarized below, with more detail provided in the paper.

- Update outdated standards and codes and increase the technical capacity of government and agency staff involved in all infrastructure decisions.
- Improve the technical and scientific basis for planning, evaluating, and implementing infrastructure projects, services, and systems. Ensure those processes better address climate-related risks, costs, and benefits, as well as uncertainties and equity, and encourage innovation.
- Leverage existing and identify new sources of funding and creative financing for climate-resilient infrastructure.
- Foster greater coordination across jurisdictions and sectors, increase transparency and inclusion in decision-making, and plan in advance for climate-smart disaster recovery efforts.

This paper focuses on actions that government and agency staff (including planners, engineers, procurement specialists, and public infrastructure investment managers) and policymakers in California can take to advance climate-smart infrastructure that is built to last. We hope that many of the lessons and recommendations will be helpful to broader audiences here in the Golden State and beyond so that California's communities and economy will be able to rely on public infrastructure to provide critical services even as we face continued worsening climate impacts in the years ahead.

[3] Governor Jerry Brown's Executive Order B-30-15 requires state agencies to account for climate change in planning and investment decisions, in addition to setting the most stringent heat-trapping emissions reduction target for 2030 in North America.

BOX 1.

What Is Infrastructure?

Infrastructure is the physical assets and networks necessary to provide essential services to people and communities and the organizational structures for operating and managing them. Roads move people and goods. Reservoirs, canals, and water treatment systems provide clean water, while the grid supplies electricity to power homes, businesses, and industry. Buildings house and shelter businesses, schools, and civic and cultural centers. Water, electricity, and transportation systems are lifelines; disruption of them can result in life-threatening conditions and in cascades of failures in other interdependent infrastructure services (NIAC 2013). Other types of infrastructure, such as communications and data information systems, housing, hospitals, and other healthcare facilities are extremely important but are beyond the scope of this white paper.

Natural and "green" infrastructure include wetlands, forests, other types of vegetation, and permeable surfaces.[4] They can play a key role in protecting communities and the built environment from extreme weather and damaging climate impacts by moderating floods, storm-water runoff, and urban heat islands. They also can provide additional benefits, such as absorbing heat-trapping emissions, improving air and water quality, and recreational uses (GCC n.d.; HUD 2015; SAGE 2015). While not the focus of this paper, planners should consider where green infrastructure can provide cost-effective alternatives to "grey" infrastructure options or complement and bolster grey infrastructure or. A combination of grey and green infrastructure may often be the most robust and optimal approach to adapting to climate change (TNC 2013).[5]

A community's social ties and support networks constitute an unseen type of infrastructure that helps it withstand and recover from extreme events and other threats, especially in times of crisis when emergency responders and local agencies cannot quickly respond. Past experiences such as Hurricane Sandy and the 1995 Chicago heat wave highlight the importance of social networks during disasters (Baussan 2015; Aldrich and Meyer 2014; NIAC 2013). They can be especially important in low-income communities and communities of color, which may depend more heavily on such networks than wealthier communities (Malik 2014). We acknowledge the rich community of practice on social capital and its central role in community resilience, but a discussion of this topic is outside this paper's scope.

[4] While the terms *natural infrastructure* and *green infrastructure* are often used interchangeably, green infrastructure specifically refers to "planned and managed natural and semi-natural systems" and can include approaches that are not nature-based, such as permeable pavements (TNC 2013).

[5] Per EO B-30-15, state agencies should prioritize natural infrastructure solutions in planning and investment decisions.

Infrastructure and the New Climate Reality

Engineering practices and standards have traditionally used historical trends for climate and weather extremes and assumed that trends would remain roughly the same in the future—a concept known as "stationarity." California's infrastructure systems were built accordingly, with a margin of safety. For instance, a commonly used standard for building and infrastructure flood protection is the 100-year flood, or a flood with a 1 percent chance of occurring in any given year. The flood event probability is usually determined from historical data for hydrological parameters.

Yet because of climate change, the past is no longer a good predictor of the future (ASCE 2015; Milly et al. 2008). Instead, **climate models project a "new normal" of ever-increasing variability and extremes, which translates to new and continually changing conditions that will exacerbate threats to California's existing and new infrastructure and the communities who depend on it** (USGCRP 2017; Minsker et al. 2015). Key climate variables include the following. We highlight important changes to date and projected changes:

- ***Sea level rise and its contribution to worsening tidal flooding and storm surge*:** Sea levels have already risen by an average of seven inches along California's coast over the last century (OEHHA 2013). San Francisco, for example, will likely see a rise of another 7 to 13 inches by 2050, increasing to 1.6 to 3.4 feet by 2100 with continued high greenhouse gas emissions levels (Griggs et al. 2017).[6]
- ***Extreme heat:*** Minimum and maximum air temperatures and summertime extreme temperatures have increased over the past century, as have nighttime heat waves (OEHHA 2013). California's population centers are projected to face an average of 40 to 53 extreme heat days by 2050,[7] compared to four days on average historically, and 40 to 99 days by 2099 (CNRA 2016). By the century's end, summers in the Golden State will likely be hotter than Texas and Louisiana summers today (Rogers, Barba, and Kinniburgh 2015).
- ***Wildfires*:** The state's fire season is starting earlier and lasting longer (Bryant and Westerling 2014; Westerling et al. 2006). Ten of the 20 largest fires by acreage in California history have occurred since 2005 (CalFire 2015a). As temperatures continue to rise due to global warming, the threat of more severe and longer wildfire seasons in the western United States is projected to grow, including in parts of California (Cleetus and Mulik 2014).
- ***Earlier snowmelt, droughts, and heavier rainfall:*** Rising temperatures mean that more precipitation will fall as rain rather than as snow, and snow will melt faster and earlier. Spring snowmelt from the Sierra snowpack to the Sacramento River has already declined 9 percent over the past century (OEHHA 2013). The Sierra snowpack, which provides up to one-third of California's water supply, is projected to shrink 48 to 65 percent from historic averages (CDWR 2017a). Droughts will also become more frequent and severe in some regions, and extreme precipitation events and flooding could increase in others (CDWR 2017a; Gao et al. 2017; Jeon et al. 2015; Dettinger 2011).

[6] Griggs et al. (2017) present updated projections and associated probabilities for sea level rise in California as the basis for updating the state's sea level rise guidance document. UCS has previously used a range of localized projections for California based on scenarios developed for the 2014 National Climate Assessment (NCA). Griggs et al.'s projections fall in the low to mid range of the localized projections based on the NCA. The full range of NCA's localized projections suggests that San Francisco could see 8 to 25 inches of sea level rise by 2050 and 1.8 to 6.7 feet of rise by 2100.

[7] Here, "extreme heat days" are days that exceed the 98th percentile of maximum temperatures for a location from 1961 to 1990 during May to October (CNRA 2016).

A Changing Climate Exacerbates Risks to Infrastructure

Exactly how these changes will affect California's infrastructure depends in part on the location of infrastructure assets, the assets' condition, and their ability to withstand or adapt to them (or their adaptive capacity[8]). Climate models predict more severe conditions for the second half of this century, and many large infrastructure projects generally have long life spans, typically of 30 to 100 years (Walsh et al. 2014; NRC 2013). Numerous existing and new infrastructure assets will last long enough to experience these future extreme conditions, which could affect their longevity and performance (see the table). The result could be increased operating and capital expenditures, shortened life spans, service disruption, or even failure, with significant negative consequences for public safety and the economy. Infrastructure owners who insure their assets could also face higher premiums. Multiple hazards occurring at the same time or shortly after each other, such as inland flooding coinciding with coastal flooding or an earthquake affecting infrastructure already weakened by previous flooding, could be particularly damaging, especially if systems are already strained and interdependent (Willis et al. 2016).

California's infrastructure is aging and deteriorating. Population growth and changing demographics, urbanization, the advanced age of existing assets, deferred maintenance, funding constraints, and technological changes place increasing pressures on the infrastructure system that may compromise its capacity to withstand and rebound quickly from various hazards (NADO 2015; re:focus partners 2015a; Poole, Toohey, and Harris 2014; Wilbanks and Fernandez 2013). This reality is reflected in the dismal grades the American Society of Civil Engineers (ASCE) has given California's levee and flood control (D), urban storm water infrastructure and programs (D+), and transportation (C-, including bridges and transit) (ASCE 2012).[9]

Extreme weather events already disrupt infrastructure function in California. Figure 1 illustrates several infrastructure disruptions and failures resulting, at least in part, from extreme events in recent years. For instance, in February 2017, unusually heavy rains and runoff combined with deferred maintenance led to damage to the Oroville Dam that caused the evacuation of more than 180,000 people (Braxton 2017). While one cannot definitively list climate change as a cause of each event in Figure 1, recent studies have demonstrated that global warming made some of them more likely to occur.[10] Moreover, **these examples and others provide us with a preview of increased challenges to our infrastructure systems.**

In addition to existing disruptions, **studies reveal future infrastructure vulnerabilities to a changing climate**. One example is the new eastern span of the Bay Bridge in Oakland, across which more than 270,000 vehicles travel daily (Caltrans n.d.). The approach lanes will be permanently underwater if we experience sea level rise of three feet; widely accepted scenarios predict one to two feet of rise by midcentury and three to five feet by 2100 (MTC 2014). If proactive measures are not taken, projected sea level rise would also inundate runways at airports in San Francisco, Oakland, and San Diego (Biging, Radke, and Lee 2012; ICLEI 2012). Energy infrastructure is vulnerable as well. As many as 25 coastal plants could be affected by sea level rise, while increased frequency and intensity of wildfires will threaten the reliability and transmission efficiency of large interstate transmission lines like Path 66, a key connector between Pacific Northwest and northern California energy markets (Sathaye et al. 2012). In addition, the Sacramento–San Joaquin River Delta levee system - which protects farms, homes, businesses, and the water supplies of two-thirds of California's population - is at risk of flooding and failure due to a combination of sea level rise, flooding, land use, overpumping of groundwater worsened by droughts, and the resulting ground-settling, risking saltwater intrusion into freshwater supplies (CDWR 2017b, DSC 2015).

Other research highlights how the temperature and water-related vulnerabilities identified in the table will affect assets and systems across the state (CDWR 2017a; PG&E 2016; AOP 2015; SACOG 2015). More frequent and intense heat waves may also place additional pressure on ill-equipped public school infrastructure, resulting in more school closures and canceled outdoor activities, as seen with the closures in northern and southern California during the August 2017 heat wave (Brenner 2017; Ting 2017; Warth 2017).

Our infrastructure systems are also increasingly interdependent, especially in urban areas. The risk for cascading negative consequences, whereby a disruption in one sector or location triggers significant disruptions in connected infrastructure near and far, has grown (Sansavini 2017; Moser and Hart 2015; re:focus partners 2015a; NIAC 2013; Wilbanks and Fernandez

---

[8] Adaptive capacity is "the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences" (IPCC 2014a). In this paper, the potential damage refers to climate-related infrastructure disruptions.
[9] ASCE grades are based on infrastructure condition, capacity, operations, and security.
[10] A recent study shows that global warming made the extreme drought twice as likely to occur (Williams et al. 2015). In addition, analyses of past extreme heat events show that climate change resulted in the vast majority being more likely to occur or more severe (NAS 2016; Herring et al. 2016; Herring et al. 2015; Herring et al. 2014; Peterson et al. 2013; Peterson, Stott, and Herring 2012).

Average Life Expectancy of Select Infrastructure Types and Potential Climate-Related Vulnerabilities

Mode	Example of Infrastructure Asset	Design Lifetime	Potential Climate-Related Vulnerabilities
Transportation	Paved Roads	10–20 Years	Softening, deterioration, and buckling caused by heat. Scour (or sediment removal) and erosion caused by flooding and storm surge. Sea level rise inundation. Accelerated corrosion in coastal areas caused by sea level rise. Road closures caused by landslides and washouts during heavy precipitation events. Damage to foundation caused by changes in soil moisture.
	Rail Tracks	50 Years	Buckling and deformation caused by heat. Scour and erosion caused by flooding, storm surges, and extreme precipitation events. Railway subsidence caused by groundwater depletion.
	Bridges	50–100 Years	Erosion and scour caused by flooding, storm surges, and sea level rise inundation. Accelerated corrosion in coastal areas caused by sea level rise and saltwater intrusion. Reduced vertical clearance over major waterways caused by sea level rise. Damage to foundation by changes in soil moisture or higher waterway levels.
Energy	Transmission Lines	50 Years	Lower transmission efficiency caused by increased temperatures; peak demand during highest temperatures compounds vulnerability. Wooden utility poles destroyed and damaged in wildfires. Lines disrupted or shut down by smoke and particulate matter ionizing the air and creating an electrical pathway away from transmission lines.
	High-Voltage Transformers	40 Years	Service disruptions caused by more frequent and severe precipitation events, flooding, and wildfires. Lower transmission efficiency caused by increased temperatures.
	Generating Plants and Substations	35–80 Years 35–45 Years	Inundation of coastal power plants and substations caused by king tides, storm surge, and sea level rise. Service disruptions caused by more frequent and severe extreme heat, precipitation events, flooding, and wildfires.
Water	Reservoirs and Dams	50–80 Years	Lower water availability caused by higher temperatures and droughts in some regions can decrease water supplies and hydropower. More severe precipitation events threaten dam integrity or dam breaching. More frequent and severe wildfires leave ash and eroded sediment in drinking water supplies.
	Treatment Plants and Pumping Stations	60–70 Years	System overwhelmed with storm water resulting from more extreme precipitation events and, in coastal areas, with seawater driven by storm surge. Increased water quality treatment needs during drought periods.
	Drinking Water Distribution and Storm and Sewage Collection Systems	60–100 Years	Storm water management and collection complicated by more extreme precipitation events and changes in water availability caused by higher temperatures.

Critical infrastructure assets are vulnerable to extreme weather and climate change, with longer-lived assets facing more severe vulnerabilities expected later this century. A particular asset's vulnerability may vary from the general vulnerabilities listed due to its location, age, design, adaptive capacity, etc. The assets listed below are illustrative, not comprehensive. (SOURCES: ASCE 2017; ASCE 2015; TRB 2014; DAVIS AND CLEMMER 2014; DOE 2013; STOMS ET AL. 2013; ASCE 2011; NRC 2008; EPA 2002).

2013). Such consequences can range from small, temporary disruptions to major failures causing significant and widespread damages. When Hurricane Sandy hit the Atlantic Coast in October 2012, its unprecedented storm surge combined with strong winds to cause the loss of life, extensive property damage, and far-reaching power outages affecting millions of people. These outages set up a domino effect in New York and New Jersey: no electricity led to hospital closures, releases of untreated sewage by wastewater treatment plants, and shortages of transportation fuel for weeks as refineries were forced to shut down due to power and flooding problems and gas stations' pumps shut off (NYC n.d.; Pescaroli and Alexander 2015).

This same pattern of damages and cascading effects occurred again—but amplified—when Hurricanes Harvey, Irma, and Maria struck in August and September 2017. Flooding and high winds led to power outages that resulted in sewage spills and hospital and nursing home closures in Florida and Texas and a chemical plant explosion caused by disabled cooling equipment. Puerto Rico's more vulnerable infrastructure was devastated by Hurricane Maria, contributing to a widespread health and humanitarian disaster. Research and analysis concerning the relationships among infrastructure assets are still relatively nascent, but these recent examples make clear that these interdependencies—and the greater risks of cascading failures as a result of climate change—must be taken into account as infrastructure projects are planned and designed (Vallejo and Mullan 2017).

A **changing climate can also modify demand for certain types of infrastructure**, including infrastructure supporting energy, transportation, or water systems. Demand for energy and water, for example, may rise in response to higher temperatures. As climate-related impacts increase, demographic shifts and changes in land use may occur as people migrate to more hospitable locations, either within California or elsewhere, which in turn could change the demand for infrastructure assets and services in these locations (Hauer 2017; ITF 2016; Wilbanks and Fernandez 2013; European Commission 2011).

These risks can also affect California's efforts to transition to a low-carbon economy (efforts that would help slow the growth rate of these risks locally and globally) because the transition strongly depends on a robust clean energy infrastructure system. Fortunately, some of the strategies aimed at reducing heat-trapping emissions—such as energy efficiency improvements and more widely distributed renewable energy generation—can bolster key infrastructure assets' ability to continue operating during and to recover quickly after extreme weather and other hazard events (McNamara et al. 2015).

While the type, frequency, and severity of climate-related hazards will vary by location, no region of California or infrastructure type will be left untouched. Recent extreme weather events and vulnerability assessments of future conditions together demonstrate that climate change is a significant threat to the safety and reliability of our critical infrastructure systems. Many of these impacts on California's infrastructure systems may be avoidable if we anticipate them and act now to incorporate climate change into how we plan, design, construct, and maintain infrastructure.

FIGURE 1 **Selective Examples of Infrastructure Services and Assets Affected by Climate Extremes in California**

1. **Extreme Rains Flood Roads** Historic rains in the winter of 2017 flooded more than 32 roads in Humboldt County, including parts of Highway 101, closing them for days.

2. **Extreme Rain Damages Oroville Dam Spillways** Record rainfall in February 2017, combined with years of deferred maintenance, led to significant damage of Oroville Dam's main and emergency spillways. More than 188,000 residents were evacuated when water threatened to breach the dam and wash out the spillways.

3. **Drought Reduces Reservoir Storage and Hydropower Generation** The historic drought starting in 2011 significantly reduced California's surface water supply: key reservoir levels dropped to 50% below average in 2014. From 2011 to 2014, total state hydropower—generated by Shasta Dam and many others—fell from 18% to 12% of the electricity mix. More natural gas was burned to compensate, raising consumers' electricity costs by $1.4 billion and increasing California power plants' carbon and air pollution emissions by 8%.

4. **Butte and Valley Fires Damage Power Lines** In September 2015, the Butte and Valley Fires destroyed nearly 3,000 structures and damaged hundreds of power lines and poles, leaving 12,700 customers without power—some for more than a week—and causing nearly $2 billion in damages.

5. **Tropical Storm Floods Major Power Substation** A tropical superstorm hit the northern California coast in December 2014, flooding a key Pacific Gas & Electric substation in San Francisco: more than 85,000 customers from Big Sur to the Oregon border lost power, closing the San Francisco electric bus system and Bay Area and High Sierra schools.

6. **Sacramento Highway Buckles during Record Heat Wave** Unseasonably high heat in June 2017 buckled four lanes of Highway 50, causing heavy traffic delays until the road was repaired overnight.

7. **Heavy Rain and Landslide Sever Big Sur Bridge** Torrential rains and a resulting landslide in February 2017 rendered Pfeiffer Canyon Bridge impassable, isolating Big Sur residents and causing a loss of about $2 million in business and tourism revenue per week until its replacement was finished in October 2017.

8. **Extreme Precipitation Halts Commuter Trains** Muddy, waterlogged tracks caused a Union Pacific freight train to derail near Stockton in February 2017, sending 22 railcars full of food into the Cosumnes River. Rerouting freight cars onto other tracks canceled Altamont Corridor Express commuter rail service for three days.

9. **Wildfire Closes Desert Highland Schools** The Pilot Fire of 2016 struck so quickly—growing 50% overnight and burning 7,500 acres in a day—that three school districts in the San Bernardino mountains were forced to close 46 schools for days due to heavy smoke and poor air quality.

10. **Fire Damages Southwest Power Transmission System** In October 2007, a massive wildfire damaged 1,000 San Diego Gas & Electric utility poles, 35 miles of overhead electric wire, and the Southwest Power Link, a high-voltage power line stretching from Arizona to San Diego, causing 80,000 customers across southern California to lose power, some for weeks.

This map highlights a few recent examples of infrastructure failures and service disruptions related to extreme storms, wildfires, heat waves, and other weather-related events that will become more frequent and/or severe in California as climate change intensifies. The combination of deferred maintenance, underinvestment in infrastructure, and continued failure to incorporate climate science in infrastructure planning will make these disruptions and failures more common in the coming century, affecting all regions and communities in California.

SOURCES: 1. GOFF 2017; 2. CBS 2017A; 3. CDWR 2014; GLEICK 2015; 4. AON BENFIELD 2015, PG&E 2015; 5. MENDOZA AND THANAWALA 2014, POGASH 2014; 6. ACOSTA 2017; 7. CBS 2017B, CBS 2017C, CURWEN 2017; 8. AP 2017, CBS 2017D, SERNA 2017; 9. WHITCOMB 2016; 10. EC 2007.

Infrastructure Disruptions Affect Community and Economic Resilience

Extreme weather and chronic climate-related stressors can leave communities without access to functioning infrastructure systems and resources critical to their safety, well-being, and resilience to a multitude of hazards, sometimes for periods lasting long after the event(s) causing the disruption. Risks can be especially great if communities rely on a single asset for a key service. For example, during the drought lasting from Fall 2011 to Spring 2017, surface water supplies decreased in California, leading to over-pumping of groundwater in some areas. In East Porterville, many wells dried up, while the water in other wells became unsafe to drink. Nearly 1,800 households that depended solely on private wells for their water were forced to rely instead on water trucked in by the state, some for more than two years (CDWR 2016a; CDWR 2016b). Many have since been connected to a reliable water supply (CDWR 2017c). California's famed coastal route, Highway 1, was closed in the Big Sur region when historic floods in 2017 caused Pfeiffer Canyon Bridge in the north to fail and massive landslides covered the road in the south. Big Sur was left with no road access for several months, and the bridge was closed for 8 months, not reopening until October 2017 (CBS 2017b). More than 400 residents were initially stranded, and food, fuel, and other supplies had to be airlifted in for days (CBS 2017c). The local economy, largely dependent on tourism, lost about $2 million in revenue per week during the bridge closure (Curwen 2017).

The impacts will not be felt evenly across communities in California due in part to decades of underinvestment and disinvestment in infrastructure that has contributed to deteriorating conditions in many low-income communities, communities of color, and tribal communities. They are already among the most vulnerable communities to climate change impacts such as extreme heat, flooding, and sea level rise (Morello-Frosch et al. 2009). While the state's entire, aging infrastructure system generally needs increased investment and upkeep, structural racism and disenfranchisement have frequently left these communities underserved with inadequate, and sometimes entirely absent, infrastructure. For example, experiences vary across the state and the country, but the built environment in low-income communities and communities of color is often of lower quality—from transportation infrastructure to drinking water infrastructure, public school facilities, and affordable housing—and contributes to disparities in health, economic opportunities, and quality of life (McNichol 2017; Yuen et al. 2017; Hutch et al. 2011; Sánchez, Stolz, and Ma 2003).[11]

As a result of this neglect and lower quality, transportation, transit, flood-control, and industrial infrastructure in these communities may be more vulnerable to the effects of climate change (Kelly and Ross 2014). Deteriorating flood-control infrastructure and toxic spills and hazardous debris originating in industrial sites, for instance, were significant contributors to

BOX 2.

What Is Resilience?

For the purposes of this paper, we define "resilience" as the ability of a system "to cope with a hazardous event, trend, or disturbance, responding or reorganizing in ways that maintain systems' essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation" in response to these events (IPCC 2014b). It can also refer to recovering in such a way as to be stronger and more resilient than before, to "bounce forward" rather than "bounce back" to status quo (BoCo 2016; Island Press and Kresge Foundation 2015; MSC et al. 2015). A resilient infrastructure system is proactively designed and managed to provide critical functions and services continuously by withstanding hazards, minimizing losses during damaging events, and recovering quickly if failures occur. Some key characteristics often mentioned in the literature are robustness, redundancy, flexibility, modularity, decentralization, rapidity, resourcefulness, and "safe-to-fail" (Sansavini 2017; AECOM 2015; Minsker et al. 2015; Bocchini et al. 2014; Wilbanks and Fernandez 2013). *Climate resilience* describes the capacity of a system to prepare, adapt, and evolve to function better in a future characterized by more climate extremes (Folke 2006).

[11] The history of redlining, or overt discrimination starting in the 1930s in federal housing policies, explains how mortgage lenders, developers, realtors, and government agencies denied minority communities access to loans and capital needed to maintain their buildings, which led to disrepair, declining property values, and further disinvestment (Nelson et al. 2017). Investments in transportation infrastructure in the 1950s and 1960s favored highway and road construction that benefited suburban and wealthier communities rather than public transit, which would have benefitted urban communities. Authorities often built highways directly through lower-income city neighborhoods, displacing or physically dividing entire communities, using the rationale that lower property values in these areas would reduce construction costs (Sánchez, Stolz, and Ma 2003). Similar transportation policies discriminated against African American communities in San Francisco's East Bay through 2005 (Golub,

Hurricane Katrina's devastation of New Orleans, and poorer neighborhoods generally experienced greater damage (Kelly and Ross 2014).

These underserved communities also often have fewer of the resources needed to prepare for, cope with, and recover from infrastructure disruptions and failures exacerbated by climate extremes. This is especially true when the baseline in a community includes lack of jobs, inadequate and unaffordable housing, and income inequities (Kelly, Martinez, and Hathaway-Williams 2017; Yuen et al. 2017; BoCo Strong 2016; Cleetus, Bueno, and Dahl 2015; Melillo, Richmond, and Yohe 2014; Friend and Moench 2013; Martinich et al. 2013; Kelly and Adger 2000). Additional factors, such as age, existing health conditions or disabilities, can also increase their vulnerability to climate impacts (USGCRP 2016). Focusing on the monetary value of damage caused by extreme weather events to guide reconstruction, repair, and other damage-mitigating efforts can focus public investments in wealthier communities, leaving poorer communities to rebuild more slowly (Sarmiento and Miller 2006). Climate-resilient infrastructure solutions must help address these underlying historic patterns of disinvestment and discrimination and disproportionate climate vulnerabilities so that new and existing infrastructure can sufficiently support these communities' resilience to climate change.

The economy, especially the small business segment, is vulnerable to extreme weather and climate-related stressors. The World Economic Forum listed extreme weather events and the failure to implement sufficient climate change mitigation and adaptation among the top five threats to the global economy in terms of their potential impact (WEF 2017). In 2016, the United States experienced $47.9 billion in losses, including damage to buildings and public infrastructure and business interruption, attributed just to those extreme weather and climate disasters that caused losses of over $1 billion each; this figure does not include losses attributed to smaller climate-related events (NCEI 2017; Smith and Matthews 2015). During many extreme weather events, business property is destroyed, supply chains are severed, and workers are unable to get to their jobs.

Small businesses are especially vulnerable to these damages because they often have fewer available resources and plans to prepare and recover. The Federal Emergency Management Agency (FEMA) estimates that nearly 40 percent of small businesses do not reopen after a natural or human-caused disaster (FEMA 2016a). Of the small businesses harmed by Hurricane Sandy, for example, about 30 percent permanently shut their doors (Reynolds 2013). Small businesses employ roughly half of California's private sector workforce, and they play a key role in community recovery after disasters (Maher and Peace 2017; SBA 2015). Given the critical role of business, and small businesses in particular, in California's economy, decisions about infrastructure and climate resilience should take business impacts into account.

Marcantonio, and Sanchez 2013). Low-income areas house a higher percentage of public school facilities in need of repair. In addition, aging lead water pipes are much more common in the lowest-income neighborhoods and cities, which creates the potential for dire health problems and associated economic costs, as the experience of Flint, Michigan, has demonstrated (McNichol 2017).

[SECTION II]

Climate-Smart Infrastructure: Principles for Climate Resilience

Federal, state, and local governments are spending billions of dollars each year on infrastructure projects in California to help close the existing infrastructure gap. As they focus on addressing immediate needs, they should also think about the long-term and anticipated future conditions. **We have an opportunity to invest these taxpayer dollars wisely in climate-smart infrastructure systems that will deliver key services even as the climate changes rather than unwisely in projects that will not achieve their intended life spans and will require additional funds for avoidable repairs and retrofits.** For instance, across the Golden State, there are numerous plans to invest hundreds of billions of dollars to address deferred infrastructure maintenance and new infrastructure needs.[12] The state's plans include a transportation package ($52 billion); state and federal allocations of emergency funds for water and flood protection; a public school bond ($10 billion); and other projects in the governor's 2017 Five-Year Infrastructure Plan. Localities plan significant infrastructure investments as well; for example, Los Angeles's Measure M will generate roughly $120 billion for transit improvements over the next 40 years. California also received nearly $321 million in federal assistance for publicly owned facilities to address damage caused by fires, earthquakes, severe storms, and flooding occurring from August 2013 to August 2017 (FEMA 2017).[13]

Building climate-smart infrastructure also provides opportunities to realize additional economic, health, social, and environmental benefits. There is growing recognition of the business benefits generated by climate-resilient communities, from better business conditions with fewer interruptions to increased and consistent tax revenue and a more secure workforce (OMB 2016). Infrastructure projects can be planned and designed to provide other benefits, such as enhanced public health, improved air and water quality, natural resources conservation, and environmental justice (SGA 2015; CNRA 2014). Such an approach can also increase a project's overall public benefit and support. Moreover, after careful evaluation, practitioners may find that the most climate-smart approach is to *not* build a new infrastructure asset, but rather to rehabilitate or upgrade an existing one and/or implement efficiency or demand reduction measures, or develop a green or hybrid infrastructure solution, all of which can save money and other resources. Preventative measures also save money. For instance, one often-cited study assessed FEMA-funded projects and found that every dollar spent increasing the resilience of the built environment can save society four dollars in future losses (MMC 2005).

To inform how we seize the opportunity to leverage public funds for infrastructure, UCS identified key climate-smart principles for infrastructure, outlined in Box 3. These principles build upon multiple sources, including the UCS report *Towards Climate Resilience: A Framework and Principles for Science-Based Adaptation,* reports from other organizations and researchers,[14] and the "Climate Risk and Infrastructure" expert convening. They complement other criteria often considered by infrastructure planners and designers, such as criticality (how important an asset is to the overall system's functioning), costs and benefits, vulnerabilities, design life, acceptable levels of risk, desired levels of safety and service, risk tolerance, and sustainability

---

12 California has a backlog of $59 billion in needed state highway repairs, $70 billion in needed local street and road repairs (CDOF 2014), $46 billion in needed drinking water investment, and $26 billion in needed wastewater infrastructure over the next 20 years (ASCE 2012).

13 These funds are from FEMA's Public Assistance program, which provides assistance with "debris removal, emergency protective measures, and the repair, replacement, or restoration of disaster-damaged, publicly owned facilities and the facilities of certain Private Non-Profit organizations."

14 These reports include: OPR 2017; TFCFD 2017; Yuen et al. 2017; ASCE 2015; GARI 2016; MSC et al. 2015; EPA 2014; and Rubin 2006. UCS contributed to OPR 2017 as a member of the Technical Advisory Group that provided input into its development.

BOX 3.

Principles for Climate-Smart Infrastructure

Climate-smart infrastructure refers to infrastructure that is resilient to damage caused by extreme weather and climate change and that reduces heat-trapping emissions to the maximum extent possible.[15] It also seeks to address the inequities in our infrastructure systems and decision processes and to bolster the resilience of California's communities and economy.

The following principles can help foster climate-smart infrastructure decisions and guide the weighing of trade-offs among project alternatives. They are not exhaustive, but rather highlight key considerations to inform decisions. They are also interdependent and mutually reinforcing. Some are consistent with key principles and best practices for infrastructure resilience to a variety of hazards, while others are unique to climate impacts.

Apply Rigorous Climate Science

Infrastructure plans and decisions should be consistent with the best-available science about climate change and our understanding of how it will affect human, built, and natural systems.

- Integrate climate conditions projected to occur over a project's life span, and match the risk management approach with the magnitude and timing of projected change.
- Allow opportunities to update systems, strategies, and practices as science progresses.
- Design a project, plan, or system to be robust so it can perform well under a variety of climate-related conditions or can adapt to changing conditions, especially if uncertainty exists about how and when climate impacts will occur.

Prioritize Equitable Outcomes

Place particular focus on infrastructure decisions that increase the climate resilience of underserved populations, including low-income communities, communities of color, tribal communities, and other disadvantaged communities, as well as other vulnerable populations, including people with disabilities or existing health conditions, and the elderly.

- Prioritize infrastructure investments in underserved communities to begin addressing historic disinvestment, disproportionate climate-related vulnerabilities, and inadequate infrastructure, considering the unique needs of vulnerable populations within them.
- Engage underserved and vulnerable populations in meaningful ways to ensure infrastructure decisions address their needs and provide desired co-benefits.
- Ensure the benefits of building climate-smart infrastructure, such as employment opportunities and increased access to key services, are shared equitably and flow to disadvantaged and underserved communities. The costs of paying for this infrastructure should not fall disproportionately on middle- and low-income families, and solutions should strive to avoid and minimize harm, such as potential displacement that may result from infrastructure improvements.[16]

Spend Wisely and Strengthen Financial Management

Infrastructure plans and decisions should evaluate and incorporate climate-related costs and risks in a transparent manner to ensure public funds are spent wisely.

- Include climate-related impacts in the evaluation of a project's costs and risks, as well as the fiscal and nonmonetary benefits of and opportunities presented by climate-resilient infrastructure so trade-off assessments are more accurate.
- Disclose publicly the climate-related risks and resilience of projects over their entire life spans in a manner that is consistent, comparable, and objective across projects and that provides project-specific information.
- Create efficiencies by identifying opportunities to pool public resources (financial, human, etc.) where possible.[17]

(continued next page)

[15] How to design a project to be climate resilient and/or minimize heat-trapping emissions requires thoughtful consideration of potential trade-offs. Ideally, a project would accomplish both, but this is a complicated topic that deserves lengthier discussion than space here allows.

[16] We distinguish displacement due to neighborhood improvements that lead to unaffordability and gentrification from relocation initiated in response to climate risks such as sea level rise. Community involvement is necessary in planning either community improvements or community relocation.

[17] Infrastructure decisions can create administrative and strategic efficiencies. For example, a transportation agency could work closely with public works departments to time their efforts such that road repaving with more heat tolerant or permeable materials coincides with sewer system upgrades or installation of broadband or fiber underground (re:focus partners 2015a). Retrofits to enhance a building's climate resilience could co-occur with a mandated seismic retrofit. A water utility and public works departments could together identify vacant parcels to be used for green infrastructure projects.

Plan Proactively, Holistically, and Transparently

Infrastructure processes should build upon existing climate-related goals and encourage more transparent and integrated solutions across sectors, jurisdictions, and climate impacts.

- Develop projects to be consistent with climate mitigation goals, to the maximum extent possible, as well as climate adaptation plans and guidance.
- Consider the whole system and broader context for a project ("systems thinking"), including its interconnectedness with other infrastructure, sectors, jurisdictions, and the environment; possible exposure to multiple hazards and cascading failures; potential for green infrastructure solutions; and opportunities to realize multiple benefits in order to evaluate trade-offs more accurately and avoid maladaptive decisions.[18]
- Maximize transparency and accountability in the infrastructure decisionmaking process by implementing an inclusive and responsive process. Responsibility for implementation and accountability methods should be clear.

(ASCE 2015; ICF 2013). These principles can inform infrastructure decisions to advance projects and systems that will better deliver services to California communities in the face of more extreme climate conditions.

Several projects in California and elsewhere illustrate the application of specific principles in various ways. The community-scale power microgrid on the Blue Lake Rancheria Tribe's land in Humboldt County, for example, provides a low-carbon and climate-resilient energy source. It is designed to perform under a variety of conditions, and to "island" itself during extreme weather events and other disasters, which will help preserve power for an American Red Cross disaster shelter. The project will also create local jobs and realize energy cost savings (Burger 2017; Narum, Ganion, and Carter 2016). In Stockholm, Sweden, the New Slussen project to retrofit the deteriorating Slussen Lock integrates future climate-related flooding projections for Lake Malaren over the life of the project (100 years) and takes into account potential cascading effects. The result is an infrastructure solution that is flexible, increases nonvehicular traffic (and reduces heat-trapping emissions), and includes green spaces (Vallejo and Mullan 2017). In addition, design competitions such as Rebuild by Design and Resilient by Design are encouraging the development of promising concepts related to climate resilience, and efforts to address future natural resource impacts on infrastructure services in an integrated manner, such as the San Diego Regional Airport Authority's Water Stewardship Plan, are emerging (SDCRAA 2016). The RE.invest Initiative, a public–private collaborative effort, developed an innovative grey–green strategy for Norfolk, Virginia, that combines a "self-raising flood barrier" to protect against coastal flooding and green infrastructure to address storm water concerns; project leaders also identified creative financing options, revenue sources, and possible monetary savings resulting from less flood exposure (re:focus partners 2015a).

[18] Maladaptive decisions are those that create, perpetuate, or exacerbate climate risk (Spanger-Siegfried et al. 2016). An example is using public funds to rebuild infrastructure in locations vulnerable to repetitive flooding without requiring they be built to a more protective standard. In August 2017, the Trump administration rolled back the recently updated federal flood risk management standard (FFRMS), which was aimed at ensuring that federal agencies use protective design standards to guard against flood risks when building in flood-prone areas. A revised FFRMS, when and if one is issued, must take future climate and other conditions into account in order to be truly protective and avoid maladaptive federal investments.

[SECTION III]

California's Emerging Climate Resilience Strategies for Infrastructure

Since its first climate impacts–focused executive order, issued in 2008, quickly followed by its first climate adaptation strategy, California has undertaken initiatives to advance climate resilience broadly. Several of these efforts directly or indirectly influence infrastructure, as described in Box 4. For instance, Governor Arnold Schwarzenegger's Executive Order S-13-08 required all planning decisions concerning vulnerable coastal areas to consider sea level rise. State government responded by funding studies to better understand the issue and the state's vulnerabilities and released several guidance documents detailing how to incorporate sea level rise into planning decisions (CCC 2015; CO-CAT 2013; Caltrans 2011; OPC 2011).[18][19] In 2015, Governor Brown issued Executive Order B-30-15, requiring all state agencies to consider climate change in their planning and investment decisions. It also mandates that the Five-Year Infrastructure Plan, which outlines the governor's proposed expenditures for state infrastructure projects over the next five years, must account for climate change impacts on its projects. California shortly thereafter adopted several bills that further clarified that climate adaptation must be integrated into certain state and local government activities, including SB 379, SB 246, AB 1482, and AB 2800 (see Box 4 for bill descriptions). In November 2017, the Governor's Office of Planning and Research (OPR) issued high-level guidance for state agencies on integrating climate change into the plans and investments (OPR 2017).

The Golden State is in the early stages of implementing many of these initiatives. More work is needed before consideration of climate risks and resilience is broadly operationalized in infrastructure decisions. Moreover, more work is needed before it is operationalized in a manner that is consistent and analytically rigorous enough to sufficiently assess climate risks to a project, plan, or system—a key climate-smart principle—and with an urgency that matches the scale of the problem. For example, the 2017 Five-Year Infrastructure Plan briefly discusses at a high level how each sector incorporates consideration of climate change into planning and investments, but there are few analytical details regarding climate-related effects on projects or how projects are prioritized to address a changing climate. Many of the descriptions, for instance, focus on climate mitigation actions, some of which have resilience benefits, and broad sustainability efforts such as energy conservation, while others reference studies of climate vulnerabilities or climate adaptation plans that are underway. Because many of the vulnerability assessments referenced in the plan are not publicly available yet, it is difficult to determine how well the projects described in the plan—for which billions of dollars of public funding are being sought—address climate impacts.

The state also provides considerable funding for infrastructure through its grants and bonds, but these decisions do not yet integrate consideration of climate impacts in an overall consistent manner. This lack of consistency makes it difficult to compare climate-related criteria across different projects objectively and to ensure their climate risks and opportunities were evaluated well. For example, state grants to some local agencies for infrastructure projects require they assess climate change vulnerabilities and adaptation measures but do not detail what is considered acceptable or appropriate data, tools, or information; this could result in bare minimum and potentially low-quality and/or insufficient assessments (SWRCB n.d.). Other grants do require climate adaptation measures to be integrated into infrastructure projects and direct applicants to a specific climate data source and several state documents for reference. They do not, however, describe what types of data (for example, mean values from all models versus extreme values) should be considered when applying for funds (SGC 2017). A much more detailed, specific, and rigorous analysis

[19] Because sea level rise has received attention over the past decade, awareness of this risk has progressed more than other climate-related risks (Ekstrom, Bedsworth, and Fencl 2017).

BOX 4.

Overview of California Efforts to Encourage Climate Resilience

Below are several state policies and efforts to increase climate resilience and provide data and guidance that affect infrastructure decisions. Illustrative examples of local actions are included.

State Policies

- Governor Schwarzenegger issued EO-S-13-08 in 2008, directing that planning decisions concerning vulnerable areas along the coast consider sea level rise and ordering the development of a statewide climate adaptation strategy. Governor Brown issued EO-B-30-15 in 2015, an order that directed state investments and planning to take climate change into account.
- The State Water Resources Board released a climate change resolution in 2017, requiring that all the board's actions integrate consideration of climate impacts.
- California adopted a suite of laws in 2015 and 2016 that requires cities and counties to incorporate climate adaptation and resiliency strategies into their general plans' safety elements (SB 379); better coordination among state, local, and regional climate adaptation efforts (SB 246); regular updates of Safeguarding California, the state's climate adaptation strategy (AB 1482); and establishment of the Climate-Safe Infrastructure Working Group to develop recommendations on how to better integrate consideration of climate science into infrastructure design and construction (AB 2800).

State Data and Guidance

- The state produces climate data through its Climate Assessments and research partnerships and provides public access to this data through the online platform Cal-Adapt. The California Governor's Office of Planning and Research (OPR) coordinates and maintains the newly established Adaptation Clearinghouse.
- Several state agencies, including the California Department of Transportation and the California Department of Water Resources, are conducting vulnerability assessments of their assets and beginning to incorporate considerations of climate change to varying degrees in plans and investments.
- The California Natural Resources Agency is leading the current update of Safeguarding California (the state's climate adaptation strategy) and the State of California Sea-Level Rise Guidance Document in partnership with the California Ocean Protection Council and several other entities.
- OPR, with input from a Technical Advisory Group, developed high-level guidance to state agencies as they take climate change into account in investments and plans. OPR also recently released updated General Plan Guidelines that include consideration of climate change.
- As part of the most recent Sustainability Roadmap, the Department of General Services is requiring state agencies to evaluate existing and new facilities' risks related to certain climate-related effects; identify strategies they could implement to reduce negative consequences at the most at-risk existing facilities; and describe how climate considerations are integrated into infrastructure decisions for new facilities.

Local Action

- Local jurisdictions, utilities, and regional entities are demonstrating leadership by updating capital plans and ordinances to account for climate change and conducting vulnerability assessments. Specific examples include San Francisco's *Guidance for Incorporating Sea Level Rise into Capital Planning,* Los Angeles's Cool Roofs Ordinance, and a joint effort between San Diego Gas and Electric and ICF International to assess the climate vulnerabilities of the region's natural gas and electricity infrastructure.

is required for applicants for a recently approved bond-funded project, but this level of analysis may not be appropriate or practical for smaller, shorter-lived, and less costly projects (CWC 2016). Similar challenges exist regarding other infrastructure decisions, such as project evaluation and design (Caltrans 2016).

This field is evolving, as are the data, tools, and best practices, and, in some cases, local applicants may have access to better and more relevant information and tools than state agencies. The state should therefore not be overly prescriptive, but rather should specify a required minimum acceptable level of information and analysis and empower applicants to go beyond this minimum baseline (or to explain why it should not apply). The recently released OPR guidance should provide a helpful framework for state agencies to begin using a more standardized approach, if implemented consistently and meaningfully across all infrastructure decisions (OPR 2017). However, additional resources, such as readily actionable data and more detailed analytical guidance, are still needed to help implement the guidance in a way that helps to address some of the barriers and needs described in this paper.

California is ramping up its implementation of these policies and efforts as it continues to plan and invest in public infrastructure projects. This presents an important opportunity to ensure projects are done well, in a manner that is consistent with climate-smart principles and that bolsters infrastructure systems' ability to withstand climate risks and other hazards, recover quickly, and adapt to changing conditions in a way that benefits all people.

[SECTION IV]

Key Barriers and Recommendations for Advancing Climate-Smart Infrastructure

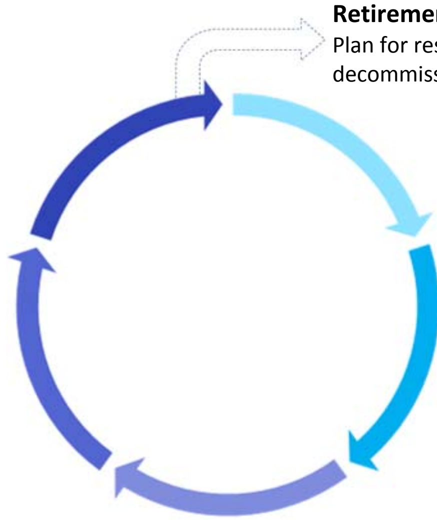
UCS conducted a series of interviews and a selective literature review and convened experts to help identify key barriers and develop recommendations for how to advance better infrastructure decisions. Our research focused on how climate science and the climate-smart infrastructure principles can inform state-level decisions for public infrastructure throughout the infrastructure life cycle. Figure 2 illustrates numerous points throughout the project cycle at which decisionmakers can integrate climate-smart principles. There are also many public agencies and private interests involved at the local, state, and federal levels throughout the project cycle—including planners, engineers, contractors, regulators, financial actors, and community members—who can work to apply these principles.

UCS identified several barriers to more systematically advancing climate-smart infrastructure decisions, described below. Our discussion is not meant to be exhaustive but rather to outline the most pressing issues that frequently appeared across different infrastructure sectors and concerning different climate impacts during our research. Practitioners may face multiple barriers at once, and the specific challenges will vary depending on where they are in the infrastructure life cycle and their organizations' internal capacities and available resources. Several barriers we discuss are consistent with known barriers to better infrastructure decisions in general; these barriers will be exacerbated by climate change. For this reason, systematically addressing these barriers provides an opportunity to fix some of the current issues facing the state's infrastructure and also an even bigger opportunity to minimize climate risks.

Just as these barriers vary considerably, so do the recommendations for overcoming them. There is no single "silver bullet" solution. For instance, updating design specifications for equipment, materials, or infrastructure assets is a crucial piece of moving towards a more climate-smart infrastructure system. New design standards alone, however, will not fully address or advance key solutions such as the following: integration of structural and nonstructural or green infrastructure solutions; application of systems thinking to minimize cascading failures and maladaptive investments; engagement of underserved and vulnerable populations and prioritization of equitable outcomes; and development of innovative financing mechanisms to fund needed improvements.

Our policy recommendations are intentionally high-level so they can be applied and tailored to various contexts across different sectors and regions of the state. They generally focus on state-level activities and are informed by the climate-smart infrastructure principles. UCS believes that all infrastructure solutions should help advance more equitable outcomes, so equity principles are integrated into relevant solutions rather than addressed separately. Local action is also critical to ensuring California's infrastructure system is resilient to a changing climate, because state and local infrastructures are interconnected and interdependent and a significant portion of California's infrastructure is funded and overseen at the local level. We highlight several complementary actions that local governments, local and regional agencies, and municipal utilities can undertake, as well as key ways that state agencies can provide additional support and assistance to local actors. While the federal government also has an important role in infrastructure, it is not the focus of the solutions presented here. We include examples of solutions throughout this section to illustrate how particular concepts are being tested or put into practice in different places, but many other innovations are emerging in this exciting and growing field.

FIGURE 2. Key Decisionmaking Points in the Infrastructure Life Cycle: Opportunities to Integrate Climate Resilience



Project decisionmakers can integrate climate-smart principles into infrastructure development at these key decisionmaking points in the infrastructure life cycle. The capacity to build climate resilience is greatest in the planning and design phases, but it should still be considered in decisions made throughout the cycle.

ADAPTED FROM UNDP 2011. ADDITIONAL INFORMATION FROM ASCE 2015; EUROPEAN COMMISSION 2011.

UCS hopes that identifying barriers and recommendations will help inform and accelerate implementation of California's recent statutes and executive orders so that climate-smart infrastructure practices are advanced and consideration of climate risks is mainstreamed in decisions across projects' life cycles. In addition, we highlight some of the remaining gaps and promising solutions that could be more broadly applied across California and beyond.[20]

[20] For additional reading concerning some challenges and solutions for particular sectors, such as transportation and water utilities, see Ekstrom, Bedsworth, and Fencl 2017; WCX 2016; and ICF 2013. Many of their conclusions are consistent with findings from our interviews and expert convening. Similarly, other papers in our selective literature review confirmed many of our interview and convening findings. Several of these papers can serve as helpful sources of additional information. For example, Kelly, Martinez, and Hathaway-Williams 2017; Moser and Ekstrom 2012; and Bedsworth and Hanak 2010 discuss specific challenges and opportunities to address resilience and adaptation generally at the local and regional levels, which in turn can impact infrastructure decisions. In addition, Vallejo and Mullan 2017 and ASCE 2015 offer a climate-resilience lens through which to view infrastructure decisions; Andersen et al. 2017 offers a sustainable infrastructure financing lens; and re:focus partners 2015a offers a resilient, systems-based lens for pre-development decisions.

Improve Data, Tools, and Standards for Planning, Design, Construction, and Operations and Maintenance Decisions

KEY BARRIERS

i. **Outdated design standards and codes informed by the past rather than the future**. Engineering design standards are meant to "provide acceptably low risks of failures regarding functionality, durability, and safety over the service lives of infrastructure systems and facilities" (ASCE 2015).[21] However, few standards and codes, if any, have been updated to reflect the changing extremes expected with climate change. Additionally, a lack of compliance with and enforcement of *existing* standards can result in a substandard built environment, which increases vulnerabilities to climate risks (NIST 2016; OMB 2016). Efforts by designers, builders, and engineers to go beyond existing standards and codes could be stymied by cost or other considerations such as "unacceptable professional risk" and liabilities (GAO 2013). Updates of standards and model codes by standard-developing organizations are often negotiated through a consensus-based process with a diverse set of stakeholders, which can result in a slow update process (GAO 2016; ASCE 2015). Fortunately, some efforts to update standards are underway. The ASCE developed a five-year Roadmap to Sustainable Development that includes a goal for new standards for infrastructure development, which will address climate resilience, among other issues (Liban 2017). In addition, it will release a manual for "adaptive design and risk management" next year (Radtke Russell 2017). The International Standards Organization is also reviewing its management and technical standards through a climate adaptation lens (Vallejo and Mullan 2017).

ii. **Inadequate translation of climate-related information into readily usable and relevant information** that meets the needs of engineers, planners, and other practitioners throughout the infrastructure life cycle. Climate model outputs are not generally provided in an actionable form that can readily be inserted into practitioners' existing decisionmaking processes. Projection data may not meet practitioners' exact data needs; for example, a dataset may provide maximum and minimum temperature and 24-hour precipitation data, but this information is not usable unless it is converted into more useful planning parameters for energy and water, such as cooling or heating degree days or intensity-frequency-duration curves. In addition, downscaled climate model outputs, which provide information on a smaller geographic scale than regional models, may add precision to projections, but they also widen uncertainties, and this caveat should be highlighted and understood. To a small degree, experts are already performing the necessary translation of data, but it needs to occur much more widely if we are to ensure climate-related data are readily actionable for end users. While state and local agency staff may rely on other experts for translation, it will remain important for them to maintain at least a basic knowledge of these issues so they can thoughtfully manage this work and respond proactively when knowledge advances.

iii. **Limited understanding and guidance on the most appropriate data, models, tools, and approaches to be used during infrastructure decisionmaking, especially in the face of uncertainty.** Climate change is happening and will continue even if all heat-trapping emissions were to cease today because of the lag time in global temperature increases caused by past emissions. Yet the precise timing and magnitude of future effects are uncertain in large part because they depend on the level of future emissions. As a result, practitioners are often presented with a range of projected climate futures against which to evaluate their projects. There are various datasets, models, tools, and decision-making approaches to help inform their decisions. The number of aids however can be overwhelming without user-friendly guidance for non-expert practitioners on how to navigate them, especially given their varying quality, scale, and purposes, and how to use them to make decisions in the face of uncertainties. While there is no commonly accepted process benchmark for appropriately selecting from among the projections, the state recently released its recommended approach for all state agencies.[22]

---

[21] For a helpful discussion of how design standards inform infrastructure decisions and an explanation of additional options to increase an infrastructure asset's likelihood of withstanding an extreme event, see Meyer 2006. Other options, in addition to updating standards, include location change, "smart" technologies, and increasing redundancy.

[22] OPR 2017 recommends state agencies use downscaled data from at least two of the four global climate models (GCMs) from the Fourth Climate Change Assessment. They are derived from research conducted for the state to identify 10 GCMs for use in water resources management in California (Pierce, Cayan, and Dehann 2016), Other efforts are underway to evaluate models and datasets from a usability perspective. The Hyperion Project is a Department of Energy–sponsored collaborative research effort by several universities and national research labs to develop a new approach that stakeholders can use to evaluate the applicability of different datasets and models to individual adaptation projects (DOE n.d.).

iv. **Insufficient analysis of the unique climate risks and infrastructure vulnerabilities faced by low-income communities, communities of color, and other underserved communities.** California has invested in the CalEnviroScreen tool[23] to identify communities affected by pollution, which shows a strong correlation between levels of pollution and race and socioeconomic status. It is unclear, however, whether adequate and consistent data and tools are available or regularly used to assess these communities' social, health, and climate risks, the investment gap, or how infrastructure vulnerabilities and disruptions may exacerbate or affect these risks.

RECOMMENDATIONS

i. **Review and update standards and codes.** State and local agencies should systematically evaluate which design standards and codes should be revised to integrate and address future climate conditions better. They should consider when a performance-based design standard would be more suitable than a more traditional prescriptive design standard and the best way to incorporate uncertainty, flexibility, and the ability to evolve in response to new information. A reevaluation of the standards and specifications for the most appropriate materials is also needed given changing climate conditions and heat-trapping emissions reduction goals.[24] Not all climate-related effects require a change in design, so each state agency responsible for infrastructure should also identify when an operational change, rather than a standard or code update, is more fitting to bolster the climate resilience of an asset. For example, an agency may decide to conduct maintenance of a culvert more often rather than install a larger structure (ICF 2013). State agency staff should also engage standards-developing organizations, such as the American National Standards Institute, to update the model codes underlying many of the state's standards and consider implementing policies that exceed existing standards in the meantime. The Climate-Safe Infrastructure Working Group, for instance, established by the California Natural Resources Authority in July 2017, as required under AB 2800, will provide recommendations to the legislature for how to better integrate climate science into infrastructure design by July 2018. State-led processes can influence infrastructure design at the local level, because jurisdictions and other local agencies and utilities can choose to adopt the state's standards or go beyond them. But they do not need to wait for the state to take action. Examples of some local efforts are described in Box 5. Local efforts should consider consistency and integration across jurisdictions to avoid creating a patchwork of standards and codes. The state could also incentivize more climate-smart design by increasing the amount of federal disaster relief cost-share covered by the state for local projects that meet certain criteria, or it could consider an approach like the one taken by Colorado's Boulder County, which requires disaster funds grantees' projects to meet a resilient-design performance standard (CRRO n.d.).

ii. **Increase local technical capacity.** California should increase its support of key regional and local technical assistance providers in order to strengthen local-level capacity for making sound climate-smart infrastructure decisions. The state could rely on universities, regional climate collaboratives, extension services, other boundary organizations and partnership models,

BOX 5.

Local Examples of Improving and Updating Standards and Codes

New York City recently released its draft *Climate Resiliency Design Guidelines* for addressing increased heat, precipitation, and sea level rise in the design of its capital projects (NYC 2017). Los Angeles has started a process to update its building codes, policies, and procedures, called Building Forward LA (OLA n.d.). The City of Boston requires all projects subject to a specific portion of the city's zoning code to complete a *Climate Change Preparedness and Resiliency Checklist* as part of the project review process (City of Boston 2015). These varied local efforts show a diversity of approaches to improving and updating codes and standards.

[23] For more information on CalEnviroScreen, *see https://oehha.ca.gov/calenviroscreen*.
[24] In 2017, the California legislature passed and Governor Brown signed into law the Buy Clean Act (AB 262, Bonta), which creates new procurement rules for state purchases of infrastructure materials, such as steel and glass. Purchases must now include consideration of the amount of heat-trapping pollution emitted during materials' production.

and local agencies to bolster local capacity, or it could identify and support new organizations or a circuit rider model for climate resilience. [25] Local and regional technical assistance providers are often very familiar with local decisionmaking contexts and have trusted relationships with local practitioners, yet few are currently providing much-needed climate-related information services. Technical assistance would most productively be focused on bolstering predevelopment capacity by providing the best information on risks and costs and the benefits and opportunities of climate-smart infrastructure; helping to identify the most appropriate data and models and translating their output; providing useful guidance on different approaches to decision-making under uncertainty; and assisting practitioners and communities in finding and applying for funding.[26] These technical assistance providers should also relay the local information needs and on-the-ground challenges that they encounter to the state to facilitate a two-way discussion about how to improve state-level activities to better support local action. They should help address the specific capacity needs of underserved and vulnerable populations in low-income, tribal, and rural communities and communities of color so they can meaningfully participate in infrastructure decisions. By partnering with nonprofits and community-based organizations, they can also help increase awareness of these communities' perspectives in other local and regional infrastructure-related processes and conversations. State support for the technical assistance providers could take many forms, including grants, trainings, and providing access to state agency data, tools, case studies, and expertise.

iii. **Establish a well-resourced coordinating center at the state level to support state agencies.** The state should create a center to provide state agency staff with consistent, standardized, and *actionable* climate-related information and guidance that is regularly updated. This center would also respond to requests for other relevant information and technical assistance, such as help identifying the most appropriate tools for assessing social and climate vulnerabilities and risks in different communities (and ensuring the tools are regularly updated) and help with implementing best practices for incorporating equity considerations into infrastructure decisions.[27] Because this expertise is currently spread across several agencies, the center would serve a coordinating role and include experts from across state government. Individual state agencies and their staffs would remain responsible for considering climate impacts in all their infrastructure decisions; the center would play a supportive role and would focus its efforts on assisting agencies that have less robust internal capacity. It could also serve as a resource for regional and local agencies and the local technical assistance providers who will provide key climate-related information and support to local practitioners and communities. It could immediately play a positive role by expanding on the OPR guidance document for state agencies to provide more detailed and readily usable guidance on specific analytical approaches and suitable data that could be used to implement the framework, using infrastructure as an initial case study.[28] Experts at the center should work with OPR's recently established Adaptation Clearinghouse (possibly a good home for much of this information) to gather best practices and case studies of how these approaches have been successfully used to inform climate-smart infrastructure, in addition to examples of other innovative structural, policy, or administrative infrastructure solutions. To ensure that it makes use of the latest advances and innovation, the center should have an advisory group composed of experts from academia, the private sector, and nongovernment organizations. Its success will depend in part on having sufficient resources, so policymakers should prioritize its funding.

Integrate Climate Science and Risks in Financial and Economic Assessments and Investments

KEY BARRIERS

i. **Limited consideration of both climate-related costs and climate-resilience benefits in infrastructure decisions and inadequate data, metrics, and tools available to quantify them.** Governments, utilities, investors, and other infrastructure

[25] The circuit rider model gives access to experts who provide direct technical assistance on an as-needed basis within a defined area (SGA 2015). The National Rural Water Association uses this approach to provide assistance to rural water systems (USDA 2017).

[26] Predevelopment activities include all parts of the infrastructure life cycle prior to construction, such as planning, design, assessments (economic, vulnerability, social, environmental, etc.), funding and financing opportunities, permitting, and outreach (OPS 2015).

[27] Tools and best practices to consider, for instance, include the Environmental Justice Screening Method (EJSM) and the Health Disadvantage Index (HDI) for identifying climate change threats, which should be regularly updated to ensure the underlying data is accurate, and the Equity Checklist (OPR 2017). For more information on the EJSM, see https://dornsife.usc.edu/pere/cumulative-impacts/, and for the HDI see: http://phasocal.org/ca-hdi/.

[28] The center could provide a discussion of the benefits, drawbacks, and appropriate uses of different approaches in this evolving field, such as robust decisionmaking, adaptive management approaches such as adaptive pathways or the observational method, and other analytical approaches for decisionmaking under uncertainty (ASCE 2015; Lempert et al. 2013).

decisionmakers do not normally include climate-related cost and benefit information as a standard consideration when evaluating different infrastructure investments. They may therefore overlook opportunities climate-smart infrastructure presents to avoid damages and maximize cost and risk savings and the many other economic and nonmonetary benefits it can provide. Climate-smart projects may be perceived as more complicated or costly, especially if they involve higher upfront costs. There are currently few appropriate metrics, data, and approaches that can be used to quantify the risks and benefits, especially in light of uncertainties, making it difficult to establish the economic or business case for climate-smart infrastructure. The current state of data, metrics, and methodologies also makes it challenging to simply insert climate impacts into existing tools for project evaluation, such as life-cycle cost assessment (LCCA),[29] cost-benefit analyses, or financial risk assessments, and can lead to a lack of transparency in investment decisions. In addition, there is often a mismatch among the time horizons of the useful life of an infrastructure project (often longer than 50 years), longer-term climate stressors, and the 5-to-30-year decision timeframe used by most private investors. All these factors together can result in investments in projects that turn out to be riskier than anticipated (GARI 2016; CIEL 2015; EPA 2014).

ii. **Inadequate funding and financing for infrastructure compared to the level of need.** Infrastructure in California is generally underfunded, and a significant need for additional investment coincides with dwindling federal and state resources. Climate-smart infrastructure projects may have a harder time securing funding than others. Some of the possible reasons may include higher perceived costs; inadequate information regarding the costs and risks of not building such infrastructure; lack of understanding of and real-world data documenting their performance and other benefits; uncertainties regarding climate-related risks (physical and financial) and return on investment, especially given short investor timeframes; and/or administrative complications. For example, projects that utilize green infrastructure or a hybrid green-grey approach may depend on siloed funding streams that have different timelines and requirements, which can present challenges. Existing finance mechanisms, state and local procurement practices, and lack of awareness among agency staff and infrastructure financiers can also hamper financing of innovative climate-smart infrastructure solutions.

iii. **Underinvestment in infrastructure in the most vulnerable communities.** Although the state's infrastructure system as a whole is in dire need of additional investment, the most vulnerable communities often face higher levels of deferred maintenance and underinvestment, including low-income and tribal communities and communities of color, as well as many rural communities. These communities often have less access to other resources as well. This undermines their ability to cope with infrastructure disruptions and failures exacerbated by climate extremes as well as their ability to participate meaningfully in infrastructure decisionmaking processes in order to ensure that solutions address their specific needs.

RECOMMENDATIONS

i. **Incorporate the costs of climate change and benefits of climate resilience into projects' economic assessments.** State and local governments and agencies should update the methodologies they use to conduct economic assessments, such as cost-benefit analyses and LCCAs, to better integrate consideration of climate-related risks and costs and the benefits and opportunities of climate-smart projects. (State agencies have been slow to revise their LCCA approaches to account for climate change, as required under EO B-30-15.) Analyses of costs should go beyond those associated with just repair or replacement to include the economic and nonmonetary costs associated with negative social, economic, environmental, and health effects of infrastructure disruptions, not neglecting those costs to marginalized communities. In addition, the state should devote sufficient resources to developing better data for these analyses. It should also provide specific guidance on the appropriate methods to be used to quantify costs, benefits, and risks in a way that can be readily inserted into economic analyses and replicated at the local level and suggest possible modifications to current economic analytical approaches to better incorporate this information. For instance, if the state created a centralized database for cost data gathered from extreme weather incidents reported by operations and maintenance programs, asset management programs, emergency services, and crowdsourcing, it could provide a baseline of cost information and measurable data on secondary impacts, such as traffic delays or public safety

[29] LCCA is an analytical approach that accounts for the costs of infrastructure over its entire lifetime, including operating and maintaining the asset and initial upfront costs. It can be used to quantify the effect of a changing climate on total project costs, if the appropriate information is available. Performance metrics that demonstrate the performance benefits of climate-smart infrastructure are important, but currently limited.

problems.[30] The state coordinating center (discussed earlier) should have a key role in this process, and the information could be housed in the Adaptation Clearinghouse. In cases in which this type of data is not available, the state should establish cost-effective and standardized monitoring systems, which can help in developing a baseline of information and have the additional benefits of tracking the performance of infrastructure solutions and progress on resilience goals.

ii. **Require meaningful climate-smart criteria, deliverables, and monitoring and evaluation for use of existing public funds.** State and local governments, public agencies, and municipal utilities should require meaningful climate-smart criteria and deliverables for all infrastructure-related capital outlay projects and capital improvement plans, contracts and other procurement vehicles, grants and bond funding, and asset management plans. This will enable objective comparisons across projects and ensure that public funds are invested wisely in projects that will deliver services in the face of climate extremes while also encouraging innovative solutions that maximize benefits. All project proposals and plans should avoid qualitative statements asserting a project's climate resilience without providing a supporting climate-risk analysis that follows a common set of baseline guidelines. The appropriate level of analysis will, of course, vary based on the stage of the infrastructure life cycle and the project's characteristics. Criteria should incorporate other climate-smart principles in addition to the application of rigorous climate science, including the prioritizing of equitable outcomes and holistic planning. Funding programs and mechanisms should also use performance-based criteria and metrics more widely, including climate resilience and social equity metrics, to help focus decisions on preferred outcomes. They can also then be used to help track progress towards meeting these goals. Procurement practices should help ensure that the most vulnerable and disadvantaged communities share in the employment opportunities created by construction and maintenance of infrastructure. While specific procurement challenges are beyond the scope of this paper, we recognize that the ability to deliver innovative infrastructure solutions is often hampered by current state procurement practices and level of staff awareness. Local governments and agencies can draw from a growing number of novel approaches to transform their procurement process and capital planning; Box 6 describes some of these approaches.

iii. **Identify new sources of funding and employ innovative financing and risk-transfer mechanisms to access additional capital.** Because the need is often greater than currently available resources, state and local government agencies and other public agencies should identify and evaluate new potential funding opportunities and creative financing mechanisms that are well suited to support climate-smart infrastructure projects for both new and existing assets. These include less traditional projects that employ a more decentralized approach across a specific area or a hybrid grey-green approach. Agency staff should share the information they gather concerning new prospects for funding and finance mechanisms online in an easily navigable and publicly accessible manner. State and local agencies usually use bonds, loans, taxes, fees, grants, and/or public–private partnerships to fund public infrastructure (McNichol 2017). Several efforts are currently underway to identify new funding and financing opportunities, both at the state level (through the Fourth Climate Change Assessment and the Technical Advisory

BOX 6.

Examples of Local Agencies Integrating Climate Effects into Capital Planning and Procurement

The City and County of San Francisco outlines a comprehensive approach to integrating sea level rise into its capital planning process, based on a project's location, life span, and adaptive capacity, in *Guidance for Incorporating Sea Level Rise into Capital Planning in San Francisco* (CCSFSLC 2015). Other cities are exploring novel procurement mechanisms that encourage creativity and innovation in infrastructure solutions. One example is Boston's "request for information" (rather than the traditional request for proposals, which already specifies project design) (City of Boston 2016).

30 For example, the Chicago Transportation Authority developed cost estimates for heavy precipitation events based on reimbursement information submitted for a FEMA claim (ICF 2013).

Committee for the Integrated Climate Adaptation and Resiliency Program) and at the local level in partnership with the private sector and nonprofit organizations such as the West Coast Infrastructure Exchange. Box 7 highlights some of these new mechanisms and opportunities. In addition, state and local governments must identify ways to lower the barriers to both accessing finance for vulnerable communities and better investing in small towns and rural areas. They should also intentionally target infrastructure investments to address the needs of these vulnerable and underserved communities and to help build their resilience to climate change. Similar to the studies undertaken by the California Public Utilities Commission and the Air Resources Board efforts under California's SB 350 law to assess barriers to energy efficiency, renewable energy, and zero-emissions transportation in low-income communities, the state should conduct a study of barriers to climate-smart infrastructure in vulnerable communities that results in actionable next steps to overcome them. By supporting design competitions, such as the Bay Area's Resilient by Design, public agencies can also encourage the formation of creative partnerships to develop pioneering funding and financing sources in addition to innovative design solutions.

iv. **Encourage transparency through climate-risk disclosure for investments and develop improved financial data, metrics, and tools**. Private financial sector actors should develop transparent metrics, criteria, and methodologies for incorporating the risks of a changing climate into credit ratings assessments and financial valuations for public infrastructure projects, including bonds. These financial sector actors include professionals from credit ratings agencies and insurance and reinsurance companies as well as bond analysts and infrastructure investors, such as those focused on project finance. They should build on recent efforts in the sector to better integrate consideration of climate risks into financial decisions.[32] Some ratings agencies, such as Moody's and Standard and Poor's, have recognized the need to incorporate climate risk in their analyses and are beginning to develop approaches to do so (Moody's 2016; Kraemer 2014). Multilateral development banks, including the World Bank, are also including this lens in their loan requirements (World Bank n.d.). The emerging field of green bond ratings now incorporates evaluation of a project's resilience to climate impacts as well (S&P 2017). New metrics and methodologies should also capture the full scope of financial benefits accruing from climate-smart projects, which can vary from those resulting from more traditional large, centralized, and grey infrastructure projects. Once developed, financial actors should make this information publicly available, respecting liability and proprietary consideration when necessary, to help facilitate

BOX 7.

Examples of Funding, Financing, and Risk-Transfer Mechanisms for Climate-Smart Infrastructure

New approaches to securing the resources needed for climate-smart infrastructure are emerging. State and local governments are experimenting with new taxes, fees, grants, and revolving loans for green and grey infrastructure and with incentives and value capture, such as tax increment financing and project savings and revenue creation. Others have raised funds through bonds such as green bonds and Washington, DC's "pay-for-success" environmental impact bond (EPA 2017). Insurance and reinsurance companies are increasingly providing risk-transfer options so governments can protect against climate risks via parametric insurance, catastrophic bonds, and resilience bonds.[31] Other new potential sources of revenue include pooled financing among cities and proceeds from California's cap-and-trade auction of emissions allowances. Public–private partnerships may play an increasing role in the future, depending on many factors, including successfully addressing some of the barriers perceived by the private sector discussed in this paper. Philanthropy could also play a role in helping to facilitate innovation of financing mechanisms (Bernasconi and Buchner 2016).

---

31 Resilience bonds "link insurance coverage that public sector entities can already purchase (including parametric insurance policies and catastrophe bonds) with capital investments in resilience projects (such as flood barriers and building retrofits) that reduce expected losses from disasters." Catastrophe bonds, or cat bonds, behave "more like insurance policies than traditional municipal bonds and are designed to reduce the financial risks associated with very low-probability, high-consequence natural disasters" (re:focus partners 2017).

32 Recent efforts include work by the Task Force on Climate-Related Financial Disclosures, criteria approved by the Climate Standards Board for climate-resilient water bonds (CBI 2016), development of a Sustainable and Resilient Underwriting Standard by Global Infrastructure Basel and Santam, and the use of catastrophic models by AIR and RE:bound Program to quantify and address risks and quantify the benefits of proactive resilience actions (GIB n.d.; GARI 2016; re:focus partners 2015b).

state and local agencies' understanding of financial sector considerations so they can develop climate-smart projects that are more likely to be viewed as investible opportunities and potentially access additional capital. Increased transparency and disclosure may contribute to more accurate assessments of the true financial risks posed by climate change to physical assets and debt repayment ability. They may also reveal when analyses and decisions rely too much on past data and trends and short time horizons that could lead to false minimization of longer-term fiscal risks (TFCFD 2017). The state should regularly disclose its projects' climate risks in a transparent manner consistent with mandatory reporting requirements, voluntary best practices, and liability considerations to both the financial sector and the public; this will inform investment decisions and encourage the state to use resources wisely. State agencies should also engage financial sector interests as they develop their criteria, methodologies, and metrics, and should consider facilitating a dialogue among government, private sector, and community representatives to share their views on successful investments from a climate risk perspective, on different investment mechanisms, and on climate risk metrics and methodologies, among other climate risk disclosure topics.

Strengthen Institutional Capacity and Good Governance

KEY BARRIERS

i. **Insufficient capacity and resources for predevelopment activities**. While predevelopment activities represent a small percentage of the overall cost of a project, they can have an outsized effect on the types of projects that are built, including how and where they are built, how they are funded, and who they benefit (BAII 2015). Cities, particularly smaller cities, often have limited staff capacity and resources devoted to predevelopment activities. As a result, they may forego the opportunity for a more robust assessment of a project's climate-related risks and benefits and innovative approaches to address these risks by increasing its climate resilience, maximizing co-benefits, incorporating community input, and possibly increasing return on investment and access to financing solutions.

ii. **Limited coordination across siloes.** Infrastructure systems are interdependent and interconnected across sectors and jurisdictions and across departments within agencies. But many infrastructure decisions take place within silos. This can inhibit awareness of unintended consequences in other sectors and jurisdictions; it can also hinder focus on a consistent set of factors to be considered throughout the decisionmaking process. Extreme weather and more gradual climate stressors do not respect these artificial divisions. An oft-cited example is coastal armoring, such as sea walls, that can affect shoreline dynamics in a way that exacerbates risks to unarmored areas in neighboring communities (Spanger-Siegfried et al. 2016; Kates et al. 2006). Another is the fragmentation of staff working independently on capital outlay, design, and operations and maintenance. Opportunities for cross-sector benefits, cost sharing, and multidisciplinary and integrated approaches that help minimize maladaptive decisions can be missed if adequate coordination is lacking. Practitioners need to understand these interdependencies better so they can plan well and prevent cascading effects; more research is needed to illuminate this issue and support this process (ASCE 2015; Minsker et al. 2015; Wilbanks and Fernandez 2013). Siloed decisionmaking can also deter more equitable outcomes because many of the root causes of inequities rarely lie in just one sector (Yuen et al. 2017).

RECOMMENDATIONS

i. **Plan in advance to build better after a disaster.** State and local governments, agencies, and utilities should prepare in advance for how they will utilize post-disaster responses as opportunities to rebuild infrastructure in a more climate-smart way. After a natural disaster strikes, departments and agencies work furiously to replace and repair damaged infrastructure assets and restore system functioning as soon as possible, often without time or resources to ensure it is more resilient. They can address this dilemma by developing plans beforehand for how to rebuild in a more climate-smart yet timely way and by updating key policies to facilitate this process; this would be akin to building more climate-smart predevelopment capacity specifically focused on infrastructure projects built in response to disasters (ICF 2013). The state should incentivize these proactive approaches and provide technical assistance and resources to support them. One possible incentive could follow a model proposed by FEMA, in which a state's investments in resiliency decrease the amount of disaster funding it must expend before receiving federal public assistance (FEMA 2016b). A similar approach could be used to decrease the local portions of cost sharing for public assistance in federally declared disasters. Boulder County, Colorado, currently uses another previously mentioned approach: it requires projects applying for disaster assistance to meet a resilience performance standard (CCRO n.d.).

ii. **Devote resources to building predevelopment capacity and increasing transparency and inclusion in decisionmaking at the local level.** State and local governments should dedicate more resources specifically to predevelopment activities for public infrastructure to ensure that the projects that do break ground are thoughtfully planned and designed with public input to be climate-smart and to maximize co-benefits and creative financing options. Key staff in local governments and public agencies should receive training, as needed, to deepen their understanding of the best risk management approaches for addressing climate risk in infrastructure decisions and evolving best practices for planning, design, funding, and operations and maintenance. The state center and local technical assistance providers, as well as professional associations, can play a supportive role here. In addition, public infrastructure decisions should be transparent and inclusive so they can be tailored to address the specific needs of communities in a climate-smart way; staff at local governments and public agencies must have enough resources to seek and incorporate community input.

iii. **Ensure better cross-sectoral and cross-jurisdictional coordination at the state and local levels.** State agencies should improve their collaboration to ensure that important infrastructure issues spanning multiple sectors receive a robust and timely discussion during critical planning and decisionmaking activities. The Safeguarding California Climate Action Team could be a helpful platform; its focus is on climate impacts and it includes agencies responsible for planning and designing state infrastructure. Agencies would identify shared risks and/or priority infrastructure initiatives on which to partner using pilot projects, guidelines development, or other vehicles. They would also develop and address a combined list of conflicting policies with the goal of reducing the number of maladaptive infrastructure projects. Similarly, local governments, agencies, and utilities should better coordinate their infrastructure decisions across sectors and jurisdictions.[33] One helpful step would be to develop a robust, agreed-upon multisectoral and/or multijurisdictional vision for climate resilience that includes concrete goals, timelines, agreements on data and tools, and ways to measure success that is regularly updated and that can guide regional and local actions (Lubell 2017). For counties or regions that already have one, state agencies should incentivize projects consistent with or resulting from these efforts through, for example, special preference for funding or improved coordination of permitting decisions across different authorities. They also should support efforts to develop such a vision in areas without one by first identifying key barriers to its development and then providing assistance in overcoming them, whether through policy changes, resources and technical support, facilitation, or other incentives. These efforts should consider multiple hazards to infrastructure assets and systems, to the extent possible, because they are often vulnerable to more than one hazard. The state and regions should consider sponsoring climate-smart design competitions to encourage creative local cross-sectoral and cross-jurisdictional conversations and projects, such as the Bay Area's Resilient by Design challenge. Other governance challenges—such as who is "in charge" of these efforts and how to make decisions about difficult trade-offs among jurisdictions and sectors—should also be addressed. Box 8 highlights several efforts to improve cross-sectoral collaboration at various levels of government.

[33] The San Francisco County Lifelines Council is a useful model for cross-sectoral and cross-agency collaboration that is not explicitly focused on climate risks. Established in 2009, its membership includes representation from energy, water, transportation, and communication sectors and the public and private sectors. It "explores the interconnectedness and interdependencies of lifelines in order to improve development and restoration plans, disperse information about recovery plans and projects and create processes for restoring lifelines after a major disaster" (NACo 2014).

BOX 8.

Examples of Successful State and Local Cross-Sectoral and Cross-Jurisdictional Efforts on Climate Risk

Caltrans and the California Coastal Commission recently participated in a process that culminated in a partnership agreement for planning processes, including sea level rise efforts (Caltrans & CCC 2016). The Southeast Florida Climate Compact, which helps coordinate climate action across four counties, including efforts related to sea level rise and resilience, produced sea level rise information, vulnerability assessments, and a climate action plan that many municipalities are implementing to v8rying degrees. Silicon Valley 2.0–Santa Clara County established a framework for collaboration among cities, county, local agencies, and other stakeholders to evaluate and prepare for a range of climate impacts on multiple infrastructure asset categories, public health, and ecosystems (CSCOS 2015).

An additional overarching challenge to mainstreaming the integration of climate science and climate-smart principles into infrastructure decisions, and to advancing climate action more generally, is the level of political, organizational, and social will needed to change how we plan and build infrastructure. Climate-smart infrastructure can require making tough decisions about significant upfront costs (with potential long-term savings) or changes to existing regulatory processes, policies, or staff responsibilities. The support of decisionmakers—from elected officials and utility board members to leadership in public agencies—and the public can be instrumental in moving these projects forward and facilitating institutional change. It can also help create a civic culture that encourages innovation (Andersen et al. 2017). Recent extreme weather events—California's five-year historic drought followed by historic rains in 2017, massive wildfires across the West, and the record-breaking hurricanes hitting the Southeast, Puerto Rico, and the US Virgin Islands—are resulting in growing public and political support for better preparation of our communities and our infrastructure for climate extremes. Visionary change agents and champions can also initiate needed organizational changes and cultural shifts to pave the way for more systematic and coordinated climate-smart infrastructure decisions (Andersen et al. 2017; Moser and Ekstrom 2012).

Progress is, however, being made, as evidenced by the illustrative examples of climate-smart infrastructure approaches described throughout this paper. By implementing the climate-smart infrastructure principles and recommendations, barriers can be overcome and the transformation of our infrastructure systems can be replicated and accelerated in ways that are appropriate for each asset's or system's context and community.

[SECTION V]

Conclusion

Across California, extreme weather events—from extreme heat and wildfires to droughts and floods—are already threatening communities and the infrastructure they depend on, and global warming has increased the likelihood of these events. These impacts, along with sea level rise, are projected to become more frequent and severe over the near future as a result of climate change. Just as California considers seismic risks as we build and retrofit our long-lived infrastructure even though we do not know exactly when, where, or how the next big earthquake will happen, we need to consider climate risks. This consideration is ultimately in service of two goals: (1) minimizing the damage to people, nature, and the economy caused by climate-related infrastructure disruption or failure; and (2) maximizing infrastructure projects' benefits and creating opportunities to think creatively about the best way to provide key services reliably and safely. This white paper focuses on California, but we believe the problems and solutions it describes are relevant elsewhere. We hope it will spark discussion about how we plan, design, fund, operate, and maintain infrastructure assets and systems as we all face more extreme weather events and increasingly severe climate stressors.

By making our existing and new infrastructure climate-smart, we will more wisely spend our public funds, minimize costly and destructive disruptions, protect our communities and the economy from the harm caused by extreme weather and climate stressors, and reduce the disproportionate effects of climate impacts on low-income communities and communities of color, who are more vulnerable to these consequences. At the same time, climate-smart infrastructure can be designed to reap additional social, economic, health, and environmental benefits. Integrating climate-smart principles into decisions throughout the infrastructure life cycle is critical to ensuring our infrastructure systems are built to last and will deliver needed services to help California communities thrive now and in the changing climate future.

[REFERENCES]

All online references accessed on October 1, 2017, unless otherwise noted.

AECOM. 2015. Resiliency indicator framework. Los Angeles: Los Angeles County Metropolitan Transportation Authority. Online at *http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf.*

Acosta, S. 2017. Highway 50 lanes reopen in west Sacramento after buckling repairs. *Fox 40*, June 19. Online at *http://fox40.com/2017/06/19/highway-50-lanes-reopen-in-west-sacramento-after-buckling-repairs/*, accessed August 8, 2017.

Aldrich, M., and M. Meyer. 2014. Social capital and community resilience. *American Behavioral Scientist* 59(2):254–269. Online at *https://doi.org/10.1177/0002764214550299*, accessed July 22, 2017. doi: 10.1177/0002764214550299.

American Society of Civil Engineers (ASCE). 2017. *2017 infrastructure report card: Energy*. Reston, VA. Online at *www.infrastructurereportcard.org/wp-content/ uploads/2017/01/Energy-Final.pdf*, accessed August 8, 2017.

American Society of Civil Engineers (ASCE). 2015. *Adapting infrastructure and civil engineering practice to changing climate*. Edited by J.R. Olsen. Reston, VA: Committee on Adaptation to a Changing Climate. Online at *http://ascelibrary.org/doi/book/10.1061/9780784479193*, accessed August 8, 2017. doi:10.1061/9780784479193.

American Society of Civil Engineers (ASCE). 2012. *California infrastructure report card: A citizen's guide—2012*. Reston, VA. Online at *www.ascecareportcard.org/*.

American Society of Civil Engineers (ASCE). 2011. *Failure to act: The economic impact of current investment trends in water and wastewater treatment infrastructure.* Reston, VA. Online at *www.asce.org/uploadedFiles/Issues_and_Advocacy/ Our_Initiatives/Infrastructure/Content_Pieces/failure-to-act-water-wastewater-report.pdf*, accessed August 8, 2017.

Andersen, F., C. Becker-Birck, L. Hanson, S. Shyduroff, W. Sloan, K. Wright, D. Gangi, N. Kapur, and A. Morse. 2017. *Unlocking private capital to finance sustainable infrastructure.* New York: Environmental Defense Fund. Online at *http://business.edf.org/files/2017/09/EDF_Unlocking-Private-Capital-to-Finance-Sustainable-Infrastructure_FINAL.pdf.*

Aon Benfield. 2015. Global catastrophe recap: September 2015. London, UK. Online at *http://thoughtleadership.aonbenfield.com/Documents/20151007-if-september-global-recap.pdf.*

Aquarium of the Pacific (AOP). 2015. *City of Long Beach climate resiliency assessment report*. Long Beach, CA. Online at *www.aquariumofpacific.org/downloads/AOPs_2015_Report_on_Resiliency_(1-7-16).pdf.*

Associated Press (AP). 2017. Union Pacific: Flooding likely factor in train derailment. Sacramento, CA: KTXL FOX40, February 12. Online at *http://fox40.com/2017/02/12/union-pacific-flooding-likely-factor-in-train-derailment/*, accessed August 8, 2017.

Baussan, D. 2015. *Social cohesion: The secret weapon in the fight for equitable climate resilience*. Washington, DC: Center for American Progress. Online at *https://cdn.americanprogress.org/wp-content/uploads/2015/05/SocialCohesion-report2.pdf.*

Bedsworth, L.W., and E. Hanak. 2010. Adaptation to climate change. *Journal of the American Planning Association* 76(4):477–495. Online at *www.tandfonline.com/doi/abs/10.1080/01944363.2010.502047.* doi:10.1080/01944363.2010.502047.

Bernasconi, L., and B. Buchner. 2016. Philanthropy's role in financing a climate-resilient world. New York: The Rockefeller Foundation. Blog, June 15. Online at *www.rockefellerfoundation.org/blog/philanthropys-role-financing-climate-resilient-world/.*

Biging, G., J.D. Radke, and J.H. Lee. 2012. Impacts of predicted sea-level rise and extreme storm events on the transportation infrastructure in the San Francisco Bay region. CEC-500-2012-040. Sacramento, CA: California Energy Commission. Online at *www.energy.ca.gov/2012publications/CEC-500-2012-040/CEC-500-2012-040.pdf.*

Bocchini, P., D.M. Frangopol, T. Ummenhofer, and T. Zinke. 2014. Resilience and sustainability of civil infrastructure: Toward a unified approach. *Journal of Infrastructure Systems* 20(2). Online at *http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29IS.1943-555X.0000177.*

BoCo Strong. 2016. *Putting on a resilience lens: BoCo Strong resilience assessment for Boulder County*. Online at *http://bocostrong.org/en/resilience-assessment/.*

Braxton, J. 2017. California dam crisis could have been averted. *Scientific American*, February 20. Online at *www.scientificamerican.com/article/california-dam-crisis-could-have-been-averted/*, accessed August 8, 2017.

Brenner, K. 2017. Novato schools to close early Friday due to extreme heat. *Marin Independent Journal*, August 31. Online at *www.marinij.com/article/NO/20170831/NEWS/170839967.*

Bryant, B., and A. Westerling. 2014. Scenarios for future wildfire risk in California: Links between changing demography, land use, climate, and wildfire. *Environmetrics* 25:454–471. Online at *http://onlinelibrary.wiley.com/doi/10.1002/env.2280/abstract,* accessed August 8, 2017. doi:10.1002/env.2280.

Build America Investment Initiative (BAII). 2015. *Federal resource guide for infrastructure planning and design.* Washington DC: US Department of Housing and Urban Development. Online at *https://s3.amazonaws.com/nyclimatescience.org/huddoc_id =BAInfraResGuideMay2015.pdf.*

Burger, A. 2017. Public-private partnership results in low-carbon community microgrid for Blue Lake Rancheria Native American tribe. Minneapolis, MN: Microgrid Media. Online at *http://microgridmedia.com/public-private-partnership-results-low-carbon-community-microgrid-blue-rancheria-native-american-tribe/.*

California Coastal Commission (CCC). 2015. *Sea level rise policy guidance*. San Francisco. Online at *https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0_Full_Adopted_Sea_Level_Rise_Policy_Guidance.pdf.*

California Department of Finance (CDOF). 2014. *California's five-year infrastructure plan.* Sacramento, CA. Online at *www.ebudget.ca.gov/2014-Infrastructure-Plan.pdf,* accessed September 27, 2017.

California Department of Forestry and Fire Protection (CalFire). 2015a. Top 20 largest California wildfires. Sacramento, CA. Online at *www.fire.ca.gov/communications/downloads/fact_sheets/20LACRES.pdf.*

California Department of Transportation (Caltrans). No date. The San Francisco/Oakland Bay Bridge facts at a glance. Sacramento, CA. Online at *www.dot.ca.gov/hq/esc/tollbridge/SFOBB/Sfobbfacts.html.*

California Department of Transportation (Caltrans). 2016. *Design product evaluation criteria handbook.* Sacramento, CA. Online at *www.dot.ca.gov/hq/oppd/quality/Design-Product-Evaluation-Criteria_2016.pdf.*

California Department of Transportation (Caltrans). 2011. *Guidance on incorporating sea level rise: For use in planning and development of Project Initiation Documents.* Sacramento, CA. Online at *www.dot.ca.gov/ser/downloads/sealevel/guide_incorp_slr.pdf.*

California Department of Transportation and California Coastal Commission Integrated Planning Team (Caltrans & CCC). 2016. *Plan for improved agency partnering.* Sacramento, CA.

California Department of Water Resources (CDWR). 2017a. Climate change. Sacramento, CA. Online at *www.water.ca.gov/climatechange/.*

California Department of Water Resources (CDWR). 2017b. Delta Risk Management Strategy. Sacramento, CA. Online at *http://www.water.ca.gov/floodsafe/fessro/levees/drms/,* accessed on November 15, 2017.

California Department of Water Resources (CDWR). 2017c. 321 East Porterville households now connected to reliable water supply. Press release, August 18. Online at *www.water.ca.gov/news/newsreleases/2017/081817anniversary.pdf,* accessed September 5, 2017.

California Department of Water Resources (CDWR). 2016a. East Porterville homes connected to water system; pipes help residents at drought's "ground zero." Press release, August 19. Online at *www.water.ca.gov/news/newsreleases/2016/081916v2.pdf,* accessed September 29, 2017.

California Department of Water Resources (CDWR). 2016b. East Porterville emergency water project: October 2016. Sacramento, CA. Online at *http://water.ca.gov/waterconditions/docs/East-Porterville-Summary_English_200-Oct2016.pdf,* accessed September 29, 2017.

California Department of Water Resources (CDWR). 2014. Year's final snow survey comes up dry. Press release, May 1. Online at *https://cida.usgs.gov/ca_drought/,* accessed July 14, 2017.

California Natural Resources Agency (CNRA). 2016. Safeguarding California: Implementation action plans. Sacramento, CA. Online at *http://resources.ca.gov/docs/climate/ safeguarding/Safeguarding%20California-Implementation%20Action%20Plans.pdf.*

California Natural Resources Agency (CNRA). 2014. Safeguarding California: Reducing climate risk. Sacramento, CA. Online at *http://resources.ca.gov/climate/safeguarding.*

California Ocean Protection Council (OPC). 2011. *Resolution of the California Ocean Protection Council on sea-level rise.* Sacramento, CA. *Online at www.opc.ca.gov/webmaster/ftp/pdf/docs/OPC_SeaLevelRise_Resolution_Adopted031111.pdf.*

California State Water Resources Control Board (SWRCB). No date. *Technical package. Financial assistance application. Clean Water State Revolving Fund.* Sacramento, CA. Online at *www.waterboards.ca.gov/water_issues/programs/grants_loans/srf/docs/forms/application_technical_package.pdf.*

California Strategic Growth Council (SGC). 2017. *Affordable Housing and Sustainable Communities Program FY 2016-2017 program guidelines*. Sacramento, CA. Online at *http://sgc.ca.gov/Grant-Programs/AHSCResources/AHSC16-17GuidelinesPost-Errata.pdf.*

California Water Commission (CWC). 2016. *Water Storage Investment Program: Draft technical reference.* Sacramento, CA. Online at *https://cwc.ca.gov/Documents/2016/WSIP/WSIP_Draft_TechRefDoc_Compiled.pdf.*

CBS San Francisco Bay Area (CBS). 2017a. 188,000 evacuated near Oroville Dam spillway. February 12. Online at *http://sanfrancisco.cbslocal.com/2017/02/12/emergency-spillway-flow-slows-oroville-dam/,* accessed July 14, 2017.

CBS San Francisco Bay Area (CBS). 2017b. New Pfeiffer Canyon Bridge Opens on Big Sur Coast to Replace Damaged Span. October 13. Online at *http://sanfrancisco.cbslocal.com/2017/10/13/pfeiffer-bridge-reopens-highway-1-big-sur/*, accessed November 2, 2017.

CBS San Francisco Bay Area (CBS). 2017c. Food, fuel, and mail airlifted to stranded Big Sur residents. March 3. Online at *http://sanfrancisco.cbslocal.com/2017/03/03/food-fuel-mail-airlifted-to-stranded-big-sur-residents/,* accessed August 8, 2017.

CBS San Francisco Bay Area (CBS). 2017d. ACE trains cancelled through Wednesday after flooding, derailment. February 13. Online at *http://sanfrancisco.cbslocal.com/2017/02/13/ace-trains-cancelled-central-valley-flooding-elk-grove-derailment/,* accessed August 8, 2017.

Center for International Environmental Law (CIEL). 2015. (Mis)calculated risk and climate change: Are rating agencies repeating credit crisis mistakes? Washington, DC. Online at *www.ciel.org/wp-content/uploads/2015/06/CIEL_CRA_Brief_24Jun2015.pdf*.

City of Boston. 2016. Boston smart city RFI. Boston, MA. Online at *https://assets.documentcloud.org/documents/3242553/Boston-Smart-City-RFI-2016.pdf*

City of Boston. 2015. *Climate change preparedness and resiliency checklist performance criteria*. Boston, MA. Online at *www.bostonplans.org/getattachment/0518c9ed-8768-4481-883e-3d27ce5b56dd.*

City of New York. 2013. Sandy and its impacts. In *A stronger, more resilient New York.* New York: City of New York, 10–18. Online at *www.nyc.gov/html/sirr/downloads/pdf/final_report/Ch_1_SandyImpacts_FINAL_singles.pdf.*

City and County of San Francisco Sea Level Risk Committee (CCSFSLC). 2015. *Guidance for incorporating sea level rise into capital planning in San Francisco: Assessing vulnerability and risk to support adaptation.* San Francisco: One San Francisco. Online at *http://onesanfrancisco.org/sites/default/files/inline-files/Guidance-for-Incorporating-Sea-Level-Rise-into-Capital-Planning1.pdf*.

Cleetus, R., R. Bueno, and K. Dahl. 2015. *Surviving and thriving in the face of rising seas: Building resilience for communities on the front lines of climate change.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/sites/default/files/attach/ 2015/11/surviving-and-thriving-full-report.pdf*.

Cleetus, R., and K. Mulik. 2014. *Playing with fire: How climate change and development patterns are contributing to the soaring costs of western wildfires.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/sites/default/files/legacy/assets/documents/global_warming/playing-with-fire-report.pdf.*

Climate Bonds Initiative (CBI). 2016. *The water criteria of the climate bonds standard. Phase 1: Engineered water infrastructure*. San Francisco: Ceres. Online at *www.ceres.org/sites/default/files/reports/2017-04/Water_Criteria_of%20the_ClimateBondsStandard_October2016.pdf.*

Coastal and Ocean Working Group of the California Climate Action Team (CO-CAT). 2013. *State of California sea-level rise guidance document. March 2013 update.* Sacramento, CA: California Ocean Protection Council. Online at *www.opc.ca.gov/webmaster/ftp/pdf/docs/2013_SLR_Guidance_Update_FINAL1.pdf.*

Colorado Resiliency and Recovery Office (CRRO). No date. Resilient design performance standards. Denver, CO. Online at *https://static1.squarespace.com/static/573a4027e3214017eb2e590c/t/594d8ead6b8f5b79100ef16c/1498255023071/Resilient+Design+Performance+Standards.pdf.*

County of Santa Clara Office of Sustainability (CSCOS). 2015. Silicon Valley 2.0: Climate adaptation guidebook: Executive summary. San Jose, CA. Online at *www.sccgov.org/sites/osp/Documents/150519_ExecSum_FINAL.pdf.*

Curwen, T. 2017. Big Sur lost a bridge and slipped back in time. Now residents are wondering what happens next. *Los Angeles Times*, March 26. Online at *www.latimes.com/local/california/la-me-big-sur-isolation-20170326-htmlstory.html*, accessed July 14, 2017.

Davis, M., and S. Clemmer. 2014. *Power failure: How climate change puts our electricity at risk—and what we can do.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/powerfailure.*

Delta Stewardship Council (DSC). 2015. *Managing Flood Risk with a Delta Levees Investment Strategy.* Sacramento, CA. Online at *https://cwc.ca.gov/Documents/2017/03_March/March2017_Agenda_Item_11_Attach_5_DLISFactSheet.pdf*, accessed November 15, 2017.

Dettinger, M. 2011. Climate change, atmospheric rivers, and floods in California: A multimodel analysis of storm frequency and magnitude changes. *Journal of the American Water Resources Association* 47(3):514–523. Online at *https://ca.water.usgs.gov/pubs/2011/climate-change-atmospheric-rivers-floods-california-dettinger.pdf.* doi:10.1111/j.1752-1688.2011.00546.

Ekstrom, J.A., L. Bedsworth, and A. Fencl. 2017. Gauging climate preparedness to inform adaptation needs: Local level adaptation in drinking water quality in CA, USA. *Climatic Change* 140(3–4):467–481. Online at *https://link.springer.com/article/10.1007/s10584-016-1870-3.*

Electrical Contractor (EC). 2007. California wildfires damage transmission lines. December. Online at *www.ecmag.com/section/miscellaneous/california-wildfires-damage-transmission-lines*, accessed July 14, 2017.

European Commission. 2011. *Non-paper guidelines for project managers: Making vulnerable investments climate resilient*. Brussels, Belgium. Online at *http://climate-adapt.eea.europa.eu/metadata/guidances/non-paper-guidelines-for-project-managers-making-vulnerable-investments-climate-resilient/guidelines-for-project-managers.pdf.*

Federal Emergency Management Agency (FEMA). 2017. *FEMA public assistance funded projects summary: Open government initiative.* Washington, DC. Online at *www.fema.gov/media-library/assets/documents/28344.*

Federal Emergency Management Agency (FEMA). 2016a. Protecting your businesses. Washington, DC. Online at *www.fema.gov/protecting-your-businesses.*

Federal Emergency Management Agency (FEMA). 2016b. FEMA deductible supplemental advance notice of proposed rulemaking. Washington, DC. Online at *https://www.gpo.gov/fdsys/pkg/FR-2017-01-12/pdf/2017-00467.pdf*.

Folke, C. 2006. Resilience: The emergence of a perspective for social-ecological systems analyses. *Global Environmental Change* 16(3):253–267. Online at *https://doi.org/10.1016/j.gloenvcha.2006.04.002.*

Friend, R., and M. Moench. 2013. What is the purpose of urban climate resilience? Implications for addressing poverty and vulnerability. *Urban Climate* 6:98–113. Online at *https://doi.org/10.1016/j.uclim.2013.09.002*.

Gao, X., C.A. Schlosser, P. O'Gorman, E. Monier, and D. Entekhabi. 2017. Twenty-first-century changes in US regional heavy precipitation frequency based on resolved atmospheric patterns. *Journal of Climate* 30:2501–2521. Online at *https://doi.org/10.1175/JCLI-D-16-0544.1*.

Georgetown Climate Center (GCC). No date. *Green infrastructure toolkit*. Washington, DC. Online at *www.georgetownclimate.org/adaptation/toolkits/green-infrastructure-toolkit/introduction.html.*

Gleick, P. 2015. Impacts of California's ongoing drought: Hydroelectricity generation. Oakland, CA: Pacific Institute. Online at *http://pacinst.org/publication/impacts-of-californias-ongoing-drought-hydroelectricity-generation*, accessed July 14, 2017.

Global Adaptation & Resilience Investment Working Group (GARI). 2016. *Bridging the adaptation gap: Approaches to measurement of physical climate risk and examples of investment in climate adaptation and resilience.* Online at *http://427mt.com/ wp-content/uploads/2016/11/GARI-2016-Bridging-the-Adaptation-Gap.pdf.*

Global Infrastructure Basel (GIB). No date. Sustainability and resilience underwriting. Basel. Online at *www.gib-foundation.org/sustainability-and-resilience-underwriting/*.

Goff, A. 2017. (Updating) A running list of Humboldt storm-related road closures and hazards. *Lost Coast Outpost*, January 10. Online at *https://lostcoastoutpost.com/2017/jan/10/updating-running-list-humboldt-storm-related-road/*, accessed August 4, 2017.

Golub, A., R.A. Marcantonio, and T.W. Sanchez. 2013. Race, space, and struggles for mobility: Transportation impacts on African Americans in Oakland and the East Bay. *Urban Geography* 34(5):699–728. Online at *www.tandfonline.com/doi/abs/10.1080/02723638.2013.778598.*

Griggs, G., J. Árvai, D. Cayan, R. DeConto, J. Fox, H.A. Fricker, R.E. Kopp, C. Tebaldi, and E.A. Whiteman (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. Online at *www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf.*

Hauer, M.E. 2017. Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change* 7: 321-325. Online at *https://www.nature.com/articles/nclimate3271*.

Herring, S.C., A. Hoell, M.P. Hoerling, J.P. Kossin, C.J. Schreck III, and P.A. Stott, eds. 2016. Explaining extreme events of 2015 from a climate perspective. *Bulletin of the American Meteorological Society* 97(12): S1–S145. Online at *www.ametsoc.net/eee/2015/2015_bams_eee_low_res.pdf.*

Herring, S.C., M.P. Hoerling, J.P. Kossin, T.C. Peterson, and P.A. Stott, eds. 2015. Explaining extreme events of 2014 from a climate perspective. *Bulletin of the American Meteorological Society* 96(12):S1–S172. Online at *http://journals.ametsoc.org/doi/suppl/10.1175/BAMS-ExplainingExtremeEvents2014.1/suppl_file/10.1175_bams-explainingextremeevents2014.2.pdf.*

Herring, S.C., M.P. Hoerling, T.C. Peterson, and P.A. Stott, eds. 2014. Explaining extreme events of 2013 from a climate perspective. *Bulletin of the American Meteorological Society* 95(9):S1–S96. Online at *http://journals.ametsoc.org/doi/pdf/10.1175/1520-0477-95.9.S1.1*.

HUD Office of Economic Resilience. 2015. *Green infrastructure and the sustainable communities initiative.* Washington, DC: US Department of Housing and Urban Development. Online at *www.hud.gov/sites/documents/GREENINFRASTRUCTSCI.PDF.*

Hutch, D.J., K.E. Bouye, E. Skillen, C. Lee, L. Whitehead, and J.R. Rashid. 2011. Potential strategies to eliminate built environment disparities for disadvantaged and vulnerable communities. *American Journal of Public Health* 101(4):587–595. Online at *http://doi.org/10.2105/AJPH.2009.173872*.

ICF International. 2013. *Assessment of the body of knowledge on incorporating climate change adaptation measures into transportation projects.* FHWA-HEP-14-016. Washington, DC: US Department of Transportation Federal Highway Administration. Online at *https://ntl.bts.gov/lib/51000/51500/ 51556/transportationprojects.pdf.*

ICLEI-Local Governments for Sustainability USA. 2012. *Sea level rise adaptation strategy for San Diego Bay: Executive summary.* Denver: Public Agency Steering Committee. Online at *http://icleiusa.org/wp-content/uploads/2015/08/San-Diego-Sea-Level-Rise.pdf.*

Intergovernmental Panel on Climate Change (IPCC). 2014a. Annex II: Glossary. In *Climate change 2014: Synthesis report.* Contribution of working groups I, II, and III to the fifth assessment report of the Intergovernmental Panel on Climate Change, edited by K.J. Mach, S. Planton, and C. von Stechow. Geneva: IPCC, 117–130. Online at *www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_Glossary.pdf.*

Intergovernmental Panel on Climate Change (IPCC). 2014b. Annex II: Glossary. 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, edited by 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. Cambridge, UK, and New York: Cambridge University Press, 1757–1776. Online at *www.cambridge.org/core/ books/climate-change-2014-impacts-adaptation-and-vulnerability-part-b-regional-aspects/036A899BD52861D61B0D519C5F2B9334.*

International Transport Forum (ITF). 2016. *Adapting transport to climate change and extreme weather: Implications for infrastructure owners and network managers*. Paris: Organisation for Economic Co-operation and Development. Online at *http://dx.doi.org/10.1787/9789282108079-en.*

Island Press and Kresge Foundation. 2015. *Bounce forward: Urban resilience in the era of climate change.* Washington, DC, and Troy, MI. Online at *http://kresge.org/sites/default/files/ Bounce-Forward-Urban-Resilience-in-Era-of-Climate-Change-2015.pdf.*

Jeon, S., Prabhat, S. Byna, J. Gu, W.D. Collins, and M.F. Wehner. 2015. Characterization of extreme precipitation within atmospheric river events in California. *Advances in Statistical Climatology, Meteorology and Oceanography* 1:45–47. Online at *www.adv-stat-clim-meteorol-oceanogr.net/1/45/2015/ascmo-1-45-2015.pdf.*

Kates, R.W., C.E. Colten, S. Laska, and S.P. Leatherman. 2006. Reconstruction of New Orleans after Hurricane Katrina: A research perspective. *Proceedings of the National Academy of Sciences* 103:14653–14660. doi:10.1073/pnas.0605726103.

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. Online at *www.americanprogress.org/issues/ green/reports/2017/09/28/439712/framework-local-action-climate-change/*

Kelly, C., and T. Ross. 2014. *One storm shy of despair: A climate-smart plan for the administration to help low-income communities.* Washington, DC: Center for American Progress. Online at *https://cdn.americanprogress.org/wp-content/uploads/2014/07/ ResilienceTaskforce-report.pdf.*

Kelly, P.M., and W.N. Adger. 2000. Theory and practice in assessing vulnerability to climatic change and facilitating adaptation. *Climatic Change* 47:325–352. Online at *http://gambusia.zo.ncsu.edu/readings/KellyAdger_2000.pdf.*

Kraemer, M. 2014. *Climate change is a global mega-trend for sovereign risk*. New York: Standard and Poor's Ratings Services. Online at *www.maalot.co.il/publications/ GMR20140518110900.pdf.*

Lempert, R.J., S.W. Popper, D.G. Groves, N. Kalra, J.R. Fischbach, S.C. Bankes, B.P. Bryant, M.T. Collins, K. Keller, A. Hackbarth, L. Dixon, T. LaTourrette, R.T. Reville, J.W. Hall, C. Mijere, and D.J. McInerney. 2013. *Making good decisions without predictions: Robust decision making for planning under deep uncertainty.* Santa Monica, CA: RAND.

Liban, C. 2017. Personal communication with the author, October 4. Cris Liban is the Executive Officer for Environment Compliance and Sustainability at the Los Angeles County Metropolitan Transportation Authority.

Lubell, M. 2017. *The governance gap: Climate adaptation and sea-level rise in the San Francisco Bay Area.* Davis: University of California, Davis. Online at *http://climatereadinessinstitute.org/ wp-content/uploads/2014/03/UC-Davis-Governance-Gap-Sea-Level-Rise-Final-Report.pdf.*

Maher, K., and J. Peace. 2017. *Framework for engaging small- and medium-sized businesses in Maryland on climate resilience*. Washington, DC: Center for Climate and Equity Solutions. Online at *www.c2es.org/docUploads/framework-engaging-small-medium-sized-business-maryland-climate-resilience.pdf.*

Malik, K. 2014. *Sustaining human progress: Reducing vulnerabilities and building resilience.* New York: United Nations Development Programme. Online at *http://hdr.undp.org/sites/ default/files/hdr14-report-en-1.pdf.*

Martinich, J., J. Neumann, L. Ludwig, and L. Jantarasami. 2013. Risks of sea level rise to disadvantaged communities in the United States. *Mitigation and Adaptation Strategies for Global Change* 18(2):169–185. doi:10.1007/s11027-011-9356-0.

McNamara, J., S. Clemmer, K. Dahl, and E. Spanger-Siegfried. 2015. *Lights out? Storm surge, blackouts, and how clean energy can help*. Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/sites/default/files/attach/ 2015/10/lights-out-fullreport.pdf.*

McNichol, E. 2017. It's time for states to invest in infrastructure. Washington, DC: Center on Budget and Policy Priorities. Blog, August 10. Online at *www.cbpp.org/research/state-budget-and-tax/its-time-for-states-to-invest-in-infrastructure.*

Melillo, J.M., T.C. Richmond, and G.W. Yohe. 2014. *Climate change impacts in the United States: The third national climate assessment.* Washington, DC: US Global Change Research Program. doi:10.7930/J0Z31WJ2.

Mendoza, M., and S. Thanawala. 2014. Power outages, flooding hit northern California due to massive storm. *Christian Science Monitor*, December 11. Online at *www.csmonitor.com/USA/Latest-News-Wires/2014/1211/Power-outages-flooding-hit-northern-California-due-to-massive-storm*, accessed September 5, 2017.

Metropolitan Transportation Commission (MTC). 2014. *Climate change and extreme weather options for transportation assets in the Bay Area pilot project.* Oakland, CA. Online at *http://files.mtc. ca.gov/pdf/MTC_ClmteChng_ExtrmWthr_Adtpn_Report_Final.pdf.*

Milly, P.C., J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer. 2008. Stationarity is dead: Whither water management? *Science* 319(5863):573–574. doi:10.1126/science.1151915.

Minsker, B., L. Baldwin, J. Crittenden, K. Kabbes, M. Karamouz, K. Lansey, P. Malinowski, E.U. Nzewi, A. Pandit, J. Paker, S. Rivers, C. Queiroz Surbeck, W.A.Wallace, and J. Williams. 2015. Progress and recommendations for advancing performance-based sustainable and resilient infrastructure design. *Journal of Water Resources Planning and Management* 141. Online at *http://ascelibrary.org/doi/full/10.1061/%28ASCE%29WR.1943-5452.0000521*. doi:10.1061/(ASCE) WR.1943-5452.0000521.

Moody's Investors Service. 2016. *Environmental risks—sovereigns: How Moody's assesses the physical effects of climate change on sovereign issuers.* New York. Online at *www.eticanews.it/wp-content/uploads/2017/01/Moodys-climate-change-and-sovereigns-November-7.pdf*.

Morello-Frosch, R., M. Pastor, J. Sadd, and S. Shonkoff. 2009. *The climate gap: Inequalities in how climate change hurts Americans & how to close the gap.* Los Angeles: University of Southern California Dornsife Program for Environmental and Regional Equity (PERE) Publications. Online at *https://dornsife.usc.edu/pere/climategap.*

Moser, S., and J. Ekstrom. 2012. *Identifying and overcoming barriers to climate change in the San Francisco Bay: Results from case studies.* CEC-500-2012-034. Sacramento, CA: California Energy Commission. Online at *www.energy.ca.gov/2012publications/CEC-500-2012-034/CEC-500-2012-034.pdf.*

Moser, S.C., and J.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. doi:10.1007/s10584-015-1328-z.

Movement Strategy Center (MSC), Movement Generation, The Praxis Project, and Reimagine! RPE. 2015. *Pathways to resilience: Transforming cities in a changing climate.* Oakland, CA: Movement Strategy Center. Online at *http://pathways-2-resilience.org/ebook/about/*, accessed October 10, 2017.

Multihazard Mitigation Council (MMC). 2005. *Natural hazard mitigation saves: An independent study to assess the future savings from mitigation activities.* Washington, DC: National Institute of Building Science. Online at *www.nibs.org/resource/resmgr/MMC/hms_vol1.pdf.*

Narum, D., J. Ganion, and D. Carter. 2016. *Developing a low-carbon microgrid on tribal lands: A case study.* Online at *http://aceee.org/files/proceedings/2016/data/papers/11_459.pdf.*

National Academies of Sciences, Engineering, and Medicine (NAS). 2016. *Attribution of extreme weather events in the context of climate change*. Washington, DC: National Academies Press. doi:10.17226/21852. Online at *www.nap.edu/catalog/21852/attribution-of-extreme-weather-events-in-the-context-of-climate-change.*

National Association of Counties (NACo). 2014. *Resilient counties lifelines.* Washington, DC. Online at *www.naco.org/sites/default/files/documents/NACo_ResilientCounties_Lifelines_Nov2014.pdf.*

National Association of Development Organizations (NADO). 2015. *Planning for a more resilient future: A guide to regional approaches.* Washington, DC. Online at *www.planningforresilience.com/.*

National Centers for Environmental Information (NCEI). 2017. US billion-dollar weather and climate disasters. Washington, DC: National Oceanic and Atmospheric Administration. Online at *www.ncdc.noaa.gov/billions/.*

National Infrastructure Advisory Council (NIAC). 2013. *Strengthening regional resilience: Final report and recommendations.* Washington, DC: US Department of Homeland Security. Online at *www.dhs.gov/sites/default/files/publications/niac-regional-resilience-final-report-11-21-13-508.pdf.*

National Institute of Standards and Technology (NIST). 2016. *NIST special publication 1190: Community resilience planning guide for buildings and infrastructure systems, volume II*. Washington, DC: US Department of Commerce. Online at *http://dx.doi.org/10.6028/NIST.SP.1190v2*.

National Research Council of the National Academies (NRC). 2013. *Abrupt impacts of climate change: Anticipating surprises.* Washington, DC: National Academies Press. Online at *https://doi.org/10.17226/18373.*

National Research Council of the National Academies (NRC). 2008. *Transportation Research Board special report 290: Potential impacts of climate change on US transportation*. Washington, DC: Transportation Research Board. Online at *http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf*.

Nelson, R.K., L. Winling, R. Marciano, N. Connolly, et al. 2017. Mapping inequality: Redlining in New Deal America. *American Panorama*, edited by R.K. Nelson and E.L. Ayers. Richmond, VA: Digital Scholarship Lab, University of Richmond. Online at *https://dsl.richmond.edu/panorama/redlining/#loc=4/36.71/-96.93&opacity=0.8&text=intro*, accessed September 25, 2017.

New York City Mayor's Office of Recovery and Resiliency (NYC). 2017. *Preliminary climate resiliency design guidelines*. New York. Online at *www1.nyc.gov/assets/orr/images/content/header/ORR_ClimateResiliencyDesignGuidelines_PRELIMINARY_4_21_2017. pdf.*

Office of Environmental Health Hazard Assessment (OEHHA). 2013. *Indicators of climate change in California*. Sacramento, CA: California Environmental Protection Agency. Online at *https://oehha.ca.gov/media/downloads/risk-assessment/document/climatechangeindicatorsreport2013.pdf.*

Office of Los Angeles Mayor Eric Garcetti (OLA). No date. *Building forward LA*. Online at *www.lamayor.org/BuildingForwardLA*, accessed September 27, 2017.

Office of Management and Budget (OMB). 2016. Standards and finance to support community resilience. Washington, DC: White House Executive Office of the President. Online at *https://obamawhitehouse.archives.gov/sites/default/files/omb/reports/omb_resilience_finance_report.pdf.*

Office of Planning and Research (OPR). 2017. *Planning and investing for a resilient California: A guidebook for state agencies.* Sacramento, CA. Online at *http://opr.ca.gov/planning/icarp/resilient-ca.html*, accessed November 15, 2017.

Office of the Press Secretary at the White House (OPS). 2015. Presidential memorandum: Expanding federal support for predevelopment activities for nonfederal domestic infrastructure assets. Press release, January 16. Online at *https://obamawhitehouse.archives.gov/the-press-office/2015/01/16/presidential-memorandum-expanding-federal-support-predevelopment-activit.*

Pacific Gas & Electric Company (PG&E). 2016. Climate change vulnerability assessment. San Francisco, CA. Online at *www.pgecurrents.com/wp-content/uploads/2016/02/PGE_climate_resilience.pdf.*

Pacific Gas & Electric Company (PG&E). 2015. PG&E supporting first responders on three major wildfires, assessing impacts to portions of the electric grid. *Currents,* September 15. Online at *www.pgecurrents.com/2015/09/13/pge-supporting-first-responders-on-three-major-wildfires-assessing-impacts-to-portions-of-the-electric-grid/*, accessed July 14, 2017.

Pescaroli, G., and D. Alexander. 2015. A definition of cascading disasters and cascading effects: Going beyond the "toppling dominos" metaphor. *Planet@Risk,* 2(3):58–67. Online at *https://planet-risk.org/index.php/pr/article/view/208/355.*

Peterson, T.C., M.P. Hoerling, P.A. Stott, and S. Herring, eds. 2013. Explaining extreme events of 2012 from a climate perspective. *Bulletin of the American Meteorological Society* 94(9): S1–S74. Online at *http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-13-00085.1*.

Peterson, T.C., P.A. Stott, and S. Herring, eds. 2012. Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society* 93(7):1041–1067. Online at *http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00021.1*.

Pierce, D.W., D.R. Cayan, and L. Dehann. 2016. *Creating climate projections to support the 4th California Climate Assessment.* La Jolla, CA: Scripps Institution of Oceanography. Online at *http://docketpublic.energy.ca.gov/PublicDocuments/16-IEPR-04/TN211805_20160614T101821_Creating_Climate_projections_to_support_the_4th_California_Clim.pdf.*

Pogash, C. 2014. Rainstorm turns the San Francisco area arid to soggy in hours. *New York Times,* December 11. Online at *www.nytimes.com/2014/12/12/us/california-storm-pineapple-express-san-francisco-braces.html*, accessed September 5, 2017.

Poole, E., C. Toohey, and P. Harris. 2014. Public-infrastructure: A framework for decision-making. In *Financial Flows and Infrastructure Financing*, conference volume, edited by A. Heath and M. Read. Sydney, Australia: Reserve Bank of Australia, 97–135. Online at *www.rba.gov.au/publications/confs/2014/pdf/poole-toohey-harris.pdf.*

Radtke Russell, P. 2017. ASCE tackles climate change in new guide for resilient structures. *Engineering News-Record.* October 18. Online at *https://www.enr.com/articles/43131-asce-tackles-climate-change-in-new-guide-for-resilient-structures?v=preview,* accessed November 1, 2017.

re:focus partners. 2017. *A guide for public-sector resilience bond sponsorship*. La Jolla, CA: RE:bound Program. Online at *www.refocuspartners.com/wp-content/uploads/2017/02/RE.bound-Program-Report-December-2015.pdf.*

re:focus partners. 2015a. *Re:invest: A roadmap for resilience*. La Jolla, CA: RE.invest Initiative. Online at *www.reinvestinitiative.org/wp-content/uploads/pdf/RE.invest_ Roadmap-For-Resilience.pdf.*

re:focus partners. 2015b. *Leveraging catastrophe bonds as a mechanism for resilient infrastructure project finance.* La Jolla, CA: RE.bound Program. Online at *www.refocuspartners.com/wp-content/uploads/2017/02/RE.bound-Program-Report-December-2015.pdf.*

Reynolds, L. 2013. *Climate change preparedness and the small business sector*. Washington, DC: Small Business Majority and American Sustainable Business Council. Online at *http://asbcouncil.org/sites/default/files/small_business_climate_report.pdf*.

Rogers, J., J. Barba, and F. Kinniburgh. 2015. *From boom to bust: Climate risk in the golden state*. New York: Risky Business. Online at *https://riskybusiness.org/site/assets/uploads/2015/09/California-Report-WEB-3-30-15.pdf.*

Rubin, V. 2006. *Safety, growth, and equity: Infrastructure policies that promote opportunity and inclusion.* Oakland, CA: PolicyLink. Online at *http://policylink.org/sites/default/files/SAFETYGROWTHEQUITY-INFRAPOLICIES_FINAL.PDF.*

Sacramento Area Council of Governments (SACOG) and CivicSpark. 2015. *Sacramento region transportation climate adaptation plan.* Sacramento, CA. Online at *www.sacog.org/sites/main/files/file-attachments/ fullplanwithappendices.pdf.*

Sánchez, T.W., R. Stolz, and J.S. Ma. 2003. *Moving to equity: Addressing inequitable effects of transportation policies on minorities.* Cambridge, MA: The Civil Rights Project at Harvard University. Online at *www.civilrightsproject.ucla.edu/research/metro-and-regional-inequalities/transportation/moving-to-equity-addressing-inequitable-effects-of-transportation-policies-on-minorities/sanchez-moving-to-equity-transportation-policies.pdf.*

San Diego County Regional Airport Authority (SDCRAA). 2016. *Water stewardship plan: Protecting our water resources.* San Diego, CA. Online at *http://san.org/Portals/0/Documents/Environmental/2016_0509_Water%20Stewardship%20Plan%20Document_F2.pdf.*

Sansavini, G. 2017. Engineering resilience in critical infrastructures: Discussion paper on risk and uncertainty modeling in energy systems. In *Navigating the roadmap for clean, secure, and efficient energy information*. Vienna, Austria: Technische Universität Wien. Online at *www.set-nav.eu/sites/default/files/common_files/deliverables/WP10/Discussion%20Paper_Engineering%20Resilience%20in%20Critical%20Infrastructures.pdf.*

Sarmiento, C., and T.R. Miller. 2006. *Costs and consequences of flooding and the impact of the National Flood Insurance Program*. Calverton, MD: Pacific Institute for Research and Evaluation. Online at *www.fema.gov/media-library-data/20130726-1602-20490-4555/nfip_eval_costs_and_consequences.pdf.*

Sathaye, J., D. Larry, P. Larsen, G. Fitts, K. Koy, S. Lewis, and A. Lucena. 2012. *Estimating risk to California energy infrastructure from projected climate change.* CEC-500-2012-057. Sacramento: California Energy Commission. Online at *www.energy.ca.gov/2012publications/CEC-500-2012-057/CEC-500-2012-057.pdf.*

Serna, J. 2017. 22 freight train cars tumble into flooded northern California river after derailment. *Los Angeles Times*, February 10. Online at *www.latimes.com/local/lanow/la-me-ln-train-derailment-cosumnes-20170210-story.html*, accessed July 14, 2017.

Smart Growth America (SGA). 2015. *Building resilient states: A framework for agencies*. Washington, DC. Online at *www.smartgrowthamerica.org/app/legacy/documents/building-resilient-states.pdf.*

Smith, A.B., and J.L. Matthews. 2015. Quantifying uncertainty and variable sensitivity within the US billion-dollar weather and climate disaster cost estimates. *Natural Hazards* 77(3):1829–1851. Online at *https://doi.org/10.1007/s11069-015-1678-x.*

Spanger-Siegfried, E., J. Funk, R. Cleetus, M. Deas, and J. Christian-Smith. 2016. *Toward climate resilience: A framework and principles for science-based adaptation.* Cambridge, MA: Union of Concerned Scientists. Online at *www.ucsusa.org/resilience_principles.*

Standard & Poor's Global Ratings (S&P). 2017. S&P Global Ratings green evaluation: Time to turn over a new leaf? New York. Online at *www.spratings.com/documents/20184/1481001/Green+Evaluation/bbcd37ba-7b4f-4bf9-a980-d04aceeffa6b*, accessed September 28, 2017.

Stoms, D., G. Franco, H. Raitt, S. Wilhelm, and S. Grant. 2013. *Climate change and the California energy sector.* CEC-100-2013-002. Sacramento, CA: California Energy Commission. Online at *www.energy.ca.gov/2013publications/CEC-100-2013-002/CEC-100-2013-002.pdf.*

Systems Approach to Geomorphic Engineering (SAGE). 2015. *Natural and structural measures for shoreline stabilization*. Online at *http://sagecoast.org/docs/SAGE_LivingShorelineBrochure_Print.pdf*, accessed August 12, 2017.

Task Force on Climate-Related Financial Disclosures (TFCFD). 2017. *Final report: Recommendations of the task force on climate-related financial disclosures.* Online at *www.fsb-tcfd.org/wp-content/uploads/2017/06/FINAL-TCFD-Report-062817.pdf*, accessed September 27, 2017.

The Nature Conservancy (TNC). 2013. *The case for green infrastructure: Joint-industry white paper*. Arlington, VA. Online at *www.nature.org/about-us/the-case-for-green-infrastructure.pdf.*

Ting, E. 2017. Orinda schools to close early Friday due to extreme heat. *SF Gate*, August 31. Online at *www.sfgate.com/bayarea/article/Orinda-schools-closing-early-Friday-due-to-12165911.php.*

Transportation Research Board (TRB). 2014. *Strategic issues facing transportation, volume 2: Climate change, extreme weather events and the highway system: Practitioner's guide and research report.* Washington, DC: National Cooperative Highway Research Program, Transportation Research Board. Online at *www.trb.org/Main/Blurbs/169781.aspx.*

United Nations Development Programme (UNDP). 2011. *Paving the way for climate-resilient infrastructure: Guidance for practitioners and planners*. New York. Online at *www.uncclearn.org/sites/default/files/inventory/undp_paving_the_way.pdf.*

US Department of Agriculture (USDA). 2017. Circuit rider program technical assistance for rural water systems. Washington, DC. Online at *www.rd.usda.gov/files/fact-sheet/RD-FactSheet-RUS-CircuitRider08_2017.pdf.*

US Department of Energy, Office of Science (DOE). No date. *Hyperion: Understanding hydroclimate data with use-inspired metrics.* Washington, DC. Online at *http://climate.ucdavis.edu/hyperion/index.php.*

US Department of Energy (DOE). 2013. *US energy sector vulnerabilities to climate change and extreme weather*. DOE/PI-0013. Washington, DC. Online at *https://energy.gov/sites/prod/files/2013/07/f2/20130710-Energy-Sector-Vulnerabilities-Report.pdf.*

US Environmental Protection Agency (EPA). 2002. *The clean water and drinking-water infrastructure gap analysis*. EPA-816-R-02-020. Washington, DC. Online at *https://nepis.epa.gov/Exe/ZyPDF.cgi/901R0200.PDF?Dockey=901R0200.PDF*, accessed August 8, 2017.

US Environmental Protection Agency Climate Ready Water Utilities (EPA). 2014. *Risks & resilience: Considering the integration of climate readiness into financial analyses of drinking water & wastewater utilities*. Washington, DC. EPA 817-S-14-001. Online at *www.epa.gov/sites/production/files/2016-06/documents/risks_and_resilience_synthesis_document_final_09_09_14.pdf.*

US Environmental Protection Agency Water Infrastructure and Resiliency Finance Center (EPA). 2017. *DC Water's environmental impact bond: A first of its kind.* Washington, DC. Online at *www.epa.gov/sites/production/files/2017-04/documents/dc_waters_environmental_impact_bond_a_first_of_its_kind_final2.pdf.*

US Geological Survey (USGS). 2017. California drought, visualized with open data. Washington, DC: US Department of the Interior. Online at *https://cida.usgs.gov/ca_drought/*, accessed September 5, 2017.

US Global Change Research Program (USGCRP). 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I,* Edited by D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock. Washington, DC. Online at *https://science2017.globalchange.gov/downloads/ CSSR2017_FullReport.pdf*, accessed November 14, 2017.

US Global Change Research Program (USGCRP). 2016. *The impacts of climate change on human health in the United States: A scientific assessment*, Edited by A. Crimmins, J. Balbus, J.L. Gamble, C.B. Beard, J.E. Bell, D. Dodgen, R.J. Eisen, N. Fann, M.D. Hawkins, S.C. Herring, L. Jantarasami, D.M. Mills, S. Saha, M.C. Sarofim, J. Trtanj, and L. Ziska. Washington, DC. Online at *http://dx.doi.org/10.7930/J0R49NQX*, accessed on October 26, 2017.

US Government Accountability Office (GAO). 2016. *Climate change: Improved federal coordination could facilitate use of forward-looking climate information in design standards, building codes, and certifications.* GAO-17-3. Washington, DC. Online at *www.gao.gov/assets/690/681300.pdf.*

US Government Accountability Office (GAO). 2013. *Climate change: Future federal adaptation efforts could better support local infrastructure decision makers*. GAO-13-242. Washington, DC. Online at *www.gao.gov/assets/660/653741.pdf.*

US Small Business Association (SBA). 2015. *Small business profile: California*. Washington, DC. Online at *www.sba.gov/ sites/default/files/advocacy/CA_1.pdf*.

Vallejo, L., and M. Mullan. 2017. *Climate-resilient infrastructure: Getting the policies right.* Environment Working Paper 121. Paris: Organisation for Economic Co-operation and Development. Online at *www.oecd.org/officialdocuments/ publicdisplaydocumentpdf/?cote=ENV/WKP(2017)8&docLanguage=En.*

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville. 2014. Our changing climate. In *Climate change impacts in the United States: The third national climate assessment,* edited by J.M. Melillo, T.C. Richmond, and G.W. Yohe. Washington, DC: US Global Change Research Program, 19–67. Online at *http://nca2014.globalchange. gov/report/our-changing-climate/introduction.*

Warth, G. 2017. Heatwave causes early school closures Friday. *San Diego Union-Tribune,* August 31. Online at *www.sandiegouniontribune. com/news/education/sd-me-school-closures-20170831-story.html.*

West Coast Infrastructure Exchange (WCX). 2016. *Toward a more resilient water and wastewater infrastructure in the Pacific region*. Portland, OR. Online at *http://westcoastx.com/documents/water-infrastructure-resilience-report.html,* accessed October 23, 2017.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western US forest wildfire activity. *Science* 313(5789):940–943. doi:10.1126/science.1128834.

Whitcomb, D. 2016. Out-of-control California wildfire grows, forces schools to close. *Reuters,* August 9. Online at *www.reuters.com/article/us-california-fire/out-of-control-california-wildfire-grows-forces-schools-to-close-idUSKCN10K1ZV,* accessed September 12, 2017.

Wilbanks, T., and S. Fernandez, editors. 2013. *Climate change and infrastructure, urban systems, and vulnerabilities: Technical report for the US Department of Energy in support of the National Climate Assessment.* Washington, DC: Island Press. Online at *www.ourenergypolicy.org/wp-content/uploads/2014/03/ document_cw_01.pdf.*

Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cool, J.E Smerdon, and E.R. Cook. 2015. Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters* 42(16):6819–6826. doi:10.1002/2015GL064924.

Willis, H.H., A. Narayanan, J.R. Fischbach, E. Molina-Perez, C. Stelzner, K. Loa, and L. Kendrick. 2016. *Current and future exposure of infrastructure in the United States to natural hazards.* Santa Monica, CA: RAND. Online at *www.rand.org/pubs/research _reports/RR1453.html.*

World Bank (WB). No date. *Enabling resilient growth*. Washington, DC. Online at *https://climatescreeningtools. worldbank.org/content/enabling-resilient-growth,* accessed September 28, 2017.

World Economic Forum (WEF). 2017. *The global risks report 2017,* 12th edition. Geneva. Online at *www3.weforum.org/docs/ GRR17_Report_web.pdf.*

Yuen, T., E. Yurkovich, L. Grabowski, and B. Altshuler. 2017. *Guide to equitable, community-driven climate preparedness planning.* Urban Sustainability Directors Network. Online at *www.usdn.org/uploads/cms/documents/usdn_guide_to_equitable_ community-driven_climate_preparedness-_high_res.pdf.*

Attendees of UCS "Climate Risk and Infrastructure" Convening

The following experts attended the "Climate Risk and Infrastructure" convening in Oakland, California, in April 2017. Acknowledgment on this list does not imply endorsement of the white paper.

Allison Brooks, *executive director, Bay Area Regional Collaborative*
Andree Johnson, *senior water resources specialist, Bay Area Water Supply & Conservancy*
Dr. Andrew Jones, *deputy director, Climate Readiness Institute, Lawrence Berkeley National Laboratory*
Chione Flegal, *senior director, PolicyLink*
Chris Godley, *director of emergency management, Tetra Tech*
Dr. Cris Liban, PE, *executive officer, Environment Compliance and Sustainability, Los Angeles County Metropolitan Transportation Authority*
Diane Ross-Leech, *director, Environmental Policy, Pacific Gas and Electric Company*
Ellory Monks, *co-founder, The Atlas Marketplace & Partner, re:focus partners*
Justin Vandever, PE, *coastal engineer, AECOM*
Dr. Kif Scheuer, *climate change director, Local Government Commission*
The Rev. Kirsten Snow Spalding, *director of the Investor Network, Ceres*
Laura Engeman, *director, San Diego Regional Climate Collaborative*
Dr. Mike Antos, *senior watershed manager, Santa Ana Watershed Project Authority*
Phoebe Seaton, *cofounder and codirector, Leadership Counsel for Justice and Accountability*
Raef Porter, *senior analyst, Sacramento Area Council of Governments*

UCS management and staff in attendance included the following:
Adrienne Alvord, *Western States director*
Deborah Moore¸ *Western States campaign manager*
Jamesine Rogers Gibson, *Western States senior climate analyst*
Dr. Juliet Christian-Smith¸ *Western States senior climate scientist (former)*
Katharine Cullen¸ *Western States outreach intern*