Paying it Forward:

The Path Toward Climate-Safe Infrastructure in California








A Report of the Climate-Safe Infrastructure Working Group to the California State Legislature and the Strategic Growth Council

September 2018

Table of Contents

Preface

"The world as we have created it is a process of our thinking.
It cannot be changed without changing our thinking."
— Albert Einstein

The science is clear: our climate is changing. Our traditional ways of thinking, of doing business, of building things – including the processes we have devised to design, finance, construct and operate our infrastructure – must change as well. With change, however, always comes opportunity and resistance. People can agree on the need for change, but reasonably disagree on how to move forward in the face of it. We – the AB 2800 Climate-Safe Infrastructure Working Group – encountered many tensions around viable ways forward. This report lays them out and offers our answers.

We wrestled with irreducible uncertainties about the future and the familiar, seemingly stable averages and patterns of variability of the past.

We struggled with the need to build to one number – common in traditional engineering and building practice – versus the need to plan for a range of future states.

We grappled with focusing not just on one bridge, one building, one transmission pole or one levee, but rather on infrastructure as a system, including the interdependencies and the interconnections among them all.

We worked to find a way to balance the needs of all – especially those traditionally underserved, neglected, or forgotten – with those who have the resources, finances and already a seat at the table.

We tried to stay focused on forward-looking climate science but recognized that more than the climate is changing, thus requiring additional forward-looking science.

We vacillated between what is and what is not "state infrastructure" and thus with how narrowly or widely applicable this report should be.

In all these ways, we lived in the tension between a narrow interpretation of AB 2800 and a broader one – more adequate to the task, and more adequate to the challenge that is not just faced by California State agencies, but by local jurisdictions, other states, federal agencies, and engineers and architects the world over.

Through months of discussions, deepening of our understanding, and the input we received from others, we have come to this resolution: California can and should lead the nation in – in the same way that it leads on greenhouse gas mitigation – building climate-safe infrastructure for the benefit of all. Given observed climate extremes and the science of climate change, doing nothing is simply not part of our State's future that we envision.

The late Stephen Hawking once said, "Intelligence is the ability to adapt to change." Through the work we have done and compiled in this report, we have found that we need the collective contributions of physical and social scientists, engineers and architects, as well as well a multitude of others – planners, legal experts, financial advisors, community leaders, unions, elected officials and advocates – to build the California we want. All hold pieces of information – and often wisdom – without which we would not get to a safe, reliable, resilient and sustainably functioning infrastructure that supports society. We offer this report as a down payment on the debt we owe not just the forward-thinking leaders of the past, but that we owe to our future.

Acknowledgements

The members of the Climate-Safe Infrastructure Working Group and the Project Team would like to extend their gratitude to all who have contributed to the deliberations of the Working Group.

First are all the webinar speakers who offered their expertise, experience and wisdom on the many aspects involved in making climate-safe infrastructure a reality: Mike Sanio, Kathryn Wright, Peter Adams, Dan Cayan, Patrick Barnard, Nicolas Luco, Morgan Page, Gurdeep Bhattal, James Deane, Cris Liban, Kate White, Amir AghaKouchak, Andrew Schwarz, Maya Hayden, Jeff Odefey, Tina Hodges, J. Alfredo Gomez, Stephen A. Cauffman, Ira Feldman, Nancy Ander, Tom Wells, Guido Franco, Martha Brook, Kristin Heinemeier, Chester Widom, Jennifer Goldsmith-Grinspoon, Leslie Chapman-Henderson, Andreas Georgoulias, Shalini Vajjhala, David Dodd, John Cleveland, Vladimir Antikarov, Karl Schultz, Deborah Moore, Chione Flegal, Katie Grace Deane, Richard Moss, Susi Moser, Alex Wilson, David Groves, Wes Sullens, Kristin Baja, Jennifer Jurado, Peter Murdoch, Andreas Georgoulias, Caitlin MacLean, Brad Benson, Joyce Coffee, Cara Pike, Edward Maibach and Colin Wellenkamp (see Appendix 3 for affiliations and topics). Your contributions have served as an invaluable resource to us. Thank you also to the California Energy Commission and University of Southern California's Sea Grant Program for lending us their webinar platforms to host these important and informative events. We also appreciate the many webinar attendees who gave of their time and offered valuable questions to the speakers.

Next, we similarly would like to acknowledge and thank the experts who joined our meetings and who provided detailed insights into the various challenges we all face in building climate-safe infrastructure: Secretary John Laird, Hon. Bill Quirk, Jamesine Rogers Gibson, Bruce Blanning, Deputy Secretary for Climate and Energy Keali'i Bright, Sabrina Bornstein, Matt Barnard, Steve Reel, John Thomas, Kit Batten, Bob Battalio, Nate Kaufman, Jim Thorne, Nicole Meyer-Morse, Millie Levin, Louise Bedsworth, Phil Gibbons, Cody Hooven, Ralph Redman, Andrew Martin, Beverly Scott and Bilal Ayyub (see Chapter 1, Table 1.1 for affiliations and topics). Your example and expertise pushed us to think harder and bigger about what is needed to integrate forward-looking science into infrastructure planning, design, construction and operation. In addition, thank you to the invited experts and interested individuals – too many to mention – who joined the Working Group meetings and contributed during public comment periods or actively joined interactive exercises. This bolstered the collective expertise and we benefited greatly.

Our appreciation also goes to the many researchers who contributed to Fourth and prior California Climate Change Assessments – too numerous to mention individually, but greatly appreciated for all their work to help us better understand the risks California is facing from climate change.

Many others have contributed in various ways to this project and report, and we are thankful to all even if we cannot name them all individually: those who have helped us find or grant permission to use photos and illustrations; pointed us to important sources of information, tools, platforms and reports; helped us secure venues for meetings; and provided us insight into related efforts happening across the country, in local, state and federal governments, professional societies, cross-agency working groups, and even in other countries. A special thanks goes to Susan Fischer Wilhelm, Tom Wells, Elisa Ragno, Farshid Vahedifard, Charlotte Stevenson and Carol Berzonsky.

Abbreviations

AAAS	American Association for the Advancement of Science
AB 2800	Assembly Bill 2800 (Quirk, 2016)
AGU	American Geophysical Union
APG	Adaptation Planning Guide
ASCE	American Society of Civil Engineers
BCA	Benefit-cost analysis
CAAP	Clean Air Action Plan
CalEMA	California Emergency Management Agency
CalOES	California Office of Emergency Services
Caltrans	California Department of Transportation
Cal-MOP	California-centric Manual of Practice (see MOP)
CAS	Climate Adaptation Strategy
CAT	Climate Action Team
CC	Climate change
CCC	California Coastal Commission
CCTAG	Climate Change Technical Advisory Group (DWR)
CEC	California Energy Commission
CNRA	California Natural Resources Agency
CO2	Carbon dioxide
CoSMoS	Coastal Storm Modeling System (USGS)
CPUC	California Public Utilities Commission
CSIWG	Climate-Safe Infrastructure Working Group
DGS	Department of General Services (California)
DMDU	Decision Making Under Deep Uncertainty
DMUU	Decision Making Under Uncertainty
DOF	Department of Finance (California)
DWR	Department of Water Resources (California)
EIFD	Enhanced Infrastructure Finance District
EO	Executive Order
ESCO	Energy Service Company
ESG	Environmental, Social and Governance factors important o investors
FEMA	Federal Emergency Management Agency
GAO	General Accounting Office
GSA	General Service Administration
GDP	Gross Domestic Product
G/NBI	Green/Nature-based infrastructure
GRC	General Rate Case

HSRA	High Speed Rail Authority
HVAC	Heating, Ventilation and Air Conditioning
IOU	Investor-owned utility
IPCC	Intergovernmental Panel on Climate Change
LAO	Legislative Analyst's Office (California)
LID	Low-impact development
M&E	Monitoring and Evaluation
MOP	Manual of Practice (ASCE)
MWDBEs	Minority-owned, women-owned, and disadvantaged business entities
NCA4	Fourth National Climate Assessment
NCSE	National Council for Science and the Environment
NFIP	National Flood Insurance Program
NSRDB	National Solar Radiation Database
OPC	Ocean Protection Council (California)
OPR	Office of Planning and Research (California)
PA	Public Assistance (FEMA)
PACLIM	Pacific Climate conference
PNPs	Private nonprofit
RAMP	Risk Assessment Mitigation Phase (related to natural gas risk mitigation)
RCP	Representative Concentration Pathway
RDM	Robust Decision-Making
ROI	Return on Investment
SDG&E	San Diego Gas & Electric Company
SPFC	State Plan of Flood Control (DWR, California)
TMY	Typical Meteorological Year
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey

Paying It Forward:
Executive Summary

Introduction

During the fall and winter of 2017-18, California residents lived through a devastating series of disasters. After years of drought, devastating wildfires ravaged hundreds of homes from Northern to Southern California; deluge rain events after the fires led to catastrophic floods, mudslides and debris flows that washed away bare soil, houses and cars and closed stretches of Highway 101, crippling transportation routes. Over this time, the state received five Major Disaster Declarations, three Emergency Declarations and 23 Fire Management Assistance Declarations – a combination never experienced before. Sixty-five Californians lost their lives and thousands of homes, numerous roads, communication towers, phone and electricity distribution lines, fleet vehicles, parks and so on either were destroyed or sustained damages that are still being tallied and remedied. Against a backdrop of infrastructure that some describe as “crumbling,” these extreme events offer a first-row seat to the fragility of our infrastructure systems and give us a glimpse of the future in a changing climate. For people to be safe, our communities must be prepared. Our infrastructure must be resilient and sustainable to withstand these growing threats, particularly from worsening extreme events. Yet California’s infrastructure is not.

The state’s infrastructure is aging and deteriorating and – despite recent increases in investment – still requires better upkeep and modernization. Lack of emergency action plans for high-hazard infrastructure, a long backlog of deferred maintenance projects and billion-dollar gaps in spending on infrastructure upkeep plague the state of infrastructure in the fifth largest economy in the world. These truths provide a stark backdrop to the rapidly growing need of investing in new infrastructure and preparing for the accelerating negative impacts of climate change.

Through the Climate-Safe Infrastructure Bill, AB 2800 (Quirk), and with State leadership and foresight in climate change adaptation planning, California is seeking to understand how it can better prepare its existing and new infrastructure for climate conditions that will be increasingly different from the current ones. The State is seeking to ensure a climate-safe future.

California is already experiencing the impacts of climate change as well as more extreme events that exceed the standards (and the environmental conditions underlying them) to which the state’s infrastructure was built. This – together with existing infrastructure modernization needs – places urgency on State policy-makers to determine how to spend infrastructure dollars wisely. Through various propositions, the State has nearly $62 billion dollars available in voter-approved bond sales to invest in built and nature-based infrastructure. Billions of dollars in recovery funding after recent disasters, a good portion of which can be used toward rebuilding infrastructure, provide additional resources for a new generation of infrastructure.

Our infrastructure must be resilient and sustainable to withstand these growing threats, particularly from worsening extreme events.

While these billions of dollars may seem like a windfall, they are only a down-payment on the statewide infrastructure investment needed. These available funds could easily be squandered on maladaptive projects if climate-safe infrastructure policies and guidelines are not put in place today. The State thus has a crucial opportunity to be a national and even international leader on modernizing and building critical infrastructure that is fit not just for today, but for a climate-change impacted tomorrow.

Mandate and Goals of this Report

AB 2800 mandated that a panel of scientists, registered engineers and architects be convened to help the State of California understand how it can best incorporate forward-looking climate information into the state's infrastructure design, planning and implementation (Chapter 1, Box 1.2). This Executive Summary highlights the Climate-Safe Infrastructure Working Group's (CSIWG) major findings and recommendations.

This report summarizes the CSIWG's deliberations in response to the mandate of AB 2800 and offers recommendations to the California State Legislature and the Strategic Growth Council. Together, these recommendations chart a path toward helping California invest in climate-safe infrastructure. The report addresses the infrastructure that was built decades, even a century, ago – from historical bridges, to major dams, highways and buildings – and the infrastructure that will be built in the coming years and is meant to last for many decades to come (Figure ES.1).

While this effort initially sought to solve the as-yet-unresolved challenge of incorporating forward-looking climate information into infrastructure design (something engineers and architects have struggled with for years), the Working Group discovered that the science challenge in moving toward climate-safe infrastructure is significant, but not intractable. Equally, if not more, difficult are those challenges that require profound shifts in values, thinking, priority setting and policy commitments.

This report responds to the legislative intent for AB 2800, which is to make California communities safer and to save lives. While saving lives is more likely if decisions are informed by the best available knowledge, science alone will not guarantee our safety. Saving lives is a matter of what and who we value as a society. It requires reckoning with what we believe deserves our dedicated investment and is ultimately dependent upon the decisions we make and actions we take. Investing in a climate-safe future for all is a way of creating a positive legacy. It is *paying it forward*.

The recommendations in this report aim to incentivize and inspire legislators, public agency leaders, engineers, architects, scientists, consultants and contractors, planners and residents to commit to creating a climate-safe future for California.

Box 1: The Mandate of AB 2800

As mandated in the AB 2800 legislation, the Working Group has a very specific charge, at a minimum, to consider and investigate:

1. The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design;
2. The critical information that engineers [and architects] responsible for infrastructure design and construction need to address climate change impacts; and
3. How to select an appropriate engineering design for a range of future climate scenarios as related to infrastructure planning and investment.

It further mandates that, in a report to the State Legislature and the Strategic Growth Council, the Working Group shall make recommendations to the Legislature that address:

1. Integrating scientific knowledge of projected climate change impacts into state infrastructure design;
2. Addressing critical information gaps identified by the working group; and
3. A platform or process to facilitate communication between climate scientists and infrastructure engineers [and architects].

Figure ES.1: Developing climate-safe infrastructure requires the establishment of a strong bridge between science and the engineering community, as well as supportive public policy aligned with the goals of resiliency. (Photo: Bixby Bridge near Big Sur, CA; Russell Mondy, flickr, licensed under Creative Commons license 2.0)

Box 2: What Do We Mean by "Climate-Safe" Infrastructure?

We define **climate-safe infrastructure** as infrastructure that is sustainable, adaptive and that meets design criteria that aim for resilience in the face of shocks and stresses caused by the current and future climate. Climate-safe infrastructure should be robust across a range of plausible climate and related socio-economic futures, as determined by the best available knowledge at the time the criteria (standards, codes and guidelines) are set. To remain "climate-safe," these criteria must be monitored and updated over time to account for changing conditions and the performance of resilience measures taken. Climate-safe infrastructure also reduces heat-trapping emissions to the maximum extent possible to not add to the climate change problem. (Mitigating climate change in this way also complies with California emissions reduction targets.) Furthermore, climate-safe infrastructure addresses socio-economic inequities so that all groups in society increasingly benefit from safe, reliable and sustainable infrastructure.

In short, "climate safety" is not a world free from change and disruption, but a world in which California has committed to seeking the greatest possible safety for all of its residents through the best available knowledge, the best technology and engineering design, a strong workforce, equitably distributed resources and sustained political will.

The Challenge

California's Fourth Climate Change Assessment (Fourth Assessment) has confirmed the consensus of the climate change science community:

- Past climate is no longer a reliable guide to future conditions;
- Science has established beyond doubt that the global climate and California's are changing rapidly;
- The dominant contribution to the observed climate change during recent decades have been greenhouse gas emissions from human activities; and
- Many trends in observed climate change are accelerating and impacts over the next several decades are unavoidable, even if human-caused emissions came to a halt today.

A growing body of studies, including those within the Fourth Assessment, offer detailed projections for, and assessments of, the vulnerability of various infrastructure sectors. Some of these are presented in the full report (Chapter 2). With this, infrastructure decisions that are made today have the benefit of considerably greater data and understanding of climate processes than decisions that were made in previous decades.

Specific localized projections of climate changes and extremes are of greatest interest to infrastructure planners, yet these will always remain uncertain. Despite the apparent perception to the contrary, the spatial and temporal variability experienced in the past is no more predictable than future spatial and temporal variability. Given the pace, intensity and makeup of California's changing climate, infrastructure planners now must contend with the uncertainties and potentially new patterns of variability that this rapid change entails.

The science challenge in moving toward climate-safe infrastructure is significant, but not intractable. Equally difficult are those challenges that require profound shifts in values, thinking, priority setting and policy commitments.

Fortunately, engineers and architects have considerable experience with building infrastructure to withstand variable conditions. It is clear now, however, that in addition to this variability, engineers and architects must also account for shifting trends in averages and for extremes around those changing averages.

Through its deliberations, the CSIWG describes an adaptive process by which infrastructure planning can proceed with the information that is currently available. It also identifies climate information gaps and needs that – if filled – would be useful moving forward. The action-oriented process entails:

- Using the information that is currently available, while allowing for more refined information to be incorporated in the future;
- Using adaptive designs for planning infrastructure; and
- Developing sustained funding source to advance climate and social science as well as adaptive engineering research to fill identified gaps.

The added threats from climate change will impact state infrastructure that is already in need of improved maintenance and modernization (Chapter 3). As recent extreme events and disasters or near-disasters illustrate – some of California's infrastructure, across all sectors, is already at risk and vulnerable to the impacts of weather and climate extremes. As we rebuild our infrastructure, we can simultaneously seize the opportunity to make our systems more sustainable in a changing climate.

In light of existing infrastructure challenges and the climate outlook, engineers and architects will need a range of new approaches to ensure that infrastructure safety and functionality remain attainable goals. To do so, infrastructure planners and designers must confront old paradigms of stationarity (i.e., assuming statistics of climate averages and extremes remain unchanged over time), and view infrastructure not as individual structures but as whole systems embedded in a more complex and interconnected world (Figure ES.2). They must also deal with the greater constraints on, and new opportunities for, infrastructure systems. Finally, they must also address the present and coming workforce crisis.

California faces a pivotal moment at which the state's political leaders – at all levels – need to become serious about sustained leadership on infrastructure and commit to making a sustained, "climate-safe" investment in the very foundation of its economy and its communities' safety and well-being as if California's future depended on it. It does.

Figure ES.2: The interconnected components of California's water infrastructure illustrate why infrastructure should not be understood as singular physical assets but instead as systems that provide multiple functions to many different users. (Photo: Chrisman Pumping Plant; DWR, used with permission)

California faces a pivotal moment at which the state's political leaders – at all levels – need to commit to making a sustained, "climate-safe" investment in the very foundation of its economy and its communities' safety and well-being as if California's future depended on it. It does.

A Vision of Climate-Safe Infrastructure for All: The Climate-Safe Path

Climate Safety Through Mitigation and Adaptation: The Climate-Safe Path

Through high-level policies, executive orders and laws, California has committed to reduce its greenhouse gas emissions by 40% below 1990 levels by 2030 and by 80% below 1990 levels by mid-century. This level of commitment puts the state on a responsible path toward helping the global community achieve the targets of the Paris Accord, namely to limit global average warming to 2 °C (3.6 °F) or less (1.5 °C or 2.7 °F) by the end of this century.

As the nearly two decades of international climate negotiations make clear, and as California's own path to increasingly stricter emissions reduction targets illustrates, stringent mitigation targets are not just a rational choice in light of potentially severe risks; they are a political choice. However difficult it may be to achieve, aiming for 2 °C or less is the choice that focuses the compass needle toward greater safety from some of the harmful climate impacts that would occur if emissions were allowed to further destabilize the Earth's climate system. However, the great difficulty involved in compelling the international community to make this commitment suggests that California must be prepared to contend with much greater climate impacts.

Thus, there is a parallel political choice to be made in setting adaptation targets. Over the past few years, California's political leaders and state lawmakers have laid some policy foundations for adaptation and now have an opportunity to strengthen adaptation as a political priority. They can send the same directional signal as they did with mitigation, namely, that the safety of communities and the infrastructure on which they and the state's economy vitally depend is of utmost importance. That choice, consistent with guidance from the Office of Planning and Research, is to ensure that long-lived infrastructure is planned, and may eventually need to be built, operated and maintained, to withstand future impacts from climate change associated with the "business-as-usual" or high-emissions pathway (currently the RCP 8.5 emissions scenario) (Figure ES.3).

Should it become apparent over time that – globally – society has safely averted a high-emissions future, the adaptive approach promoted in this report should allow for an "off ramp" to adapt to the impacts associated with a lower-emissions pathway. However, determining the point in time when such a transition to a lower-safety threshold is indicated, is both scientifically and politically complex and requires dedicated research and public debate.

By reducing the causes of climate change through mitigation and simultaneously implementing preparedness and adaptation measures, California would pursue the safest of possible climate action pathways any state can take (Figure ES.4). We call this comprehensive strategy "the Climate-Safe Path for All" (Chapter 4).

Figure ES.3: Stringent emissions reduction targets are not just a rational choice in light of potentially severe risks; they are a political choice. California now has the opportunity to take a similarly strong political stance on adaptation. (Photo: Kevin Dooley, flickr, licenses under Creative Commons License 2.0).

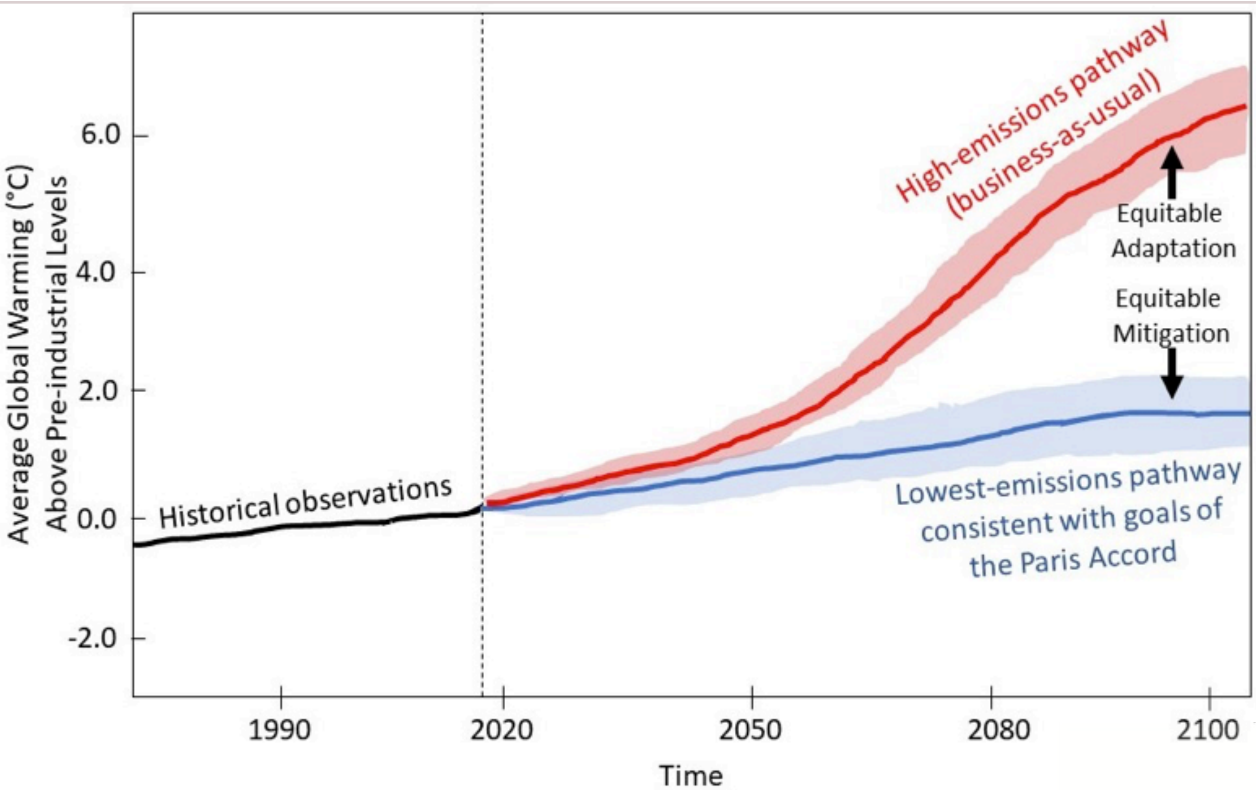


Figure ES.4: The Climate-Safe Path describes the simultaneous pursuit of stringent greenhouse gas mitigation that aims to meet the goals of the Paris Accord while charting an adaptive pathway to protect Californians against the impacts of a high-emissions scenario, both implemented with a central focus on social equity.

Realizing the Climate-Safe Path One Step at a Time: Adaptation Pathways

Preparing for the climate change impacts associated with the high-emissions pathway is an ambitious undertaking that has different implications for different types of infrastructure, for existing and newly built infrastructure, and for short- and long-term climate impacts. It does not imply that every infrastructure investment made today must build immediately to the protective level that would be required when the impacts associated with the high-emissions pathway are beginning to unfold. Realizing the Climate-Safe Path does not mean a once-and-for-all step change, but a change in many steps. This is similar to how emission reductions are achieved: not turning off all emissions at once, but successively and steadily moving toward the ultimate goal. Realizing the Climate-Safe Path means following an adaptation pathway that keeps an eye on a long-term goal but is realized through a variety of strategies in multiple stages over the course of decades (Figure ES.5).

Political leaders have laid some policy foundations for adaptation and now have an opportunity to strengthen adaptation as a political priority. They can send a directional signal that the safety of communities and the infrastructure on which they, and the state's economy vitally depend, is of utmost importance.

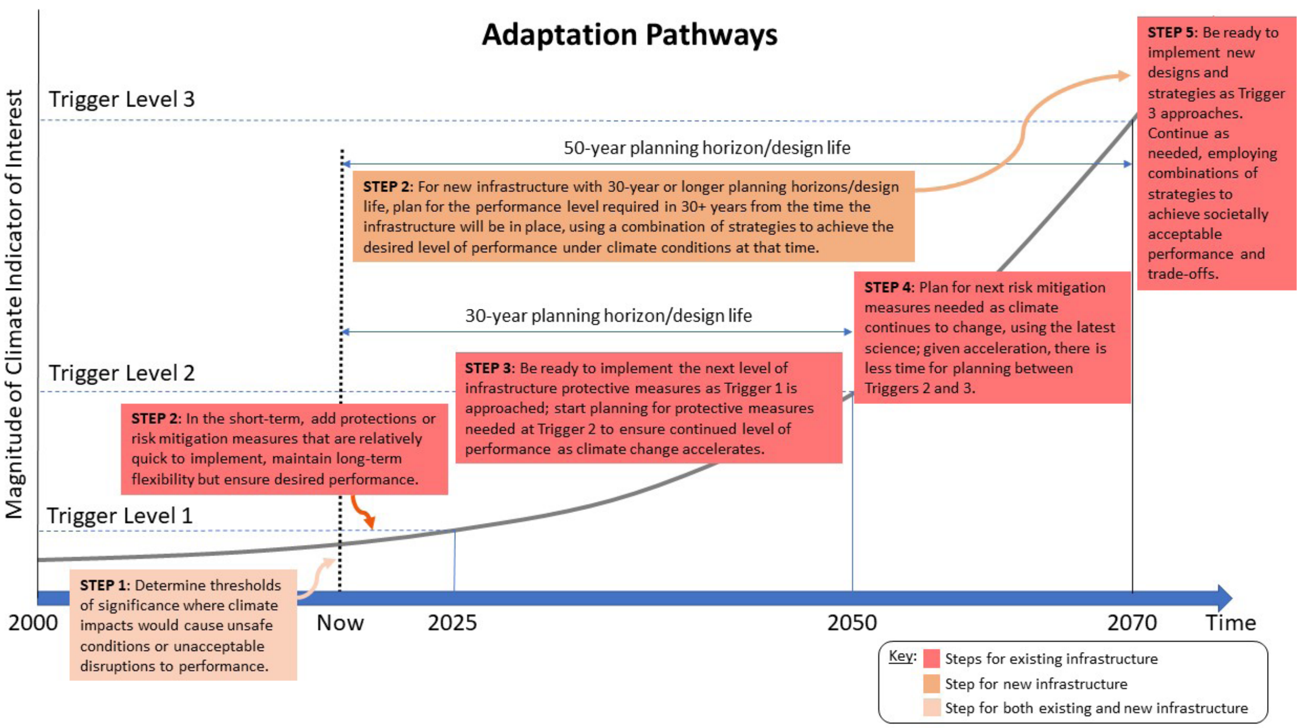


Figure ES.5 A flexible adaptation pathway begins with an agreement among relevant stakeholders as to the desired performance/ service level of infrastructure. As climate change continues, thresholds will be crossed where the performance of the existing infrastructure as it is currently built no longer fulfills societal expectations and new adaptation measures must be implemented, taking into account the best available climate science, societal trends, desired performance levels and the resources society is willing to make available for adaptive infrastructure investment. (Source: Adapted from Moser 2016, used with permission)

Realizing the Climate-Safe Path: The Tactical Level

Five different, but complementary strategies can be combined to obtain desired risk aversion levels and ensure infrastructure functionality over the changing conditions that can be expected over its lifetime. They vary in how they are being applied to existing vs. new infrastructure:

- **Robustness** – building to the protective level needed to ensure acceptable functionality and reliability over the design life of the infrastructure;
- **Resilience** – developing and practicing plans for the possibility of a situation when an extreme event exceeds the protective level and infrastructure fails, so as to improve and speed up the response and adaptive recovery;
- **Adaptability** – developing plans and integrating features into the design now that would allow structures to be adapted to a higher level of protection if necessary over time;
- **Redundancy** – developing plans now and implementing them over time to help infrastructure maintain functionality when it or parts of it fail; and
- **Avoidance (new) or Retreat/Decommissioning and Removal (existing)** – avoiding or removing infrastructure development from high-risk areas when the physical defense of infrastructure is no longer viable and the functionality of the infrastructure can no longer be assured.

A Climate-Safe Path for All

The vision of the Climate-Safe Path outlined here is not a path just for the privileged. Instead, it is envisioned to be a path for all. Following the Climate-Safe Path must include an integral commitment to remedying past injustice in infrastructure investment so as to ensure the safety, health, well-being and opportunities of those who have borne insecurity, public health burdens and lack of economic opportunity the most and the longest.

The state's most outdated and dilapidated infrastructure is not evenly distributed, neither geographically, nor socio-economically. It is not affecting Californians equally. Due to decades of underinvestment and redlining (i.e., the systematic denial of various services to residents of specific, often racially associated, neighborhoods or communities), low-income communities and communities of color often confront the largest potholes, the most outdated school buildings, the leakiest pipes and the worst connectivity to modern transportation, communication and other community infrastructure. The added risks arising from climate change are not going to be equally distributed either. These same communities often have the fewest resources to deal with the risks from climate change. As such, these communities are those where the State has the greatest opportunity to make a difference.

The Climate-Safe Path must include an integral commitment to remedying past injustice in infrastructure investment so as to ensure the safety, health, well-being and opportunities of those who have borne insecurity, public health burdens, and lack of economic opportunity the most and the longest.

Inadequate engagement during the infrastructure planning and decision-making processes, systemic ways of putting low-income communities at a disadvantage through decision criteria and cost-benefit requirements, long-standing institutionalized racism and narrow thinking about the role of infrastructure across multiple sectors and within a region or community are at the root of this inequitable investment in infrastructure.

The following principles should guide equitable infrastructure planning, policy and investment:

1. Include residents in decision-making;
2. Serve underinvested communities without pushing out existing residents;
3. Improve the environmental health and quality of life for residents of disinvested communities;
4. Be equitably owned, financed and funded;
5. Create good jobs and business opportunities for local residents; and
6. Invest in workforce training.

Holding paramount the safety, health and welfare of the public is central to the code of ethics of the engineering profession. The Working Group's strong conviction is that social equity in infrastructure development should not be a last-minute adjustment of an already-decided plan, nor merely one among many criteria to guide infrastructure decisions. If the protection of lives is the goal, social equity must be considered in the beginning, middle and end of infrastructure planning and decision-making. It is the outcome that is planned for from the start, and that means a different process must prevail. Procedurally, this means, infrastructure must be planned *with* communities, not *for* them.

Ultimately, the Climate-Safe Path for All results in climate-safe infrastructure that is designed to be resilient to a changing climate and extreme events, both now and across a wide range of uncertain future conditions.

Recommendation 1

The State Legislature should establish as official State policy "The Climate-Safe Path for All", which is a flexible adaptation pathway realized through a variety of strategies, in multiple stages over the course of decades. The Climate-Safe Path for All accounts for the full life-cycle costs of infrastructure and uses a multi-sectoral, systems approach. It prioritizes infrastructure investments based upon the greatest risks and investment gaps, as well as where investment can most reduce inequality and increase opportunity. For highly vulnerable, long-lived infrastructure, State agencies should consider climate change impacts associated with a high-emissions scenario while continuing to implement all applicable State laws related to stringent greenhouse gas emissions reductions.

From Vision to Action: A Framework for Action

In order for this vision of climate-safe infrastructure for all to be realized, integrating the best available forward-looking science will not ensure that climate-safe infrastructure is actually built. Providing actionable data and analytics constitutes one part of an action-oriented framework that will result in the ultimate intent of AB 2800: that infrastructure investments get made and that climate-safe infrastructure is built. We place the provision of forward-looking science into a comprehensive framework for action (Figure ES.6 and ES.7).

- **Data and Analytics –** Infrastructure planning and design requires many types of data, model simulations and forward-looking science – appropriately used and interpreted (for detailed discussion see Chapter 5).
- **Project Pipeline –** Infrastructure projects are often years to even decades in the making. Where and what to prioritize, to what standards of performance climate-safe infrastructure should be built, and planning and deciding about them in a transparent and inclusive fashion requires effective project management and coordination. A well-developed and prioritized project pipeline is a necessary pre-condition to attract infrastructure finance and involves successful stakeholder engagement, efficient progress through the permitting process, multi-sectoral alignment and other processes (Chapter 6).
- **Governance Structures –** Many types of infrastructure involve engagement of multiple levels and different kinds of jurisdictions and can include multiple state agencies or sectors for funding and financing, review and permitting, oversight, operation and maintenance. Appropriate and effective governance structures and processes are required for complex partnerships and financing but may be lacking or need clarification and streamlining for efficient functioning. Governance also involves the rules, codes, standards and guidelines that govern where and how infrastructure is built (Chapter 7).
- **Financing Tools –** Federal and state funding sources alone are widely seen as insufficient to catch up on past inadequate infrastructure investment, resulting in a call for private sector involvement and innovative partnerships and financial tools to generate the necessary funds (Chapter 8).
- **Implementation Aids –** Engineers, architects, planners, procurement officers and operations personnel must have the necessary professional training and know-how to appropriately use available scientific data and tools. They must also be able to understand different planning or financing options and be capable of navigating complex governance challenges. Relevant staff require professional development opportunities and accountability mechanisms. They also must embrace a cyclical, iterative approach in their work, informed by ongoing monitoring and evaluation of the performance of infrastructure. This will allow them to periodically reassess climate risks and adjust infrastructure planning and design approaches over time (Chapter 9).

Figure ES.6: To ensure that climate-safe infrastructure actually gets built on the ground, California needs a support system that addresses all aspects of infrastructure planning, design and construction. (Photo: Construction workers; Elvert Barnes, flickr, licensed under Creative Commons license 2.0)

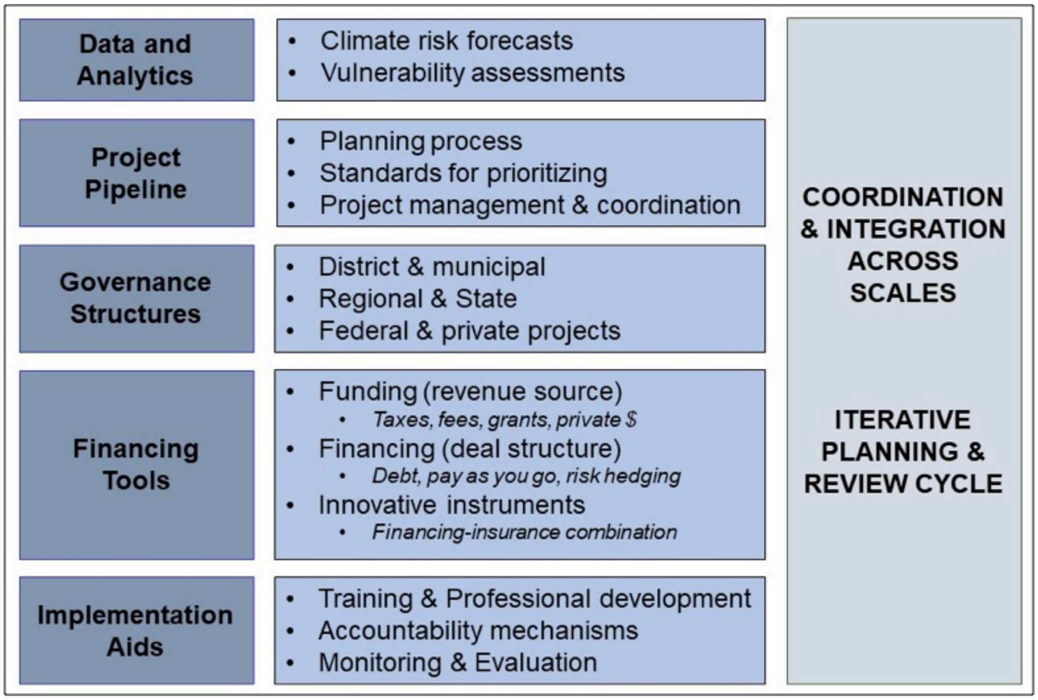


Figure ES.7: A strategic, integrated framework for action is needed to ensure that the vision of climate-safe infrastructure for all gets realized. It includes data and analytics which inform infrastructure planning and design to generate a prioritized list of projects that can be implemented with the help of appropriate governance structures, financing tools and implementation aids. (Source: Adapted from Cleveland 2018, used with permission)

Realizing the Climate-Safe Path for All

Overcoming Barriers to Building Climate-Safe Infrastructure

AB 2800 asked to identify the informational, institutional and other barriers that stand in the way of integrating forward-looking climate science into all aspects of infrastructure planning and decision-making. Through the deliberations of the Working Group, a great number of barriers were uncovered, which fall into the following categories:

- **Informational and knowledge barriers;**
- **Capacity/skills barriers;**
- **Attitudinal barriers;**
- **Political barriers;**
- **Financial barriers;**
- **Legal/regulatory barriers;**
- **Institutional barriers; and**
- **Other barriers.**

We synthesize and discuss these barriers by type in the full report (for a summary, see Chapter 10), but caution against seeing any one of these barriers in an isolated manner. Indeed, barriers of all types are encountered across the entire life cycle of infrastructure design and operation or – differently put – across every stage of the adaptation process. As barriers in the early stages of adaptation are successfully overcome, other (not yet recognized) barriers may emerge as adaptation progresses to implementation, while yet others may fade.

The remaining recommendations – each accompanied in the full report by various immediate steps to operationalize them (for a synthesis of these next steps, see Chapter 10) – either directly address or aim to help overcome these barriers.

"It Takes a System" to Realize Climate-Safe Infrastructure for All

Following the framework for action, the remaining recommendations discuss how best to bolster the state's collection of existing and needed data and analytics (Recommendations 2 and 3), develop a prioritized project pipeline (Recommendation 4 and 5), enhance existing and develop needed governance structures (Recommendation 6), create and make more accessible needed financing tools (Recommendation 7) and foster implementation through a variety of means necessary for building climate-safe infrastructure (Recommendations 8, 9 and 10).

Most recommendations point to the need for adequate funding to implement the recommendation. Agency managers have a variety of ways to meet those needs, but the Working Group feels strongly that if adaptation is a State priority, it should be adequately supported. One of the most restrictive and most frequently mentioned barriers throughout the CSIWG's deliberations is the lack of funding. Thus, the Working Group feels strongly that making climate-safe infrastructure a policy priority should be reinforced by making it a funding priority.

Recommendation 2

In the past, the State's financial support for its various climate science efforts and decision-support tools has been uneven and insufficient. At a minimum, the State Legislature should provide a permanent source of funding for the State's mandated Climate Change Assessment process, the State's ongoing Climate Change Research Program, and decision-support tools and other assistance that disseminate their findings, so as to meet the needs for improved understanding and forward-looking science information.

Building on the pioneering work of several state agencies, the state must expand its research portfolio to meet infrastructure planners' needs, and to expand state agencies' capacities to engage the climate change science community, broadly writ (Figure ES.8).

Figure ES.8: Coincident with the release of this report, the State also released its Fourth Climate Change Assessment. Through 44 technical reports and 13 summary reports on climate change, the Fourth Assessment translates global models into scaled-down, regionally relevant reports that fill information gaps and support decisions at the local, regional and state levels. Despite legislation mandating it, funding to conduct the next assessment is not assured. The Working Group believes sustained and adequate funding is an important first step to ensuring a strong foundation in research to achieve a climate-safe future.

Figure ES.9: Clockwise from left; Marty Ralph, Scripps Institute of Oceanography, Michael Anderson, State Climatologist with DWR, Jay Jasperse, Sonoma County Water Agency, and Jeanine Jones, Interstate Resources Manager at DWR, in conversation during a break at an October 2016 workshop on drought vulnerability in southern California. (Photo: Kelly M. Grow, DWR, used with permission)

Recommendation 3

Because of the diversity of State agencies, types of infrastructure and their vulnerabilities, and the specific needs for climate science, there cannot be a one-size-fits-all recipe for State agencies to engage with the climate change science community. That said, the State budget should provide full funding to State infrastructure agencies so they can dedicate time and support to their engineers and architects to substantively and collaboratively interact with climate scientists and other relevant experts in the creation of useful advice, guidance and tools on a regular and ongoing basis, in a way and at a level appropriate to their needs.

Whether it is through a national scale connection to the Sustained Climate Assessment, or through augmentation of the State's Adaptation Clearinghouse, including its Technical Advisory Group that falls under the umbrella of the Integrated Climate Adaptation and Resiliency Program, or through better use of gatherings such as the California Adaptation Forum (CAF), formalized processes should be developed in which state engineers and architects have deliberate and sustained interaction with physical and social climate change scientists from diverse research institutions and professional organizations (Figure ES.9).

Recommendation 4

During the all-important pre-development phase, projects are conceptualized, planned and designed. The State budget should improve this process by building staff capacity and greatly increasing project funding to better account for a changing and uncertain climate, by addressing social inequity, and by assessing and accounting for the true costs and benefits of integrated projects across their full life-cycle.

Critical elements of successful pre-development planning and a range of tools to assist it include:

- Effective and inclusive stakeholder engagement from the start;
- Developing a climate-screening process to help identify the level of analysis needed and prioritize projects to include in the "project pipeline;"
- Calculating the cost effectiveness of climate-safe infrastructure;
- Employing a probabilistic risk management and robust decision-making approach, in combination with other techniques, appropriate for adaptation decision-making and adaptive design in the face of uncertainty;
- Effective communication; and
- Training on adaptation principles and strategies to ensure appropriate use of these approaches.

Recommendation 5

Difficult decisions will have to be made and the impacts of potential policies or decisions on different stakeholder groups are complex and challenging to assess. It is critical therefore to engage all affected stakeholders in a meaningful way, from early on and throughout any decision-making process, using the seven principles of equitable planning and decision-making.[1] The Strategic Growth Council is well positioned to take a range of steps to encourage, improve and provide guidance on effective stakeholder engagement in the context of infrastructure development.

Stakeholder engagement is essential at every step of the process of crafting climate-safe infrastructure, from initial stages of discussion, to implementation, to maintenance and decommissioning. Decision-making at any stage should always consider whether decisions are being made *with* communities, rather than *for* communities.

Decision-making at any stage should always consider whether decisions are being made ***with*** *communities, rather than* ***for*** *communities.*

Figure ES.10: At "The Longest Table" event in Howard County, Maryland, 320 residents sat a a 320-foot long table and shared their respective vision for their community. This type of socially inclusive engagement ensures equitable respresentation; everyone had a seat at "the table." (Photo: Howard County (Md.) Library System, flickr, licensed under Creative Commons license 2.0)

[1] See Chapter 6, p. 2 for a list of the principles.

Recommendation 6

Consistent with Executive Order B-30-15 and AB 1482, State agencies should update all relevant (i.e., climate-sensitive) infrastructure standards and guidelines that they can directly affect. Alternatively, or in addition, they should develop new state-specific guidelines where there are gaps to address climate resiliency by incorporating forward-looking climate information in those standards and codes. Where State agencies rely on standards developed by standard-setting organizations, state engineers and architects should work through the relevant professional organizations to advance development of climate-cognizant standards. Until new standards and codes are in place, State agencies should develop guidelines that go above and beyond minimum standards and codes to meet the goals of the Climate-Safe Path for All. Where agencies don't have resources to fulfill this workload, they should be fully funded in the State budget.

State agencies differ in their technical capacity to make needed updates to existing standards and codes. Some can do so (and/or are developing new ones where needed) while others must await standard-setting organizations to provide those updated standards, which the State would then adopt. While policy guidance should be unambiguous, the manner in which it is implemented at the level of standards and codes would need to be flexible to reflect this range of in-house capacities.

Among the most important barriers are questions around liability, which constitute a large and complicated enough challenge that a separate panel should be convened to address all the nuances and complexities and to provide guidance and recommendations to infrastructure agencies.

New types of standards and procedural mechanisms (such as performance standards, standards of professional practice, standards of care, various procurement approaches and manuals of practice) provide opportunities for increased climate resiliency.

Recommendation 7

Because improving resilience is not a zero-sum activity, adding resilience in one area cannot be balanced by relaxing resilience requirements somewhere else. Adding requirements for resilience will come at a cost, so unfunded mandates are not feasible. The true costs over the full life-cycle of infrastructure projects should be assessed broadly, and the State should make efforts to help policy-makers and the public better understand the necessity of bearing these costs. Educational, promotional and other outreach should be conducted to generate support for the expenditures.

A follow-on activity to the work of the Working Group should explore the complex questions that arise about how to take climate change into account from a fiscal perspective. Moreover, the state needs comprehensive or reliable estimates of what climate change impacts and adaptation would cost at the state or local level. In addition, the Strategic Growth Council and other state agencies should launch serious engagement efforts to help Californians more fully understand why investment in climate-safe infrastructure is necessary.

Figure ES.11: Along an urbanized coast like California's, there are many complex jurisdictional and governance challenges. which also come with financial trade-offs. The recommendations in this report are aimed at helping the State make equitable decisions about infrastructure moving forward. (Photo: San Francisco skyline and Port of Oakland, Tony Webster, flickr, licensed under Creative Commons license 2.0)

Recommendation 8

The Strategic Growth Council should coordinate with the Government Operations Agency, the Labor and Workforce Development Agency, and other relevant agencies to develop a work plan on how to address the training and professional development gaps of its infrastructure-related workforce as identified in this report, and begin to implement that work plan as soon as feasible. Because the Strategic Growth Council does not currently have the staff capacity and funding to implement this task, it would require adequate funding to do so.

California needs to have the skilled workforce to get climate-safe infrastructure appropriately designed, built, operated and maintained. In addition to proper training in all the "hard" and professional skills needed by today's engineers and architects, this workforce development must address climate skepticism; lack of understanding of climate science; lack of familiarity with sophisticated risk and uncertainty assessment and decision-making approaches; sophisticated economic analysis methodologies and related tools and platforms; lack of knowledge of and disconnect from the adaptation literature and field; lack of comfort with performance standards; lack of familiarity with adaptive design approaches and techniques; resistance to integrative and systems thinking that crosses silos; lack of skill in effective stakeholder engagement and communication; and lack of cultural competency in working with diverse stakeholders on infrastructure projects.

Figure ES.12: The "climate-ready" workforce of the future must be trained in both the traditional "hard" engineering skills and in the professional skills needed to navigate complex science, governance, finance and stakeholder engagement issues. (Photo: Folsom Lake water purification; USACE)

California needs to have the skilled workforce to get climate-safe infrastructure appropriately designed, built, operated and maintained.

Recommendation 9

The State should establish a Standing CSIWG to devise and implement a process for coordinating and prioritizing Climate-Safe Path related resilience policies and actions at the highest level. This panel would provide a needed forum for agencies to coordinate their policies, take advantage of synergies, address potential conflicts and learn from one another. As AB 2800 is slated to sunset in 2020, the work of a standing CSIWG would require an extension of AB 2800 and adequate financial support to conduct its business.

The CSIWG proposes the development of a standing CSIWG, which would have the following roles:

- Coordination;
- Central point of contact for infrastructure across the state;
- Forum to advance climate-safe infrastructure questions; and
- Leadership in incorporating forward-looking information in engineering standards.

Some of the immediate tasks this standing CSIWG could address include prioritization of identified research needs, exploration of liability issues, assessment of the pros and cons of different procurement approaches for different types of climate-safe infrastructure and development of guidance on effective stakeholder engagement for infrastructure agencies.

Recommendation 10

The State budget should provide full funding to State agencies to make deliberate efforts in reducing or eliminating the barriers that hinder or slow down adoption of State-level climate-safe infrastructure policy into practice. Key focus areas include the translation of Climate-Safe Path policy into practice manuals and contracting language, providing incentives to account for climate change in infrastructure projects, identifying metrics of success for monitoring and evaluation and developing a best-practices compendium.

Ultimately, for all of these recommendations to be used by on-the-ground contractors (those who implement the plans developed by state architects and engineers), they must be translated and made accessible to all those working on infrastructure. This includes creating guidance on how to translate State-level climate-safe policy into contracting language, building capacity to assess and manage bids, developing model contract language, incorporating inclusive procurement procedures and other enabling steps.

In Closing

Through all of its climate-focused activities, the State of California has been laying the foundation for the work of the CSIWG. AB 2800 allowed the Working Group to propose new paths for infrastructure planning in the state (Figure ES.10). In using the systemic, action-oriented approach offered here to move from vision to implementation, and in following the recommendations that provide the bricks for the Climate-Safe Path for All, California has the opportunity to *Pay it Forward*. It must make these investments today to ensure the safety, well-being and prosperity of all Californians tomorrow.

Figure ES.13: California has the opportunity to "pay it forward." It must make sustained investments in climate-safe infrastructure investments today to ensure the safety, well-being and prosperity of all Californians tomorrow. (Photo: Sacramento-San Joaquin Delta; Paul Hames, DWR, used with permission)

1 Introduction

During the fall and winter of 2017-18, California residents lived through a devastating series of disasters. After years of drought, devastating wildfires ravaged thousands of homes from Northern to Southern California; deluge rain events after the fires led to catastrophic floods, mudslides and debris flows that washed away bare soil, housesand cars and closed stretches of Highway 101, crippling transportation routes. Over this time, the state received five Major Disaster Declarations, three Emergency Declarations and 23 Fire Management Assistance Declarations – a combination never experienced before.[1] Sixty-five Californians lost their lives and thousands of homes, numerous roads, communication towers, phone and electricity distribution lines, fleet vehicles and parks either were destroyed or sustained damages that are still being tallied and remedied. Against a backdrop of aging infrastructure that some describe as “crumbling” [1,2] these extreme events offer a first-row seat to the fragility of our infrastructure systems and they give us a glimpse of the future in a changing climate. For people to be safe, our communities must be prepared. Our infrastructure must be resilient and sustainable to withstand these growing threats, particularly worsening extreme events.

Our infrastructure must be resilient and sustainable to withstand the growing threats from climate change, particularly worsening extreme events.

Yet, as noted in the 2017 report by the Union of Concerned Scientists – *Built to Last: Challenges and Opportunities for Climate-Smart Infrastructure in California*[3] – California’s infrastructure is not. Our infrastructure is aging and deteriorating and, despite recently increasing investment, still requires better upkeep and modernization. Lack of emergency action plans for high-hazard infrastructure, a long backlog of deferred maintenance projects and billion-dollar gaps in spending on infrastructure upkeep plague the state of infrastructure in the fifth largest economy in the world. These truths provide a stark backdrop to the rapidly growing need of investing in new infrastructure and preparing for the accelerating impacts of climate change. Through the Climate-Safe Infrastructure Bill, AB 2800 (Quirk)[2], and with its leadership and foresight in climate change adaptation planning, the State of California is seeking to understand how it can better prepare its existing and new infrastructure for increasingly unpredictable climate conditions that will be significantly different from the current ones. The State is seeking to understand how it can ensure a climate-safe future.

AB 2800 builds on a strong legislative and planning record in California that has sought to lead the nation in global greenhouse gas emission reductions, energy and automotive mileage efficiency and more recently adaptation planning (Box 1.1).

The Climate-Safe Infrastructure bill seeks to build on this impressive legacy and push it forward in critical ways. AB 2800 mandated that a panel of scientists, registered engineers and architects be convened to help the State of California understand how it can best incorporate forward-looking climate information into the state’s infrastructure design, planning and implementation. To develop recommendations to the State legislature and the Strategic Growth Council (SGC), and in response to the mandate from AB 2800, the Climate-Safe Infrastructure Working Group (CSIWG) was appointed in July 2017 and convened in January 2018. It is comprised of expert engineers and architect from State agencies and special jurisdictions, bolstered by some of California’s leading scientists specializing in climate science, transportation and economics (Box 1.2, Appendix 2).

[1] See: https://www.fema.gov/disasters/state-tribal-government/0/CA.

[2] See: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800, as well as Appendix 1.

Box 1.1: Selective Legislation, Mandates and Adaptation Planning Efforts Influencing AB 2800

- Executive Order S-13-08, 2008
- Safeguarding California, 2009 (and subsequent updates and implementation plans)
- Executive Order B-30-15, 2015
- AB 1482 (Gordon), codifying regular updates to state adaptation plans, 2015
- Annual Five-Year Infrastructure Plans
- State Hazard Mitigation Plan
- California/Regional Transportation Plans, California Water Plan, Central Valley Flood Plan
- Office of Planning and Research's *Planning and Investing for a Resilient California: A Guidebook for State Agencies, 2018*

The Urgency and Opportunity to Invest in a Climate-Safe Future

AB 2800 does not come a moment too soon. From a national perspective, California has an opportunity to take a strong leadership position in the nationwide debate on modernizing and building critical infrastructure. The American Society of Civil Engineers (ASCE) regularly assesses the status of infrastructure across the United States, and has found the nation's infrastructure – on average, across infrastructure types – to deserve no more than a D+ grade[4]. "D" stands for "poor, at risk." AB 2800, building on past infrastructure efforts by State agencies, the Legislature, outside experts and deeply concerned stakeholders, offers an opportunity to show the country how infrastructure can be rebuilt and created with a forward-looking, climate-aware perspective.

In fact, through existing State bonds (e.g., SB 1 for transportation and $5.8 billion in State school bonds for modernization and $39 billion in local school district bonds) as well as recently voter-approved propositions (Prop 1 and Prop 68 for water and natural resources), the State has nearly $62 billion dollars available to invest in built and nature-based infrastructure. In 2018 alone, the Cap and Trade revenues provide another $8.4 billion that are being directed towards climate mitigation and adaptation planning; this is expected to quadruple in 2018. In addition, given the recently elevated national debate on infrastructure, federal infrastructure funds may increase above historical levels.

Box 1.2: Members of the Climate-Safe Infrastructure Working Group (in alphabetical order)

- Dr. Amir AghaKouchak, P.E., University of California, Irvine
- Nancy Ander, P.E., California Department of General Services
- John Andrew, P.E., ENV SP, California Department of Water Resources
- Gurdeep Bhattal, P.E., California Department of Transportation (alt)
- Martha Brook, P.E., California Energy Commission
- Dr. Dan Cayan, University of California, San Diego: Scripps Institution of Oceanography
- James Deane AIA, CDT, LEED AP, PMP, California High Speed Rail Authority/WSP
- Dr. Noah Diffenbaugh, Stanford University
- Dr. David Groves, RAND Water and Climate Resilience Center, Pardee RAND Graduate School
- Dr. Kristin Heinemeier, P.E., University of California, Davis: Energy Efficiency Center
- Dr. Robert Lempert, RAND Corporation, Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition (alt)
- Dr. Cris B. Liban, P.E., ENV SP, Los Angeles County Metropolitan Transportation Authority
- Dr. Kyle Meng, University of California, Santa Barbara
- Dr. Deb Niemeier, P.E, NAE, University of California, Davis
- Bruce Swanger, P.E., California Department of Transportation
- Chester Widom, FAIA, California Department of General Services, Division of State Architect

In the meantime, however, 52 of California's 58 counties declared a state of emergency at least once during the floods and fires of 2017/18 and received approximately $3.5 billion in disaster funding[3], a substantial portion of which can be used to rebuild infrastructure, and – where local codes allow – make this infrastructure stronger for a climate-changed future[5]. In addition, California is utilizing disaster funding to create resilience to future disasters exacerbated by climate change by using hazard mitigation post-disaster funds to target drought, wildfire and sea-level rise. To date, $38 million in federal cost share grants for

[3] $1 billion of that was for the debris cleanup after the Northern California fires alone. The final loss total may still change.

managed aquifer recharge projects – some of the first in the nation – have been submitted to FEMA for final review and approval, and additional sea-level rise and wildfire mitigation projects are soon to follow[5]. While these billions of dollars may seem like a windfall, they are only a down-payment on the statewide infrastructure investment needed as we will show in this report. Importantly, these available funds could easily be squandered on maladaptive projects if climate-safe infrastructure policies and guidelines are not put in place today.

Scope and Charge

As mandated in the AB 2800 legislation, the working group has a very specific charge, namely, at a minimum, to consider and investigate:

1. The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design;
2. The critical information that engineers [and architects] responsible for infrastructure design and construction need to address climate change impacts; and
3. How to select an appropriate engineering design for a range of future climate scenarios as related to infrastructure planning and investment.

It further mandates that, in a report to the State Legislature and the SGC, the working group shall make recommendations to the Legislature that address:

1. Integrating scientific knowledge of projected climate change impacts into state infrastructure design;
2. Addressing critical information gaps identified by the Working Group; and
3. A platform or process to facilitate communication between climate scientists and infrastructure engineers [and architects].

During the first CSIWG meeting, the Working Group developed a process to address the mandated requirements (Figure 1.1). In addition, members identified broader goals that both meet the legislative mandates, but also help further the intended goals of the legislation. As a result, the CSIWG identified a set of outcomes that address these goals. They aimed to identify:

- The **range of infrastructure to be considered** in the work of the WG;
- **Opportunities for State of California to affect how and where infrastructure is built**;
- **Opportunities for integrating forward-looking science** (about a non-static future into infrastructure design);
- **Critical information needs of infrastructure engineers and architects** to address climate change impacts;
- **Critical information gaps**;
- **Informational and institutional barriers** to integrating projected climate change impacts into state infrastructure design; and
- **Ways to select an appropriate engineering design for a range of future climate scenarios** as related to infrastructure planning and investment.

Figure 1.1 At the first meeting, Working Group members co-identify and rank their goals and priorities for how to guide the State in developing climate-safe infrastructure. (Photo: Susanne Moser)

To achieve these outcomes, at the outset, the CSIWG identified what they determined to be an important set of corresponding recommendations that should emerge from the working group deliberations:

- **Policy recommendations** of how to encourage forward-looking infrastructure planning and design;
- **Procedural recommendations** to affect climate-safe infrastructure development process (from planning, design, approval, construction to monitoring);
- **Principles** to guide infrastructure development, maintenance, repair to build equitable and climate-resilient infrastructure;
- **Identification of available tools and information sources** to use;
- **Recommendations on how to lower/overcome barriers** to information use;
- **Research recommendations** to fill information gaps; and
- **Recommendations on capacity building/professional development.**

This report summarizes the CSIWG's deliberations in response to the mandate of AB 2800 and offers recommendations to the California State Legislature and the SGC. Together, these recommendations chart a path toward helping California invest in climate-safe infrastructure. It addresses both the infrastructure that was built decades, even more than a century ago – from historical bridges, to major dams, highways and buildings – and the infrastructure that will be built in coming years and is meant to last and be used for many decades to come. While this effort initially sought to solve the challenge of incorporating climate information into infrastructure design (something engineers and architects have struggled with for years), the Working Group discovered that the science challenge in moving toward climate-safe infrastructure is significant, but not intractable. Equally difficult, if not more, are those additional challenges that require profound shifts in values, thinking, priority setting and policy commitments.

This report launches from the legislative intent for AB 2800, namely to make California communities safer, to save lives. While saving lives is more likely if decisions are informed by the best available knowledge, science alone will not guarantee our safety. Saving lives is a matter of what and who we as a society value, what we believe deserves our dedicated investment, and thus what decisions we make and actions we take. Investing in a climate-safe future for all is a way of creating a positive legacy for the future. It is *paying it forward*.

Thus, the recommendations in this report have the lofty, yet achievable goal, of incentivizing and inspiring legislators, agency leads, engineers, architects, scientists, consultants and contractors, planners and residents to commit to joining hands in creating a climate-safe future for California.

Key Concepts and Definitions

To ensure that the CSIWG would be able to efficiently address the legislative mandate, it was critical to identify, from the outset, the scope of the infrastructure for the deliberations and discussions, as well as agree upon definitions of the key terminology that would be used throughout the Working Group meetings.

In defining the scope of the infrastructure to be discussed and deliberated on during this process, the CSIWG also thought it important to not only consider individual infrastructure assets but to consider these individual assets as part of a broader system of assets that serve the public good. Infrastructure supports the functioning of society, and its operation and maintenance are necessary for the public's health, safety, and welfare. Infrastructure assets can cross jurisdictional boundaries, be held publicly or privately, and the benefits from these assets are generally available to a large portion of the population. They are held in public trust or their adoption is so widespread that social processes have become reliant on them. Some infrastructure is considered critical, i.e., so vital that its destruction or incapacitation would have a debilitating impact on the economy, security, public health, safety and welfare of society on a local, regional or statewide scale. The CSIWG's short definition of infrastructure encapsulates all of these points:

> **Infrastructure** is defined as the system of interconnected natural or human-made assets, as well as physical and virtual structures and facilities embedded in built and/or natural environments, that is put to social/economic uses, operated by humans, and governed by institutions, rules, social norms and expectations of their service.

Tangible examples of such infrastructure include (but are not limited to):

- **Transportation:** state highways (and connected transportation and transit systems, including rail lines and train stations) as well as all associated on- and off-ramps, signage, bridges, rest areas, office spaces and maintenance facilities;
- **Energy:** power generation plants, transmission lines, distribution lines and related equipment;
- **Criminal Justice:** correctional facilities, judicial branch facilities and crime laboratories;
- Water: water storage facilities such as dams, lakes and reservoirs, canals, pumping stations, hydroelectric powerplants, pipelines, levees and flood protection structures;
- **Natural Resources:** State parks and park-related facilities, fish hatcheries, constructed habitat, buildings and parking areas, CalFire facilities, and agricultural inspection stations;
- **Higher Education:** UC and CSU higher education campuses and community college campuses;
- **Health Services:** mental health hospitals and developmental centers; and
- **State Office Space:** State-owned or leased office structures used for governmental services[6].

Recognizing that the intent of the legislation was to provide recommendations to the State Legislature on how California could retrofit existing and create new climate-safe infrastructure, the CSIWG decided to limit their recommendations to only state infrastructure. "State infrastructure" was understood broadly, however, to include infrastructure that is:

- **State-owned:** State wholly or partially funds design and construction, operate, and maintains facility as State property;
- **State-funded:** State provides full or partial funding to another governmental body or utility; and

- **State-regulated:** State has regulatory oversight of non-government owned infrastructure elements that functions for the public good and are essential services, e.g., utilities.

The CSIWG also felt that their work and this report should serve as a model for how regional and local jurisdictions within California – as well as other communities and states across the nation and globe – could implement these recommendations for their own infrastructure design, planning, operation and maintenance. Thus, while many of the report recommendations are geared specifically to the California State Legislature and the State's SGC, they were also developed to be applicable to other interested communities. Overall, while the scope of this report is limited to state infrastructure and the impacts that state stakeholders can have on it, all the concepts discussed have relevance to the entire range of ownership and operation situations.

Disruptions from climate extremes are already commonplace now and will be an inevitable part of a climate-changed future. Thus, an important aspect of the CSIWG's conversations was agreeing on definitions of "resilience" and "climate-safe" infrastructure as these ultimately drive the CSIWG's recommendations.

Resilience is defined broadly as the capacity of an individual, community, organization, structure or environment and their associated human-made and natural systems to assess, prepare for, absorb, cope with, rapidly recover and learn from, effectively adapt to, or take advantage of, risks associated with shocks of adverse disruptive events and the stresses of continually changing conditions, including those associated with a changing climate.[4]

We have chosen this broad definition of "climate-safe" infrastructure and retained that label over potential alternative phrases common in current parlance (such as "sustainable" or "climate-smart") because of the ambition it conveys and because it is consistent with AB 2800.[5] Every scientific and infrastructure discipline has its own language, and debates over appropriate terminology are important and necessary. They should not detract, however, from the ultimate work at hand, which is to build a future that allows society, the economy and the natural environment on which we all depend to thrive, even in the face of change and disruption. As we will show throughout the report, "climate safety" is not a world free from change and disruption, but a world in which California has committed to seek the greatest possible safety for all of its residents through the best available knowledge, the best technology and engineering design, a strong workforce, and sustained political will and resources.

Climate-safe infrastructure is defined as infrastructure that is sustainable, adaptive and that meets design criteria that aim for resilience in the face of shocks and stresses caused by current and future climate. In addition, climate-safe infrastructure should be robust across a range of plausible climate and related socio-economic futures, as determined by the best available knowledge at the time the criteria (standards, codes and guidelines) are set. To remain "climate-safe," these criteria must be monitored and updated over time to account for changing conditions and the performance of resilience measures taken. Climate-safe infrastructure also reduces heat-trapping emissions to the maximum extent possible to not add to the climate change problem. (Mitigating climate change in this way also complies with California's emissions reduction targets.) Furthermore, climate-safe infrastructure addresses socio-economic inequities so that all groups in society increasingly benefit from safe, reliable and sustainable infrastructure.

Developing this Report: The Working Group's Process

With the very tight timeline following passage of AB 2800 that resulted in the appointment of the CSIWG, the State project team and co-facilitators established a formal process for:

- Engaging the CSIWG in the deliberations mandated by the legislation;
- Bringing in external expert voices to the discussion; and
- Developing a comprehensive webinar series to broaden discussion and provide an opportunity for public outreach about the legislation and the CSIWG's deliberations.

Below, we describe each in more detail to illustrate how much was accomplished in a very short time.

[4] We recognize that resilience has many different meanings to many different stakeholders. Even in the CSIWG, uses of this term differed. In this report, when specific types of strategies or interventions are discussed, the term resilience is used more narrowly but in conjunction with other strategies that together echo this comprehensive understanding delineated in this definition.

[5] Our definition of "climate-safe" infrastructure is close to what the ASCE defines as "sustainable" infrastructure.

Table 1.1: Overview of CSIWG Meetings

Meeting #	Dates	Locations	Primary Topics and Tasks	Subject Matter Experts Invited to Meetings
1	1/18/18	Sacramento	Launch of project; determine project goals; WG structure and process	**Secretary John Laird**, Natural Resources Agency **Hon. Bill Quirk**, California State Assembly **Jamesine Rogers Gibson**, Union of Concerned Scientists **Bruce Blanning, P.E.**, Professional Engineers in California Government **Deputy Secretary for Climate and Energy Keali'i Bright**, Natural Resources Agency
2	2/12/18	Los Angeles	Identify relevant infrastructure, sector-specific infrastructure standards, climate-sensitivity, information needs	**Sabrina Bornstein**, Deputy Chief Resilience Officer in the Mayor's Office, City of Los Angeles **Matt Barnard**, Principal Degenkolb Engineers
3	3/13/18	Bay Area	Linking forward-looking climate science and impacts information with standards, codes, certifications throughout infrastructure design/ implementation/ maintenance cycle	**Steve Reel, M.Eng.**, Project Manager, Port of San Francisco **John Thomas, P.E.**, City Engineer, City of San Francisco **Kit Batten, Ph.D.**, Climate Resilience Chief, PG&E **Bob Battalio, P.E.**, Chief Engineer, ESA Associates **Nate Kaufman, M.A.**, Landscape Architect, Living Edge Adaptation Project
4	4/11/18	Sacramento / Davis	Sector-specific design standards and cross-sector interdependencies	**James (Jim) Thorne, Ph.D.**, UC-Davis **Nicole Meyer-Morse**, Science and Technology Advisor, California Office of Emergency Services **Emily (Millie) Levin**, Policy Analyst, California Office of Emergency Services **Louise Bedsworth, Ph.D.**, Deputy Director, California Office of Planning and Research
5	5/9/18	San Diego	Governance of setting/ changing design standards; non-standard strategies to ensure climate-safe infrastructure; deliberation of draft report; agree on refinement needs	**Philip (Phil) Gibbons**, Program Manager Energy & Sustainability, Port of San Diego **Cody Hooven**, Chief Sustainability Officer, City of San Diego **Ralph Redman**, Manager of Airport Planning, San Diego Airport **Andrew Martin**, Senior Regional Planner, San Diego Association of Governments
6	6/20/18	Sacramento / Davis	Agree on final report revisions; delivery and outreach/promotion; project debrief and closure	**Beverly Scott, Ph.D.**, CEO, Beverly Scott Associates & Senior Partner, Parker Infrastructure Partners **Bilal Ayyub, Ph.D.**, Director, Center for Technology & Systems Management, University of Maryland

Working Group Meetings

Six Working Group meetings were held over the course of six months commencing on January 18, 2018 and ending on June 20, 2018. These were structured conversations that focused on a specific set of topics at each gathering. Meetings were highly interactive with the goal of eliciting as much knowledge, input and discussion among working group members as possible. The initial meeting was intended to focus and bound the CSIWG's discussions and goals. Meetings 2-4 focused on deliberation of topics determined through the goal and scope-setting accomplished in the first meeting. Meetings 5 and 6 focused on refining incomplete work areas and on the development of the report and its recommendations.

Meetings were open to the public and held in different locations across the state in order to provide opportunity for local engagement. To supplement the working group's discussions, each meeting involved local speakers who had subject matter expertise in the topics of each meeting (Table 1.1).

Webinar Series

To bolster the information included in the Working Group's deliberations, a webinar series at a frequency of 1-4 webinars per month was organized to run in parallel to the CSIWG meetings. The goal of these webinars was threefold:

- **Showcase CSIWG expertise** – to provide an opportunity for each CSIWG member to highlight their work and expertise;
- **Elicit input from outside experts** – to bring in outside expertise to address issues that were of interest to the CSIWG and its deliberations; and
- **Engage stakeholders** – to provide information to the interested AB 2800 stakeholders and to provide continuous updates of the work of the Group.

The webinars thus were by and for the Working Group but open to the public and usually had attendance rates of between 20-30 stakeholders in addition to the presenters. Most attendees were from within California, but some attended from federal agencies and outside California. The webinars were recorded and materials posted online. These webinars will remain on the CSIWG website and thus remain a resource to interested stakeholders in the future. Throughout this report, when relevant, we draw on and highlight webinar content that focused on relevant topics (Box 3, Appendix 2).

Box 3: The Climate-Safe Infrastructure Webinar Series (see also Appendix 3)

- **January 25, 2018 - Setting the Standards and Context: Federal to Local Roles**
- February 22, 2018 - Forward-Looking Climate Science for Use in Infrastructure Engineering: Possibilities and Limits
- **March 21, 2018 - Mobilizing the Future: Infrastructure Challenges and Opportunities in the Transportation Sector**
- March 22, 2018 - Rushing Toward the Future: Infrastructure Challenges and Opportunities in the Water Sector
- **April 6, 2018 - Green Infrastructure: Design and Integration for Climate-Safe Communities**
- April 10, 2018 - Governing Infrastructure: How Regulations, Standards, Codes and Guidelines Are Set and Changed
- **April 18, 2018 - Energizing the Future: Challenges & Opportunities in the Building/Energy Sector**
- May 15, 2018 - Building the Future: Challenges & Opportunities in the Building Sector
- **May 17, 2018 - Financing Climate-Safe Infrastructure I**
- May 29, 2018 - Financing Climate-Safe Infrastructure II
- **May 30, 2018 - Building a Climate-Safe Future for All: Social Equity and Inclusion in Infrastructure Planning**
- June 6, 2018 - Enabling Scientists and Engineers to Work Together Effectively
- **June 8, 2018 - Tools Supporting Climate-Safe Infrastructure Design**
- June 11, 2018 - Monitoring Infrastructure Performance
- **June 28, 2018 - Financing Climate-Safe Infrastructure III**
- July 12, 2018 - Communicating Climate Change – Reaching Skeptical Audiences
- **September 5, 2018 - The Findings and Recommendations of the CSIWG**

Table 1.2: Outreach During and After the AB 2800 Project

Date	Occasion / Audience
February 2018	Ann Kosmal, General Service Administration (GSA), on the CSIWG's purpose and process and relevant federal work on adaptation and resilience within the GSA
March 2018	Water Resources Adaptation to Climate Change Workgroup (per invitation of an AB 2800 webinar speaker, Dr. Kate White, US Army Corps of Engineers)
May 2018	ASCE Committee on Sustainability (per invitation by CSIWG Member, Dr. Cris Liban)
May 2018	Alicia Pegan, Climate Ready Boston Coordinator of the City of Boston, to share lessons about the CSIWG's process as Boston seeks to develop its own science-engineering working group
May/June 2018	Dr. Richard Moss, Columbia University, Sustained National Climate Assessment, to explore possible connections between the sustained assessment and California's efforts to improve science-application opportunities
June 2018	Dr. Kathy Jacobs, University of Arizona, regarding the panel of architects developing principles for climate-safe/resilient building design at the Global Climate Action Summit, San Francisco, in September 2018
July 2018	François Levesque, Infrastructure Canada, concerning communication challenges related to climate change and adaptation
August 2018	Presentation about AB 2800 and the CSIWG's process at a California Public Utilities Commission (CPUC) workshop on initiating a rulemaking proceeding on adaptation for electric and natural gas investor-owned utilities
August 2018	Presentation about AB 2800 and the CSIWG's process at a National Academy of Sciences workshop, "Making Climate Assessments Work: Learning from California and Other Subnational Climate Assessments"
August 2018	Presentation on AB 2800 and the CSIWG's report at the Third California Adaptation Forum, Sacramento, CA
September 2018	Report release via agency websites, AB 2800 webinar and news media
Post-Release (anticipated or confirmed outreach opportunities)	
October 2018	Briefing to the Strategic Growth Council
October 2018	Briefing to the California Legislature
Fall 2018	Dr. Doug Mason, Millennium Challenge Corporation, regarding the integration of climate considerations in federal international development work
Fall 2018	Briefing to Canada's Adaptation Platform Infrastructure and Buildings Working Group
Fall 2018	Presentation on the CSIWG's process, findings and recommendations to the Department of Homeland Security's National Infrastructure Advisory Council (NIAC), per invitation of NIAC Co-chair, Dr. Beverly Scott
December 2018	2018 Annual Meeting of the American Geophysical Union (AGU), paper proposed
January 2019	2019 Annual Meeting of the National Council for Science and the Environment (NCSE), session proposed, featuring CSIWG members
Spring 2019	2019 AGU Climate Solutions Conference, session proposed, featuring CSIWG members
Spring 2019	2019 National Adaptation Forum, session on infrastructure and social equity proposed

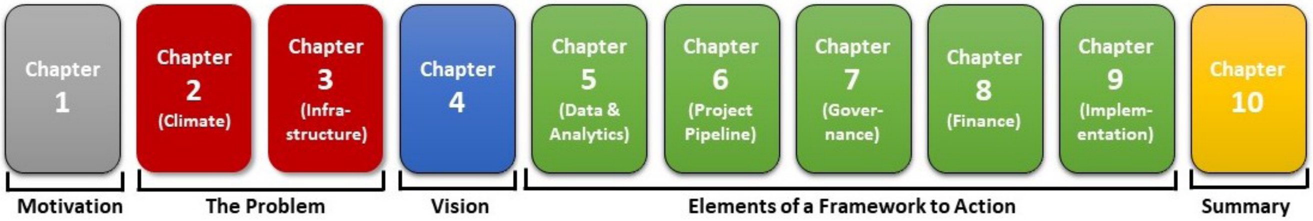


Figure 1.2 Report overview by chapter

Literature Review

Even though the incorporation of forward-looking climate science in engineering and architecture is a relatively new area of work, there is a growing body of literature that provides invaluable insight and best practices that will be relevant to California state engineers and architects as the state moves toward resilient and climate-safe infrastructure. In addition, there is a long history of state-wide and national efforts to design, improve, upgrade and modernize infrastructure across many different sectors. Working Group members also provided critical resources to inform the deliberations and the development of this report.[6]

Public Outreach

Early on in the process of the Working Group members urged to engage interested stakeholders to both educate the public about AB 2800, the necessity of building climate-safe infrastructure, and to provide an avenue for input into the Working Group's deliberations. We have accomplished this in a number of ways.

Through the AB 2800 Climate-Safe Infrastructure Webinar Series, the CSIWG was able to highlight some of their own work and expertise, as well as throughout the group's deliberations. In addition, the Co-facilitators gave a variety of presentations to various infrastructure and adaptation-interested audiences over the course of the project period (Table 1.2).

In collaboration with AB 2800 sponsors, CSIWG members, and interested stakeholder groups, outreach opportunities within and far beyond California (nationally and internationally) are continually sought and realized to ensure widespread awareness of the CSIWG's work and this report.[7]

[6] The reference list at the end of this report provides links to those accessible and/or free online.

[7] The co-facilitators in collaboration with the State agency project team and the Working Group developed an outreach plan. It is continually being updated to reflect opportunities. A summary of outreach will be prepared at the end of 2018.

Report Organization

Without even the complications of a changing and uncertain climatic future, California's infrastructure today is inadequately maintained and – in many instances – outdated[7]. With AB 2800 directing the formation of a Working Group of experts to inform its path forward, California has again proven its national leadership. It is taking stock of current infrastructure today, understanding how it may be impacted by climate change in the future and working to identify solutions and policies for planning for that future, starting today.

The goal of this report is to paint a vision and chart a path toward climate-safe infrastructure for all Californians – starting from where we are – and provide a set of strategic recommendations for how the State can realize this vision. We do so in nine chapters following this introduction, as described below (Figure 1.2).

Infrastructure design for the future must accommodate uncertainty to a greater extent than in the past. Dealing with this greater uncertainty in engineering will require some changes in engineering practice.

Chapter 2: Climate Change – The Challenge. California's climate is indisputably changing. This chapter describes the observed and projected changes in California's climate, provides a primer on the uncertainties associated with this information and how to interpret and assess those. It makes clear what is known with considerable scientific confidence and what is less well known, illustrating why infrastructure design for the future must accommodate uncertainty to a greater extent than in the past. Dealing with this greater uncertainty in engineering will require some changes in engineering practice.

Chapter 3: Infrastructure – The Starting Place. Chapter 3 provides an overview of California's infrastructure, sector by sector, including its current status, threats from climate change and opportunities to upgrade and modernize it. This baseline assessment sets the context for the discussion in subsequent chapters of how to retrofit and modernize the state's infrastructure systems.

Chapter 4: A Vision for Climate-Safe Infrastructure. Chapter 4 paints a vision for how California can develop climate-safe infrastructure. This vision entails continuing on the path of stringent emission reductions to minimize future climate change (mitigation) while planning the necessary adaptive pathways (adaptation) in case the global community fails to similarly reduce emissions. Such a failure would result in potentially grave risks to California, but the state can use a range of levers (policy, guidance, standards, funding, incentives etc.) to enact strategies that are flexible in practice but are targeted toward safety and infrastructure reliability. The vision outlined in this chapter makes equitable infrastructure investment a central motivation so that climate safety is realized for all Californians. The chapter also lays out an action-oriented framework of how to realize this vision; the elements of each are taken up in Chapters 5-9.

Chapter 5: Data and Analytics: Meeting Forward-Looking Science Needs. This chapter addresses one of the core mandates of AB 2800, namely the information needs engineers and architects have if they were to incorporate forward-looking climate science into infrastructure planning, design, construction, operation and maintenance. Because climate is not the only variable changing, the chapter also addresses non-climatic information needs to adequately plan for the future. Finally, the chapter addresses the question – asked in the legislation – what tools, platforms and processes are available or needed to facilitate interaction between scientists, engineers and architects.

Chapter 6: Project Pipeline: Pre-Development and Prioritization. Chapter 6 focuses on the all-important pre-development phase during which infrastructure projects go from concept to being ready for construction. We discuss the importance of effective and meaningful stakeholder engagement and introduce a number of tools and approaches that help with effective project design in the face of an uncertain climate future and other factors that project owners need to take into account. As the engineering and architecture community move into a new paradigm, novel design options are being introduced.

Chapter 7: Governance: Changing the Rules to Enable Climate-Safe Infrastructure. The traditional approaches to designing infrastructure are built according to prevailing standards, codes, guidelines and various non-standards-based approaches. In this chapter, we review how these standards and guidelines are set and identify which ones in California need to be updated to account for a changing climate. We introduce standards that are better suited to accommodate climate, describe efforts to translating these into practice and offer suggestions on how California can move forward in an era of changing standards and practices. We close with a discussion of institutional mechanisms needed to support the implementation of the systems-oriented, forward-looking and social equity-focused vision promoted in this report.

Chapter 8: Financing Climate-Safe Infrastructure. Chapter 8 reviews infrastructure funding trends, challenges, and the needs and opportunities to put in place finance systems that can make further progress on improving infrastructure finance in the state and address the potentially growing cost of infrastructure in the face of climate change. The analysis shows that in addition to climate science, demographic, land use and economic projections regarding future infrastructure needs, a variety of metrics of the environmental, social and governance performance of funding mechanisms and additional metrics to measure adequate progress and success of adaptive infrastructure projects are required to secure the necessary funding.

Chapter 9: Implementing Climate-Safe Infrastructure. In the final step in the framework to action, we explore some of the critical steps necessary for climate-safe infrastructure to be realized on the ground, including the need for: training, capacity building and workforce development, statewide coordination to support an integrated way forward with realizing the vision of climate safe infrastructure and concrete mechanisms for better linking state policy and guidance to project-level action or overcoming barriers that impede it.

Chapter 10: Summary: Barriers and Recommendations. We close the report in this final chapter by summarizing the barriers to moving toward climate-safe infrastructure and then summarize the recommendations that address them. Recommendations are grouped together under the headings of Chapters 3-8, thus mirroring the overarching vision and the core elements of the action-oriented framework. Together, the implementation of these recommendations will push California significantly forward on the path to realizing the compelling vision for climate-safe infrastructure across the state.

Figure 1.3 Developing climate-safe infrastructure requires the establishment of a strong bridge between science and the engineering community, as well as supportive public policy aligned with the goals of resiliency. (Photo: Bixby Bridge near Big Sur, CA; Russell Mondy, flickr, licensed under Creative Commons license 2.0)

Clarion Call

At its core, AB 2800 hones in on the critical need to establish the scientific foundation for wise infrastructure investment and planning. We fully support the commitment to evidence-based decision-making and forward-looking planning that this bill affirms.

But while developing climate-safe infrastructure will require the establishment of a strong bridge between climate science and high-quality design/construction/operation/maintenance of both physical and virtual infrastructure assets and facilities (Figure 1.3), a third – and overarching – pillar to realize the vision we lay out in this report is public policy aligned with the goals of resiliency and climate safety. This implies the need for reconsidering traditional stances and approaches to thinking about cost vs. investment.

Traditional thinking has it that building sustainable, climate-safe infrastructure costs more than traditional construction, designed typically to address only today's needs. Yet, in the second decade of the 21st century, when climate science is well established, failing to invest to protect those assets from climate change costs even more in the long run. Given the existing backlog and the need for new infrastructure, California cannot afford this added cost.

At most levels of government, as well as in the private sector, the general tendency is to put more emphasis on the initial outlay than on the long-term investment in the future of our state and the safety and well-being of our communities. It is understandable that – with limited budgets – decision-makers focus on building the most for the least. Yet we know that the initial construction cost is often only a fraction of the actual cost for maintenance, repairs and utilities. And that does not even consider the damages and losses – to structures and lives – when structures are built inadequately for the risks they will face over their lifetimes. And still, the pressure is to build at the lowest initial cost. Resilient and sustainable infrastructure do not come free, but costs can be minimized if relevant measures are built into projects from the start. Public policy must change if we are to build a sustainable future.

2 Climate Change – The Challenge

California's Climate Is Changing

At the heart of the challenge that AB 2800 aims to address is the fact that infrastructure is built to last while the climate is changing. Central to any engineer's professional goal is to build and adequately maintain infrastructure in such a way that it remains reliably functional and safe for public use at the same level over its design life, often many decades. A changing climate means that infrastructure now must be built to withstand conditions in 10, 20, 30, 50 or 100 years from now that are not perfectly predictable but certainly different from those prevalent now. Climate averages will be different, as will be the range and severity of extreme events such as storms, floods and extreme heat, which pose the greatest short-term stresses on the bridges, levees, roads, dams and so on that California's residents, visitors and the economy depend on.

Historically, infrastructure designers, architects and engineers have taken past conditions as reliable guides to the future because the climate could be assumed to be stable within a known range of year-to-year or seasonal variability. This most foundational assumption to all engineering is no longer valid. Engineers and architects must adapt the way they approach engineering design.

Moreover, not only is the climate changing, but many other factors that affect infrastructure use and reliability, ranging from climate-influenced environmental conditions to the number of people that the infrastructure is designed to serve as a result of urbanization and population growth and migration, to the economic conditions, policy priorities and changing cultural norms and expectations that affect what society values, prioritizes and does.

This is why infrastructure engineers and architects want to know what is understood with confidence by climate scientists, and how this scientific understanding can be translated into clear policy, guidance, standards, codes, useful manuals of practice and tools. This section of the report summarizes what we know about climate change, how well we know it, and how these changes may interact with the state's existing and future infrastructure.

> *Historically, infrastructure designers, architects and engineers have taken past conditions as reliable guides to the future. This most foundational assumption to all engineering is no longer valid.*

Significant Scientific Confidence in Global Climate Change

Science has established beyond doubt that the global climate – including California's climate – are changing. Scientific understanding of why these changes are occurring – mostly due to human activities – and how they may unfold in the future has grown significantly more confident over the past four decades or more. The conclusions of the most recent Fourth U.S. National Climate Assessment (NCA4) are telling in the strength of its conclusions[8] (Box 2.1).

Box 2.1: Key Findings from the Fourth U.S. National Climate Assessment

- **Global annually averaged surface air temperature has increased** by about 1.8°F (1.0°C) over the last 115 years (1901–2016). This period is now **the warmest in the history of modern civilization.**
- **It is extremely [95%–100%] likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming** since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.
- **Thousands of studies conducted by researchers around the world have documented changes** in surface, atmospheric and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor.
- **Global average sea level has risen by about 7-8 inches since 1900**, with almost half (about 3 inches) of that rise occurring since 1993. […] Global average sea levels are expected to continue to rise - by at least several inches in the next 15 years and by 1–4 feet by 2100. A rise of as much as 8 feet by 2100 cannot be ruled out.
- **Heavy rainfall is increasing in intensity and frequency** across the United States and globally and is expected to continue to increase [due to the ability of warmer air holding greater amounts of moisture].
- **Heatwaves have become more frequent** in the United States since the 1960s, while extreme cold temperatures and cold waves are less frequent.
- **Over the next few decades (2021-2050), annual average temperatures are expected to rise by about 2.5°F** [1.4°C] for the United States, relative to the recent past (average from 1976–2005), under all plausible future climate scenarios.
- **The magnitude of climate change beyond [2050] will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally.** Without major reductions in emissions, the increase in annual average global temperature relative to pre-industrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less.
- **The global atmospheric carbon dioxide (CO_2) concentration has now passed 400 parts per million (ppm), a level that last occurred about 3 million years ago** [i.e., well before the appearance of the human species], when both global average temperature and sea level were significantly higher than today.

(Source: Excerpted from USGCRP 2017[8], pp. 10-11)

The basic findings and conclusions confirm what many now experience: the climate has become more volatile and some extreme events are more intense or occur more often. Even if the science is clear that the climate is changing, building for a continually changing and more volatile future is another challenge altogether.

Observed and Projected Changes in California's Climate

As this report was completed, so was California's Fourth Climate Change Assessment, which we rely on in this chapter and which informed the Climate-Safe Infrastructure Working Group's (CSIWG) deliberations throughout[9]. Its findings are striking in their importance to the state's economy and the well-being of Californians, and they are similarly confident in tone as those from the NCA4. However, they provide greater regional specificity and thus offer important first-order insights for the state's engineers and architects.

California's Mediterranean Climate

California has a Mediterranean climate, which is characterized by warm to hot, dry summers and mild to cool, wet winters[10]. In addition to being strongly seasonal, California's climate is also highly variable across space. For example, there is a stark climatic gradient from the cool, often foggy coastal areas to hot inland areas, and big climatic differences between the Central Valley and the Sierra Nevada[10,11]. Moreover, California precipitation and other elements of its weather and climate varies greatly from year to year[12,13], in part due to its sensitivity to large-scale ocean-atmosphere oscillations[14]. In fact, California has the greatest precipitation variability among all states in the US[9]. Thus, it is not unusual to find dry years or multi-year droughts where winter storms have avoided California, followed by a year or years with ample moisture from serial North Pacific storms[15], sometimes the mark of "atmospheric rivers"[16-19]. In the past, California has adapted to this variability by, for example, building large reservoirs and dams to store water and control floods[20], by plumbing the entire state to move water from thinly populated areas where most of the precipitation falls to highly populated areas where it is needed most[21] and by pumping groundwater from aquifers to satisfy irrigation needs[22]. But increasingly, as the climate warms and societal demands for water evolve, drought risk will very likely increase[23] and there is a need for better collaboration across agencies and other water users to work out water-related trade-offs[24] and to diversify water resource portfolios[25].

The climate has become more volatile and some extreme events are more intense or occur more often.

The Big Picture of What We Know

From several decades of global, regional and local observations of myriad elements of the climate system, along with a growing production of future projections from numerous climate models, scientists have gained high confidence that climate warming is underway[26]. Furthermore, warming will very likely continue for many decades, along with those climate variables that have a similarly strong thermodynamic response to increasing greenhouse gases[27-29]. For other climate variables, such as rain- and snowfall (precipitation), wind and other variables that are more strongly governed by dynamic interaction of the atmosphere, oceans, land surfaces, ice and the biosphere, changes produced by different climate model projections are not as consistent and confidence is not as high.

Observed and expected changes can be grouped into two basic categories:

(A) **Changes in multi-year averages, resulting in long-term trends** (e.g., average temperatures going up, rising sea level and changes in the length of seasons);

(B) **Changes in some types of weather and climate extremes** (e.g., increases in the frequency, intensity and duration of high temperature extremes or more intense downpours).

In addition to human-driven climate change, the atmosphere, ocean and other parts of the climate system undergo natural variations across the time spectrum from day-to-day to multi-decadal time scales. For forecasts a week or more out, there are inherent limits to the predictability of the details of these fluctuations. As a result, researchers cannot provide precisely certain climate outlooks at time scales pertinent to short-term planning or infrastructure operation, although it is possible to quantify changes in the probability of some relevant conditions.

Figure 2.1 From several decades of global, regional and local observations of myriad elements of the climate system, scientists have gained high confidence that climate warming is underway. (Photo: King Tide in Pacifica, CA; Dave Rauenbuehler, flickr, licensed under Creative Commons license 2.0)

Spatially, there is also a limit to the predictability owing to geographic differences that result in many small-scale variations (micro-climates)[30,31]. These limits notwithstanding, there are predictable components of future climate because the relatively stable topography bears a strong influence on most meteorological and hydrological variables at or near the Earth's surface. Examples of such stable influences include California's complex topography, the long ocean-land boundary or the stark rain shadow created by the Sierra Nevada mountain range[32,33].

In summary, some elements of future climate are predictable and fairly well understood at the global and at large regional scales and on multi-decadal timescales, while other variables – governed by complex dynamics – are less well understood. Inherently, information at high spatial and temporal resolution is quite uncertain. This has always been the case: the spatial and temporal variability experienced in the past was no more predictable than it is now. In fact, infrastructure decisions that are made now have the benefit of considerably greater data and understanding of climate processes than decisions that were made in previous decades. And engineers and architects also have considerable experience with building infrastructure to withstand variable conditions. It is clear now that in addition to this variability, engineers and architects must account for trends in averages and shifts in the occurrence of extremes around those means, while natural variability will always remain an overlay over these two fundamental changes to our climate.

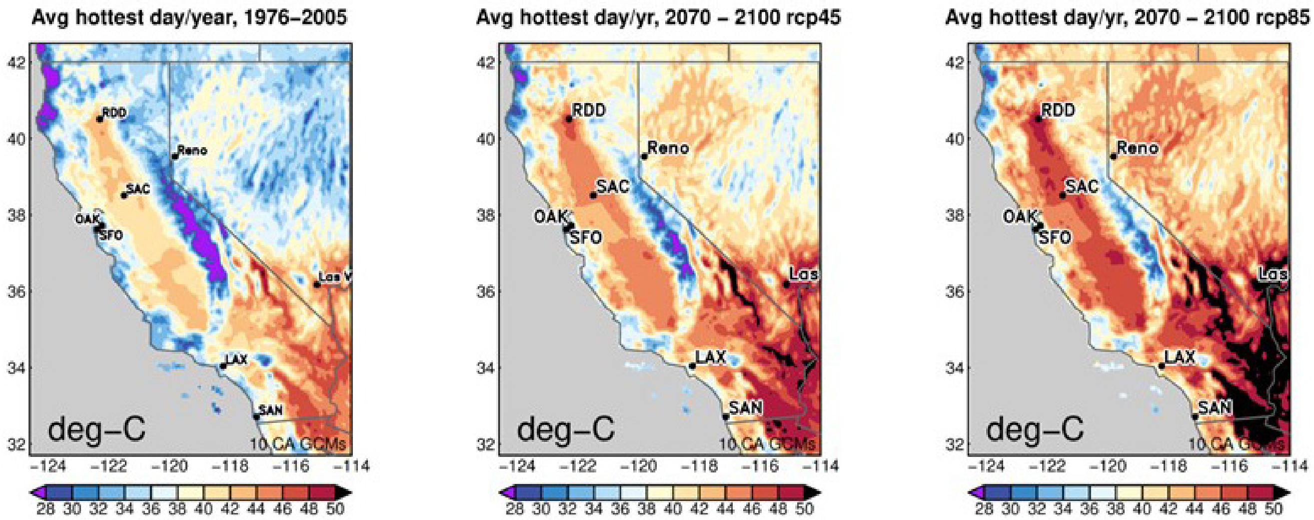


Figure 2.2 Average hottest day of the year (in °C), averaged over 10 Global Climate Models, for the historical period (left) and late-21st Century for RCP 4.5 (middle) and RCP 8.5 (right) emissions scenarios. (Source: Pierce et al. 2018[29], used with permission)

California's Climate Is Changing in Fundamental Ways

Observed climate changes in California over the past five decades are consistent with overall changes observed nationally and globally[9]. The best available climate science for California suggests there will be further changes in the state's climate, which in a number of cases will extend many already-observed trends[29,34].

Continuing warming trend and more heat extremes

- Average annual temperature in California has already increased by 1-2°F compared to the average in the early decades of the 20th century[35], updated data provided by NOAA to G. Franco). The amount of future warming depends mainly on the emissions pathway society will follow. Under any plausible greenhouse gas emissions scenario, the state will see warming of about 4°F (2.4°C) by 2050[9,29]. After mid-century, the higher greenhouse gas emissions pathway (RCP 8.5) – which does not reflect any substantial emissions reduction policies implemented from now onward – yields considerably higher greenhouse gas concentrations, and thus greater additional warming than lower emissions scenarios. The high-emissions scenario would result in warming projections of another 2.7-9°F (1.5-5°C) by 2100 (Figure 2.2).
- Under all emissions scenarios, but particularly under the high emissions scenario, extremely warm years become statistically commonplace[23] and heat waves become more intense and more frequent, last longer and occur over a longer warm season[29,36].
- Simultaneously, cold extremes will occur less frequently[37-39].
- Interior regions of California will experience greater amounts of warming than coastal margins because the latter remain under the cooling influence of marine air[40].
- Due to warming alone, California will see less of its precipitation fall as snow, which will result in diminished mountain snow packs, more rain and less snow in lower and intermediate elevations (which have historically generated spring snow accumulations). Together, these changes will result in earlier run-off and less "natural water storage" in the form of snow, demanding that California adjust its water management approaches[41-45].

Accelerated sea-level rise, worsening coastal storm impacts

- Sea level has already risen by 7 inches between 1900 and 2000, and the pace of rise has been increasing since the early 1990s[46]. In the future, sea level will be rising at a further accelerating rate, with the amount depending on emissions pathways and resulting global warming trends, as well as the consequences of this warming for the large ice sheets of the world (Antarctica and Greenland).
- The main sources of this rise include 1) the expansion of ocean water as it warms and 2) additions to the amount of water in the ocean basins from melting of land-based ice. The latter is expected to become an increasingly important factor. In fact, the rate of ice loss from the Earth's largest ice sheets – the Greenland and Antarctic Ice Sheets – is already observed to be increasing[47,48].

- Sea-level rise projections for California vary by location, which is available for all California tide gauges[49]). For San Francisco, for example, the median projection of sea-level rise by 2050 is 0.9 ft and could range from 2.54 ft (0.77 m) to ~4.5 ft (1.37 m) over 2000 levels by the end of the century, depending on the underlying assumptions about society's emissions pathway[29,46]. However, recent scientific studies point to the (as yet unquantifiable) possibility of extreme sea-level rise, resulting in a possible rise of ~10 ft. (3 m) by 2100[46,50-52].
- Over the near term, the greatest impact on coastal infrastructure will be felt from the coincidence of large winter storms with high astronomical tides and El Niño, each of which temporarily elevates sea levels, albeit by different amounts and for varying duration. But as sea level rises further, these common events and processes will unfold on an ever-higher baseline of local sea level[46].
- The greatest damages in coastal areas arise from wind-driven waves which are generated as storms move toward shore from remote North Pacific regions and build up in near-shore areas[53-55].
- Most coastal storms involve the effects of flooding from the ocean side superimposed on flooding from inland run-off sources[56]. The result is a growing compound flooding risk, resulting in greater exposure and greater loading on coastal infrastructure and buildings[57]. The ability to project these compound flooding risks for California locations has been shown but is not yet available for all locations[58,59].
- In addition, sea-level rise causes saltwater intrusion in low-lying areas such as San Francisco Bay and the Delta, as well as into coastal groundwater aquifers along many parts of the California coast. Saltwater intrusion – to date mostly driven by over-pumping of coastal aquifers – will be exacerbated in the future by rising sea level, affecting agricultural areas, underground infrastructure, and the stability of levees [60-63]. Moreover, higher sea level in low-lying areas means higher sub-surface groundwater levels and less capacity of the soil to absorb large amounts of rainfall, runoff or overland flood waters, thus altering the soil conditions in nearshore areas that are just beginning to be understood and modeled[62, 63].
- Finally, increased wave activity in concert with rising seas leads to increased coastal erosion impacting the coast's beaches, bluffs and cliffs[64,65].

Changing precipitation regime toward greater volatility

- While California's climate has always been variable in terms of daily, monthly and interannual precipitation totals[12], over the past several decades, California has already observed changes in its rain- and snowfall[66, 67], with a tendency toward greater dryness[19,67,68].
- Different causes have been implicated for recent dryness in California including Pacific Ocean-atmosphere effects[69] and effects of human-caused warming[23,70,71]. Some studies also suggest that these already observed shifts (and more in the future) could be linked to Artic sea ice loss[72-78].
- Going forward, one of the more difficult-to-project changes in climate are those related to changes in precipitation. Studies point to more dry days and more dry years in the future[23,33,79,80], but also occasionally to more intense rainfall events[81-83] (Figure 2.3).
- Geographically, scientists expect to see drier parts of the state (southern and inland) to get even drier,

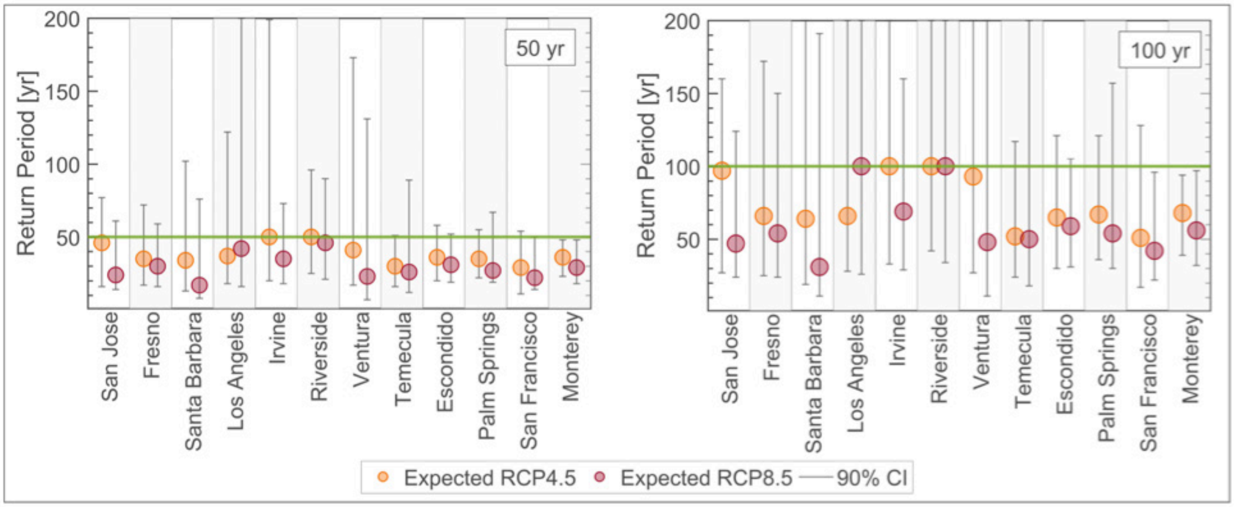


Figure 2.3 Return periods of events historically associated with return periods of 50-, and 100-year in California under climate change. The dots show the expected projected return periods and the gray lines display the 90% confidence intervals (Source: Ragno et al., 2018[58], used with permission).

while wetter (mainly northern) parts get wetter[29,34]. Thus, overall, there may not be a large statewide shift in average precipitation, but regionally specific shifts and a climate marked overall by greater precipitation extremes[29,79].

- Seasonally, models indicate that core winter months (DJF) remain wet or become even slightly wetter, but shoulder spring (MAM) and fall (SON) seasons become drier than they were on average over the historical period[23,29,81]. This would result in a "peakier" wet season separated by a longer warm dry season[33,39,79,83]. A longer warm dry season would heighten some important climate impacts including fire risk, water and energy demand and ecosystem stress[84-86].
- As temperatures increase, the rain/snow line will move to higher elevations, and more of each storm will fall as rain than as snow, resulting in greater immediate storm runoff, especially in historically snow-affected catchments[87,88]. This increased run-off poses increasing problems for dam operators as they must manage for flood protection and water storage under increasingly volatile conditions[89-91].
- At the same time, less precipitation is stored in the snowpack and thus not available for slow release over the dry warm summer season. This is particularly challenging as dry spells in the future will also be warmer, thereby intensifying water loss from soils, water surfaces and vegetation while demand for water and energy will be heightened[89].

Other changes and extremes

- The impact of climate change on high-wind events is not well understood, in part because high winds are rare, often localized, and caused by multiple factors and in the context of different large-scale patterns. Globally, average near-surface wind speeds have been reported to have declined in recent decades[92], but regionally, Santa Ana winds have not exhibited significant trends[93].
- Dry coastal winds (Santa Ana, Sundowner, Diablo) aggravate the risk of wildfires[94,95]. Observation does not suggest any weakening of these wind systems, but future projections remain contested, although most research points to hotter dry winds and the continued importance of Santa Ana winds in the future[93,96].
- The observed changes in California's climate have already contributed to more frequent and more severe wildfires[97-99]. Depending on the assumptions about climate and land use change in the underlying scenarios, future projections point to modest to large increases in wildfire risks in many parts of California, placing more buildings, infrastructure and a growing population at risk[97,98,100,101].

Figure 2.4 Observed changes in California's climate have already contributed to more frequent and more severe wildfires, and future projections point to modest to large increases in wildfire risks. (Photo: Department of Defense).

- Future changes in cloudiness over California are not well understood, in part because clouds are driven by multiple factors, some of which occur at scales smaller than represented in global climate models. Relatively low-altitude coastal stratus clouds and fog – the pre-dominant cloud type along the California coastal margin – occurs throughout the year but more frequently in spring and summer[102]. Historically, periods of anomalous cloud cover are driven by anomalous ocean and atmospheric patterns[103,104], with substantial variations over decades[103,105].
- Urban heat island effects have diminished coastal cloud cover in developed coastal areas such as Los Angeles[86,106]. As cloud cover decreases, particularly late-afternoon temperatures increase, posing growing public health risk and increasing demand for improved building envelopes and/or more air conditioning. The latter would increase energy demand to run air conditioners to mitigate those heat-related health risks[107].

Uncertainties in Climate Projections: The Plain English Digest

Climate scientists have gained significant confidence in historical (i.e., observed) and future (i.e., projected) climate changes, but uncertainties will always be an inherent part of the future[108,109]. What is certain – given the global climate changes now underway and accelerating – is that continuing to rely solely on historical data and the assumption of stasis as a basis for infrastructure-related decisions from now on would ignore empirical reality and the best science available to inform planning for the future.

These uncertainties are described below to make an emphatic case for why engineers and architects must build for change and volatility if the goal is to build the climate-safe infrastructure of the future.

Natural climate variability is the type of uncertainty already familiar to engineers. It is present in the climate now.

Natural Climate Variability

High-resolution global climate models have much improved in their ability to capture and reproduce natural climate variability, such as decadal swings in climate, periodic events such as El Niño-Southern Oscillation (ENSO), and even interannual variability. Research has vastly improved our understanding of the underlying dynamics and thus in improving the ability to forecast such interannual- and interdecadal variability. These forecasts have become increasingly important for emergency planning and for infrastructure operation and maintenance planning. That said, regardless of the future trajectory of global warming, there will always remain a stochastic, or randomly determined, element to the actual climate that unfolds in any place and time. This can be statistically analyzed for patterns but can never be predicted with absolute certainty. Natural climate variability is the type of uncertainty already familiar to engineers. It is present in the climate now.

Emissions Trajectories

One of the largest uncertainties in predicting future climate is the course human society chooses in terms of energy and land use, resulting in different greenhouse gas emissions pathways. Ultimately only one such path will be realized, but we will only know which path by hindsight. Because it is very difficult to predict which pathway society will take, scientists use a range of plausible emissions scenarios, resulting not in a single projection, but in an envelope of possible rates of warming, sea-level rise and other measures of climate change.

While California – now the fifth largest economy in the world – is continuing on its course of stringent emission reductions, the federal government is currently in the process of rolling back previously made emission reduction commitments. At the same time, many subnational actors and virtually all nations around the globe have formally committed to achieving the goals of the 2016 Paris Agreement[110-112]. This agreement aims to limit global average temperature increases to 3.6°F (2°C) above the pre-industrial average, and ideally to less than that. Emission reduction pledges made to date, however, would result in a global temperature increase of 4.7-5.8°F (2.6-3.2°C), and actual emission reduction achievements and policies in place so far point to an even larger temperature increase of 5.6-6.7°F (3.1-3.7°C) above pre-industrial levels by 2100. Many nations that have committed to the Paris targets are finding it extremely difficult to make the necessary changes (see assessment by country, especially of highly developed nations, at the Climate Action Tracker), while many others, especially least developed countries, insist on their right to development, which, still often, is energy-intensive[113,114]. These kinds of challenges are faced, in fact, at all levels and across the world, namely to decouple the economy and human well-being from high consumptions of fossil fuels. Until this succeeds and the greenhouse gas emissions stabilize, it is thus prudent to plan for a more dangerous future despite California's stringent mitigation goals.

Researchers and policy observers have concluded that it is technically feasible to achieve the lower warming targets of the Paris Accord by deploying stringent policies, market signals, available energy technologies and other technologies that draw carbon out of the atmosphere (so-called "negative emissions technologies"), perhaps after a period of overshooting that target[115-120]. However, any delays result in greater future cost[121] and increase the likelihood of creating severe impacts and passing irreversible tipping points in the climate system[122,123]. Feedback mechanisms may also result in difficult-to-impossible to predict responses of the climate system given the rapid pace at which it is being altered by greenhouse gas emissions[124,125]. Thus, the ultimate warming trajectory, particularly beyond the middle of the century, remains uncertain. Projections of future climate changes, even probabilistic projections as provided in California's Fourth Climate Change Assessment[29] or the Ocean Science Trust's recent sea-level rise report[46], will remain contingent on assumptions about the course of global emissions (Box 2.2).

Projections of future climate changes, even probabilistic projections will remain contingent on assumptions about the course of global emissions

Box 2.2: "A 90% Chance that Sea-Level Rise Will Be No More Than …" – A Word on Probabilistic Projections of Future Climate Change

One of the key advances in climate science over the past decade – aided by increasingly powerful computer models – has been the ability to provide probabilistic climate change projections. To say that "there is a 30% chance of rain in the San Francisco Bay area tomorrow" or "a 50% chance that a particular storm will come onshore on the Mendocino Coast" is fundamentally different, however, from saying, "there is a 66% chance that average warming in 2050 will be within a certain temperature range." Why is that?

Weather predictions for the next few days use high-resolution meteorological models (i.e., mathematical equations representing the changing state of the atmosphere built from past observations and adhering to the laws of physics) that receive current observations of atmospheric and surface conditions as initial conditions and then are run forward to produce tomorrow's weather. Tomorrow, we will know whether the prediction hit the mark. Their skill can be measured and subsequently forecasting models can be improved with yet another observation.

Climate projections 50 or 100 years out rely on global climate models that use essentially the same types of equations as weather forecasting models. These equations account for the conditions of the land, ocean, ice and atmosphere and integrate across time and space. They are run with historical data to validate them, for example, by starting a model in 1750 with the greenhouse gas concentrations known to have existed at that time, and then run forward to 2018 with the greenhouse gas concentrations increasing as they were observed in each year. But the key difference is the basic input into these equations. Rather than current weather conditions, climate models start out from the amount of heat-trapping greenhouse gases in the atmosphere, along with whatever else is known about natural climate variability and its causes, and the simulated outcome are climate variables, such as the surface temperature over land at a particular point in time.

Assuming known natural variability will continue into the future, superimposed on the basic state of the climate at any one time, the critical question then becomes: how much is the concentration of greenhouse gases in the atmosphere going to be changed from its current (or pre-industrial) state? No climate scientist, economist, or policy maker in the world is in a position to foresee what the exact concentration will be in 2100. Why? Because the concentration will depend on a suite of policy choices and economic incentives created by humans, as well the individual and societal responses to those policy choices and incentives. These individual and collective decisions involve countless factors – including free will – and while we all may speculate what humanity will do, no one can say for sure. This is why scientists have developed a set of internally consistent, plausible scenarios of how global emissions might unfold. These emissions scenarios (also sometimes called trajectories or pathways) are the basis for running their models.

Climate projections start out from the amount of heat-trapping gases in the atmosphere and what is known about natural factors affecting the climate. The balance of policies and incentives for either renewable energy and fossil fuel sources will shape the future climate. (Photo: Kevin Dooley, flickr, licenses under Creative Commons License 2.0).

How do we get to probabilities then, if we cannot say how likely a particular scenario is? We get to probabilities by running climate models with the same scenario often enough that we can develop probability distributions for a given emissions pathway. More specifically, scientists can run selected emission scenarios many times on a particular model; they can also run the same scenario on many different models; and they have done this now for all basic scenarios considered by the Intergovernmental Panel on Climate Change (IPCC). Pooling the results of multiple model runs for a particular emissions scenario together, scientists are able to say what the average of all these model runs is, or the distribution of projections for a given climate variable within a particular confidence interval. So, when scientists say, “there is a 66% chance that warming by 2050 will be in a particular temperature range”, that statement reflects the statistical result of many model runs for a particular emissions scenario. Alternatively, scientists may run sea-level rise projections on one or multiple climate models for a lower and higher-emissions scenario, combine all outputs, and thus be able to say that “there is a 90% chance sea-level rise by 2050 will be no more than…”

The resulting probabilities reflect the best available scientific understanding of relevant factors influencing a particular climate outcome (as reflected in the climate models used) but are conditional on the underlying emissions scenario. Such probabilities are useful to infrastructure designers only after they have made up their minds about how risk averse or risk tolerant they choose to be. Once the risk tolerance is determined, infrastructure planners can use these probabilities in a risk management process that considers sensitivity to future changes in the probability estimates. For example, if the infrastructure being considered is long-lived and of high value, and damage to it would cause very high or irreversible damages, an infrastructure owner might choose to build it so that it can withstand the climate conditions associated with a fossil-fuel heavy/high-emissions scenario. Designers can then use probabilistic climate projections for that high-emissions scenario to evaluate their design choices.

This type of probabilistic projection is the best science there is, which is considerably better than assuming that there will be no change, or simply extrapolating historical trends into the future.[4] But in the end, only one climate future out of all of these projections will unfold in reality. Infrastructure designers, along with their stakeholders and ultimate decision-makers, are thus faced with the need to become clear about how willing they are to take on the risk to be unsafe or how willing they are to pay for greater safety. The result of this values-based choice and professional judgment will manifest in the contingencies they will or will not build into their plans and designs so as to deal with the one inherently unpredictable reality that will unfold in time.

Model Uncertainties

Climate models are another source of uncertainty in climate projections. To project future climate, scientists select one or more plausible greenhouse gas emissions scenarios (as discussed above) and use them as inputs into global climate models. Climate models are linked sets of mathematical equations derived from the laws of physics, such as Newton’s equations of motion and the Ideal Gas Law. They are based on the same mathematical equations as the models that are used to make weather forecasts but are run over much longer time horizons and represent physical processes in the atmosphere, ocean, ice and land surface. In some cases, models also account for important processes in chemical, biological and human systems[126]. In recent decades, research groups around the world have developed more than 50 such global climate models of varying complexity. They vary in the degree of sophistication in representing these physical, chemical, biological and human-driven processes, as well as in the spatial and temporal detail that they can provide. Climate models also vary in how well each is capable of reproducing the natural variability that has been observed over different regions of the world in the past. Research groups continually improve models, validate them against past climate observations, and learn from thousands of analyses by the much larger group of international scientists that are not involved in the climate model development through a global inter-model comparison project (now in its sixth round of inter-model comparisons[127,128]).[5]

With growing computational speed and data storage capacities, models can now be run many times with multiple emissions scenarios, or many times with the same emissions scenario. These enhanced computational resources have significantly improved modeling approaches; enabled insights into the relationship between observed trends, extreme events, and underlying causal mechanisms (e.g., attribution of individual extreme events to natural variability vs. human-caused climate change); and give scientists the ability to develop probabilistic climate projections.

One of the most important findings from this inter-model comparison over the past few years has

[4] Scenario planning can be a viable alternative to understand the sensitivity of systems to different climate (or other) conditions.

[5] See: see: https://www.wcrp-climate.org/wgcm-cmip.

been the insight that, at the regional scale, differences between models are often neither smaller nor greater than the normal variability in climate. Put another way: when analyzing the trajectory of climate in a given region, running one emissions scenario ~40 times in one climate model often produces a range of climate outcomes that is similar in size to the range obtained when running that same emissions scenario once in each of the ~40 global climate models available[36,129,130]. In practice, however, decision-makers do not rely on 40 models to capture this full range of possible outcomes; rather, they typically only have a small number of model results available. Thus, for planning purposes and to guard against possibly missing important information, a divergent range of model outputs should be used. This range of outcomes in a single climate model run in a single emissions scenario arises from the natural climate variability described above. The resulting range of projected variables reflects the irreducible uncertainty that is inherent to all climate futures.

Future climate will never be more predictable or more certain than the past or current climate.

As a result, a general "rule of thumb" is that future climate will never be more predictable or more certain than the past or current climate: day to day, season to season, year to year, there is variability in the climate and that fact remains. However, in general, climate variables that are strongly dependent on temperature exhibit the least irreducible uncertainty, while variables that are dependent on precipitation exhibit the greatest irreducible uncertainty[34]. For example, for California, the irreducible uncertainty lies only in the magnitude of warming, but not in whether warming will occur if greenhouse gas concentrations continue to increase[129]. Likewise, although there is substantial irreducible uncertainty in the sign of precipitation over California and the broader western United States over the next few decades, the definitive likelihood of continued warming overcomes that precipitation uncertainty to create an unambiguous trend towards diminished snowpack and earlier snowmelt timing[42].

Uncertainties in Downscaling

Global climate models are – as the name denotes, global in scale – and thus use a global grid to map their outputs onto the Earth's surface. Each grid cell can be tens to hundreds of miles on one side, thereby covering large areas of different types of terrain, land cover and land use. Over the past decade or more, scientists have made significant progress in increasing the spatial (and temporal) resolution of their models (Figure 2.5), but any increase in the resolution of grid cells results in a corresponding multifold increase in the number of equations that need to be solved to obtain results, and thus in a dramatic increase in computational demand (for example, resolving the processes that produce Santa Ana winds and associated wildland fires[95], or atmospheric rivers[131], thus further increasing the need for computational capacity.)

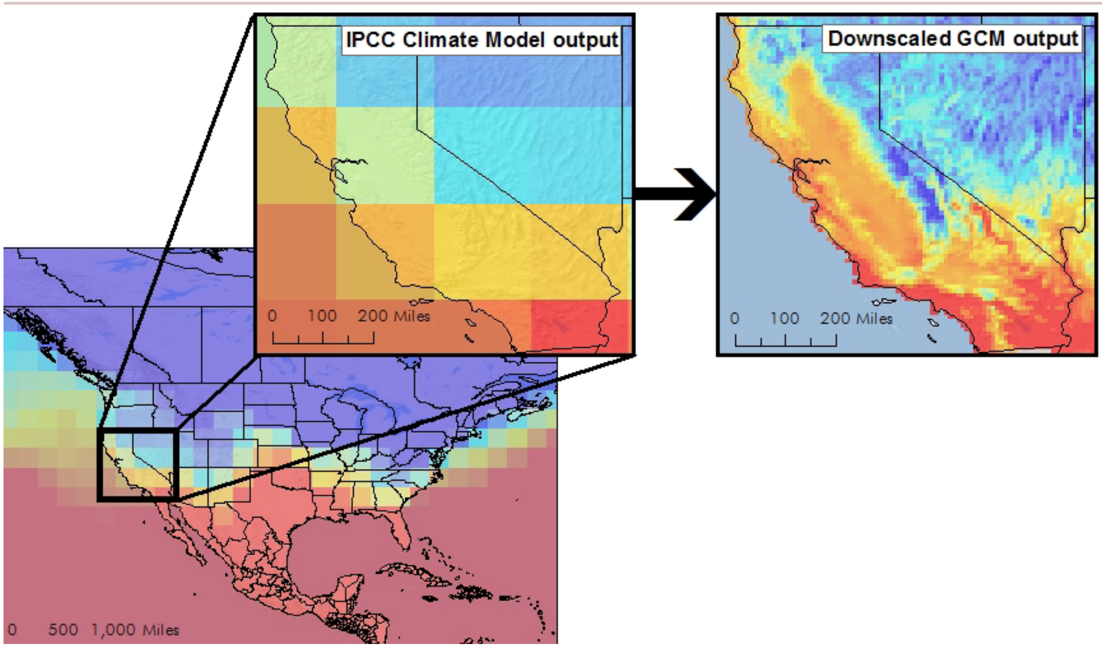


Figure 2.5 Scientists have made significant progress in increasing the spatial and temporal resolution of their models. But just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate. (Source: Cal-Adapt).

Scientists have developed two ways to relate global climate changes to regional and sub-regional changes, (e.g., on the scale of the Western United States, or within California): the first, called dynamical downscaling, links climate dynamics observed at larger scales to those witnessed at smaller scales through equations that represent how these processes interact across scales. The second, called statistical downscaling, mathematically relates (i.e., correlates) climate variables projected at larger scales to corresponding variables observed at smaller scales. Dynamical downscaling offers a more comprehensive representation of the finer-scale physical processes that govern the regional and local response to global warming, but is slower and more computationally demanding, and is subject to uncertainty arising from the physical representation of those processes[132]. Statistical downscaling is quicker and less computationally demanding, but it ignores the finer-scale physical processes, meaning that it can underestimate the magnitude of local and regional change[41].

Many planners and infrastructure designers wish for ever higher-resolution data and the scientific community, including in California, is rapidly advancing to produce the desired level and types of outputs (Box 2.3). Research shows that higher-resolution data are much preferred by practitioners because they illustrate locally familiar situations and lend themselves more easily to local planning and decision-making[133]. But just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate. Put another way, higher resolution data create the illusion of greater reliability, but this may not always be the case.

Conclusions

In this chapter we have synthesized the state of knowledge on observed and projected climate change with particular emphasis on California. The scientific community is unequivocal on the existence of global climate change, and there is very high confidence that it is mostly human caused. A large number and wide variety of independent observations as well as detailed studies to rule out alternative explanations have created this solid scientific understanding.

What we know with considerable confidence includes the following:

- Climate is no longer stationary and the past is no longer a reliable guide to future conditions;
- Climate warming will continue, likely at an accelerating rate;
- Sea level will continue to rise, also at an accelerating rate;
- Extreme weather and climate events will continue to occur amidst an envelope of these changing average conditions. Many will occur more frequently and/or be more intense than historically, a finding of particular significance to infrastructure planners;
- The most likely times of heightened risk of coastal flooding will be those when naturally-occurring events such as astronomically high tides coincide with coastal storms on an ever-higher baseline of rising sea level;
- Compounded extremes (e.g., coastal storms coinciding with freshwater floods; or Santa Ana winds coinciding with a heat wave and drought, leading to wildfires) need to be considered in planning for future climate impacts, including combinations of conditions that have not occurred historically; and
- Sequences of events also need to be considered (e.g., a wet fall that saturates soils, followed by a series of winter storms typically leads to flooding). This includes sequences of events that have been rare historically, and so are not well informed by extensive historical records, meaning that models must be called into play in order to assess the likelihood and better understand mechanisms.

Just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate.

This chapter also detailed in what ways future projections of climate change are uncertain. Some of these uncertainties are familiar to infrastructure planners already, such as natural climate variability. Patterns of this variability can be established, but it cannot be reduced or eliminated. Other uncertainties can be quantified, such as model uncertainty, but models will always only be approximations of reality, thus, they cannot fully be eliminated. The possibility of surprises (i.e., unforeseen changes in the climate system) remains. Finally, some uncertainties are extremely difficult to reduce, if at all, such as knowing the emissions pathway society will choose to take over the coming decades. Climate projections, even probabilistic ones, will therefore always be contingent on the emissions scenario selected to make those projections.

Guarding against inevitable, and in many instances worsening, extremes as the climate changes and accommodating these uncertainties thus requires particular attention from infrastructure designers. Global climate impacts that occur under global warming levels

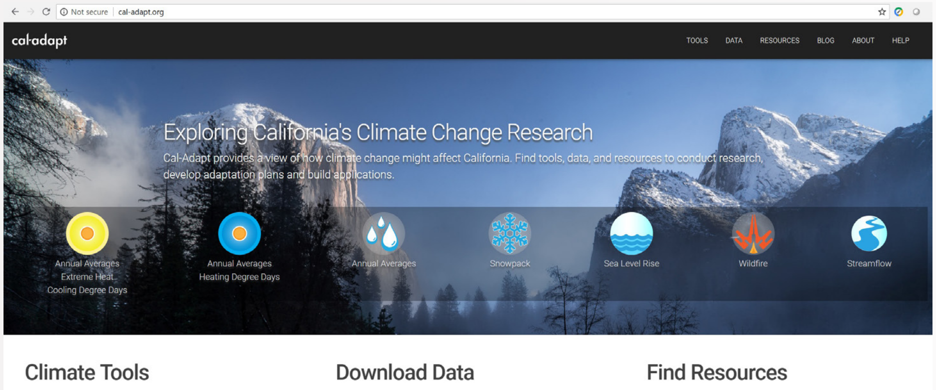
Box 2.3: Use of Climate Scenarios in California for Research and Long-Term Planning

Since 2003 California has supported the development of climate scenarios designed not only for scientific research on climate impacts and adaptation, but also to support long-term planning by State agencies[134]. California research efforts are aimed to complement federal climate research initiatives to provide insights that are more specific to California. Under direction and funding from the California Energy Commission (CEC), researchers in California tested multiple ways to translate (downscale) the outputs from global climate models to the California region at adequate temporal and geographical resolutions for practical applications[39,135]. The geographical resolution of the global climate models is roughly 100 miles, while information is needed at resolutions of 7 miles or less. Researchers used the downscaling techniques to bring the latest outputs of the global climate model runs produced for the IPCC Assessments to the California region. Under support from CEC, Scripps Institution of Oceanography developed the more recent and most advanced downscaling techniques known as Localized Constructed Analogs (LOCA)[43]. LOCA was used to develop the climate scenarios for California's Fourth Climate Change Assessment[29]. Outputs from LOCA drove a statewide hydrologic model to obtain information such as water flows and soil moisture. Recently, federal agencies adopted LOCA at the national scale and funded the application of LOCA for the nation as a whole for the 2018 (Fourth) National Climate Assessment.

The climate scenarios used in California's Fourth Climate Assessment[29] include daily maximum and minimum temperature, daily precipitation, relative humidity, wind speed, solar radiation, soil moisture, runoff and other variables. The level of geographical resolution is about 3.6 miles with daily time steps from 1950 to the end of the 21st century. The information is in the public domain and available from Cal-Adapt and other data repositories.

Since the release of the last IPCC Assessment in 2013, research groups around the world have improved their global climate models with the latest science and are running the models for the Sixth IPCC assessment cycle (2021-23). As before, under support from CEC, Scripps Institution of Oceanography is developing a new downscaling technique with improvements, such as the effects of small particles in the air, known as aerosols, on the formation and behavior of clouds and the use of an improved hydrological model. The new downscaling technique will be ready when the IPCC global climate scenarios are available, again, to develop California-specific scenarios to explore adaptation options for the energy sector and other sectors of the economy. Constant advances in science result in more advanced global climate models that should be matched by improved downscaling techniques.

In the last few years additional research groups in California have started to produce their own downscaling techniques with climate projections for different regions in California. The most notable effort is the work at the University of California at Los Angeles that has produced very sophisticated climate projections for certain periods in the future for the Los Angeles region and the Sierra Nevada. For the next California Assessment, the hope is to take advantage of these products to complement what the State is funding directly.



Source: Cal-Adapt landing page.

of, or exceeding, 3.6°F (2°C) have been described as "dangerous"[136]. California has made a policy commitment – along with many state, local, private sector and international counterparts – to work toward this target, even though the current federal administration has announced its intention to withdraw the United States from the international agreement[111, 137]; see also http://www.under2coalition.org/).

Extreme weather and climate events will continue to occur amidst an envelope of changing average conditions. Many will occur more frequently, a significant finding for infrastructure planners.

Despite this laudable commitment by California and others, it is important to note that even if all human-driven heat-trapping emissions were eliminated today, the Earth system would continue to warm because it is still reaching equilibrium with the excess greenhouse gases that have accumulated in the atmosphere over the past decades (for example, CO_2 has a residence time in the atmosphere of 100 years or more). Research suggests there are tipping points in the Earth system beyond which the global climate would enter a "hothouse" state, even if emissions continue to be reduced[138]. Thus, even under the best (but unrealistic) circumstances, further warming would occur, and sea level would continue to rise for the foreseeable future. And even under the next best (but difficult to achieve) scenario, i.e., if the global community were to meet the Paris targets, the Earth's climate and environmental conditions would continue to change, since even the most ambitious targets guarantee further emissions and warming beyond what has already occurred. The prospect of less advantageous futures, unfortunately, cannot be excluded. Given this outlook, it is accordingly prudent to consider the highest (or at least very high) warming scenarios in planning for climate change impacts to ensure the safest infrastructure possible.

In light of these trends in averages and extremes and the associated uncertainties, engineering will need a range of new approaches to ensure that safety and functionality remain viable goals. From a scientific perspective, these approaches should include scenario planning; risk-management approaches; the use of probabilities and safety factors; building-in redundancy, adaptability and resiliency; and contingency planning for when climate events overwhelm even the best engineered infrastructure.

Figure 2.6 Even if the global community were to meet the Paris Accord's targets of limiting warming to 2°C or less above preindustrial levels, the Earth's climate and environmental conditions would continue to change. But the prospect of less advantageous futures cannot be excluded. (Photo: Fremont Weir in Knights Landing, California; Florence Low, DWR, used with permission).

3 Infrastructure – The Starting Place

Overview

California's infrastructure is aging, needs increasingly more maintenance than there is funding for and – as recent extreme events and disasters or near-disasters illustrate – is already at risk and vulnerable to the impacts of weather and climate change. In this section, we discuss the current state of the infrastructure in California, with information provided by the Climate-Safe Infrastructure Working Group (CSIWG) and supplemented by additional resources such as the American Society of Civil Engineers (ASCE)'s Infrastructure Report Card and other publicly available sources.

In addition to the often-degraded physical condition of today's infrastructure, California faces significant infrastructure workforce issues. Moreover, the demand on the state's infrastructure is growing due to steady population increases: as of January 2018, 39,810,000 people lived in California, and according to California's Department of Finance, "since 2010, when the state's population was 37,253,956, population growth has averaged 333,000 a year[139].

The ASCE regularly assesses the status of infrastructure across the United States, and has found the nation's – on average, across infrastructure types – to deserve no more than a D+ grade[4]. "D" stands for "poor, at risk," which specifically translates into this overall judgement: "The infrastructure is in poor to fair condition and mostly below standard, with many elements approaching the end of their service life. A large portion of the system exhibits significant deterioration. Condition and capacity are of serious concern with strong risk of failure"[4], (p. 13).

Looking just at California's infrastructure, the state's various types of infrastructure vary from better to worse than the national average[1] (Figure 3.1). We will discuss the situation in key infrastructure sectors below but offer the ASCE's 2017 summary snapshot as an overview in Figure 3.2. The ASCE concluded its assessment with a clear clarion call to action:

> "This deteriorating infrastructure impedes California's ability to compete in an increasingly global marketplace. Success in a 21st century economy requires serious, sustained leadership on infrastructure investment at all levels of government. Delaying these investments only escalates the cost and risks of an aging infrastructure system, an option that the country, California, and families can no longer afford."[7]

Figure 3.1 California's infrastructure fares slightly better or slightly worse than the nation's, which the ASCE gave a D+ grade: poor and at risk. (Photo: Potholes in San Francisco; San Francisco Bicycle Coalition, flickr, licensed under Creative Commons license 2.0)

[1] For a nationwide comparison, see: https://www.infrastructurereportcard.org/infrastructure-super-map/.

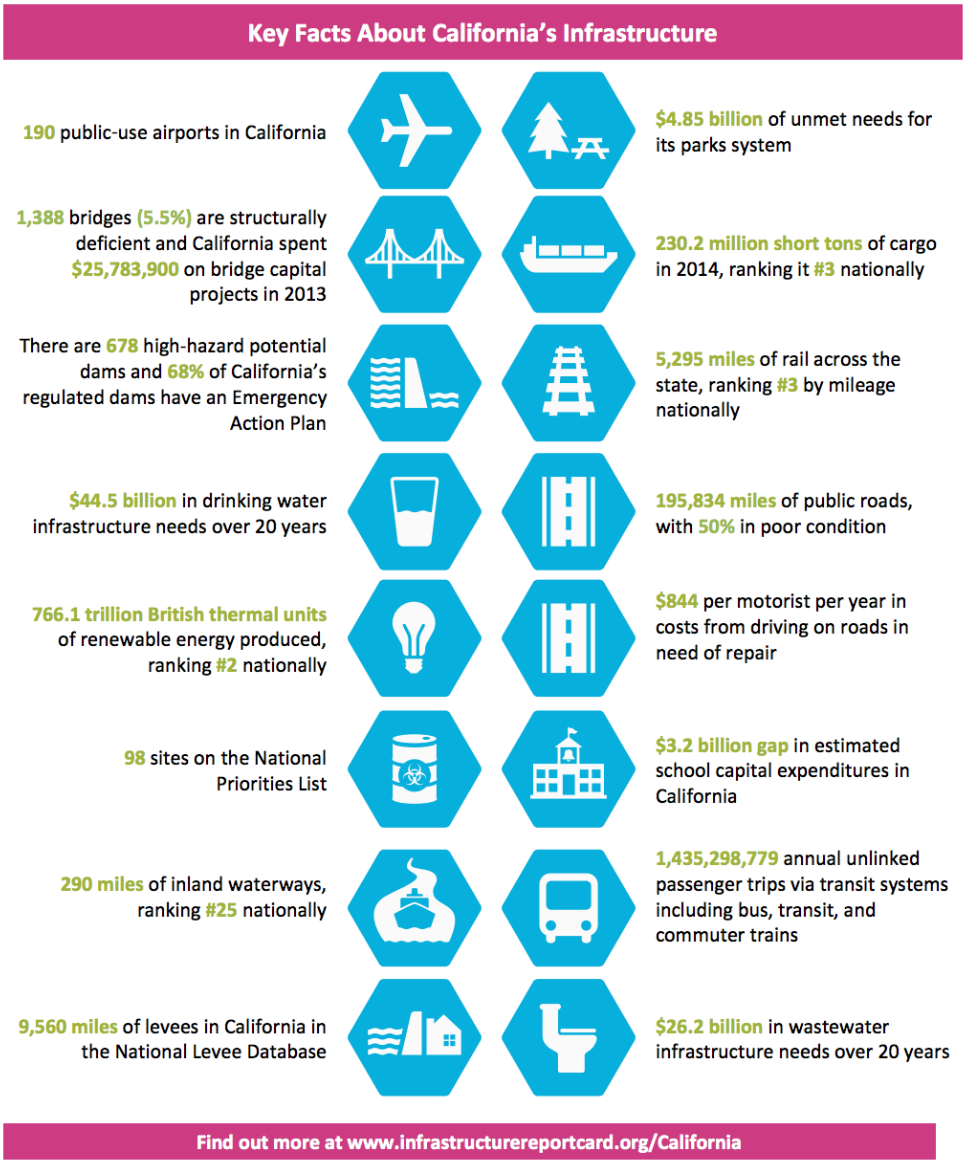


Figure 3.2 The American Society of Civil Engineers' 2017 factsheet on California's infrastructure. The state fared better in some infrastructure categories than in others compared to other states (Source: ASCE 2017[7], used with permission)

As a result of its deliberations, the CSIWG has concluded that California faces a pivotal moment at which the state's political leaders – at all levels – need to become serious about sustained leadership on infrastructure investment and commit to making it a "climate-safe" investment.

In recent years, California has begun providing this leadership, converting budget deficits to surpluses and creating significant new funding for infrastructure statewide (see Chapter 8 for detailed discussion). To fully meet the challenges ahead, to provide the basis for continued economic leadership across the nation and the world and to create a safe foundation for living and working in or visiting California, this investment will need to be sustained and even increase through all levels of government.

Below, we describe the current state of infrastructure in key sectors considered by the Working Group[2], including, where available, known threats to that infrastructure from climate change.

[2] Due to the limited time available and expertise on the Working Group, not all state infrastructure was treated in full detail, such as health or correctional facilities or parks. Some information is included in the appendices.

Rushing Toward the Future: Infrastructure in the Water Sector

California's water infrastructure consists of a complex system of dams, reservoirs, canals, pipes, pumping stations, levees and groundwater recharge facilities (Figure 3.3). One important component – the State Water Project (SWP) – is composed of 701 miles of canals and pipelines, 34 storage facilities that provide drinking water in 29 urban and agricultural water service areas for 25 million people and irrigation for 750,000 acres of farmland. It also includes Oroville Dam, the tallest dam in the US[140]. Other State-owned facilities include approximately 1,600 miles of levees, 3 main bypass systems for flood control and protection, 26 non-leveed channels, 66 flood system structures as well as DWR-operated education and visitor centers and offices[141] (Figures 3.3 and 3.4).

These facts alone about the water sector illustrate why it is important to think of infrastructure systems rather than just individual physical assets. The state's reservoirs store water and produce electricity and provide flood protection services at once. The State water agency and contractors are involved in managing the different components, and local jurisdictions must work together to manage their water resources – from the SWP and other sources – in an integrated fashion. While most wastewater systems are not State-owned, they are regulated, permitted and funded by the State Water Regional Control Board (SWRCB). Moreover, wastewater management is a critical component of keeping water supplies clean and thus the infrastructure and management of wastewater infrastructure cannot be ignored.

The water system of California in many ways is a response to the historical climate variability – seasonal, interannual and inter-decadal – described in the previous chapter. A water conveyance system was built to transport water from where it is plentiful (in the northern Sierra) to where it is needed the most (in the drier but most populous parts of southern California), with water deliveries to users all along the way. Dams and reservoirs were built to capture runoff from snowmelt and heavy rains in the wet season and to make it available to users during the dry summer months. As populations grew and supplies remained fairly constant, demand was met with increasing reliance on water recycling, water conservation, groundwater and more recently, desalinization. Even with storage capacity in reservoirs and other surface water sources, California relies on groundwater for about 40% of its water needs. According to California's Fourth Climate Assessment Synthesis report[9], "During dry years, this increases to more than half of the state's total supply and groundwater serves as a critical buffer against the impacts of drought."

As climate continues to change its historical patterns and the state population continues to grow, the existing infrastructure systems may no longer be the best suited for the climate of the future. Already, higher temperatures, declining snowpack, extended droughts and more heavy rainfall/runoff events stretch the capacity of the existing system[142]. According to the Synthesis report, "The ability of water infrastructure to withstand and rebound from climate hazards is compromised by the advanced age of existing assets, deferred maintenance, funding constraints and technological changes[143]."

Other Fourth Assessment studies reiterate previously identified vulnerabilities with the Delta levees, which are subsiding and thus are even more at risk from storms, floods and sea-level rise[144]. In coastal areas, wastewater treatment facilities – many of which are located at the lowest gravitational point, i.e., at sea level – are increasingly at risk of being compromised[145]. Other Fourth Assessment studies suggest that climate change will cause a decline in performance of the storage and conveyance system, diminish reservoir carryover storage (i.e., the amount of water available in the reservoirs before the start of the wet season in October), reduce Delta water exports, undermine drought resilience, and reduce operational control over downstream river flow temperature requirements in the future[146-148]. The experience with the recent five-year drought also revealed regulatory and administrative hurdles that resulted in inadequate flexibility and slow response time in addressing drought-stressors within the water system[149]. Another study conducted for the Fourth Assessment confirmed the challenges particularly small water utilities face in responding to climatic extremes, such as a multi-year drought[150]. Put differently, challenges

Figure 3.3 Coastal wastewater treatment facilities, many of which are located at sea level, are increasingly at risk of being compromised by flooding due to sea-level rise. (Photo: San Jose-Santa Clara Regional Wastewater Facility; Land Use Interpretation Center; licensed under Creative Commons license 3.0)

Figure 3.4 The State Water Project is a critical water infrastructure system that spans much of the state. (Source: DWR 2016[140], used with permission)

to the water system and ensuring that it is climate-safe, are not purely engineering problems, although some are. Some are regulatory, managerial and institutional, illustrating the systems approach required to address water sector challenges.

Focusing solely on the status of the physical assets, in 2012, the ASCE completed the state's second comprehensive infrastructure assessment. Even at that time, ASCE gave barely passing grades to levees/flood management (D), urban runoff (D+), wastewater (C+), and drinking water (supply) (C). These grades are roughly similar to those ASCE gave in its initial California Infrastructure Report Card in 2006, indicating little, if any, progress in improving the overall condition of California's water infrastructure over the previous six years. Regarding water supply, ASCE called out a few key issues, including aging infrastructure nearing or exceeding the end of its useful life; the vulnerability of the Sacramento-San Joaquin Delta as the "vital link" in the state's conveyance system for water depended upon by millions of Californians; continued population growth; seismic and security risks; and the unique problems posed by small water systems. Funding was an issue across all four areas of water infrastructure, with a total of $18.6 billion per year required to raise each grade by one letter.

The 2017 ASCE's nationwide report card included a number of updated facts for California's water infrastructure, suggesting that the challenges have in no way decreased and the investment need is considerable (Box 3.1).

The condition of the Delta and specifically its vulnerability to earthquakes was noted as well in the levees/flood control portion of the ASCE report card, which stated that catastrophic levee failure there could lead to a "mega-disaster" on the scale of Hurricane Katrina. With respect to flood management specifically in the Central Valley, the Department of Water Resources (DWR) issued its System Status Report of the State Plan of Flood Control (SPFC) in 2017[151]. In it, the Department evaluated the condition of the SPFC's urban and nonurban levees, channels, and flood control structures. Approximately half the levees were assessed as not meeting acceptable design criteria for a variety of characteristics (e.g., freeboard, stability, seepage), while a similar proportion of SFPC channels were found to be potentially inadequate in terms of capacity.

Box 3.1: Water Infrastructure Challenges in California

- **678** high hazard dams
- **32%** of the State-regulated dams do not have an Emergency Action Plan
- **$44.5 billion** in drinking water infrastructure needs over the next 20 years
- **9,560 miles** of levees
- **$26.2 billion** in wastewater infrastructure needs over the next 20 years

Source: ASCE (2017)[7]

Figure 3.5 The interconnected components of California's water infrastructure illustrate why infrastructure should not be understood as singular physical assets but instead as systems that provide multiple functions to many different users. (Photo: Chrisman Pumping Plant; DWR, used with permission)

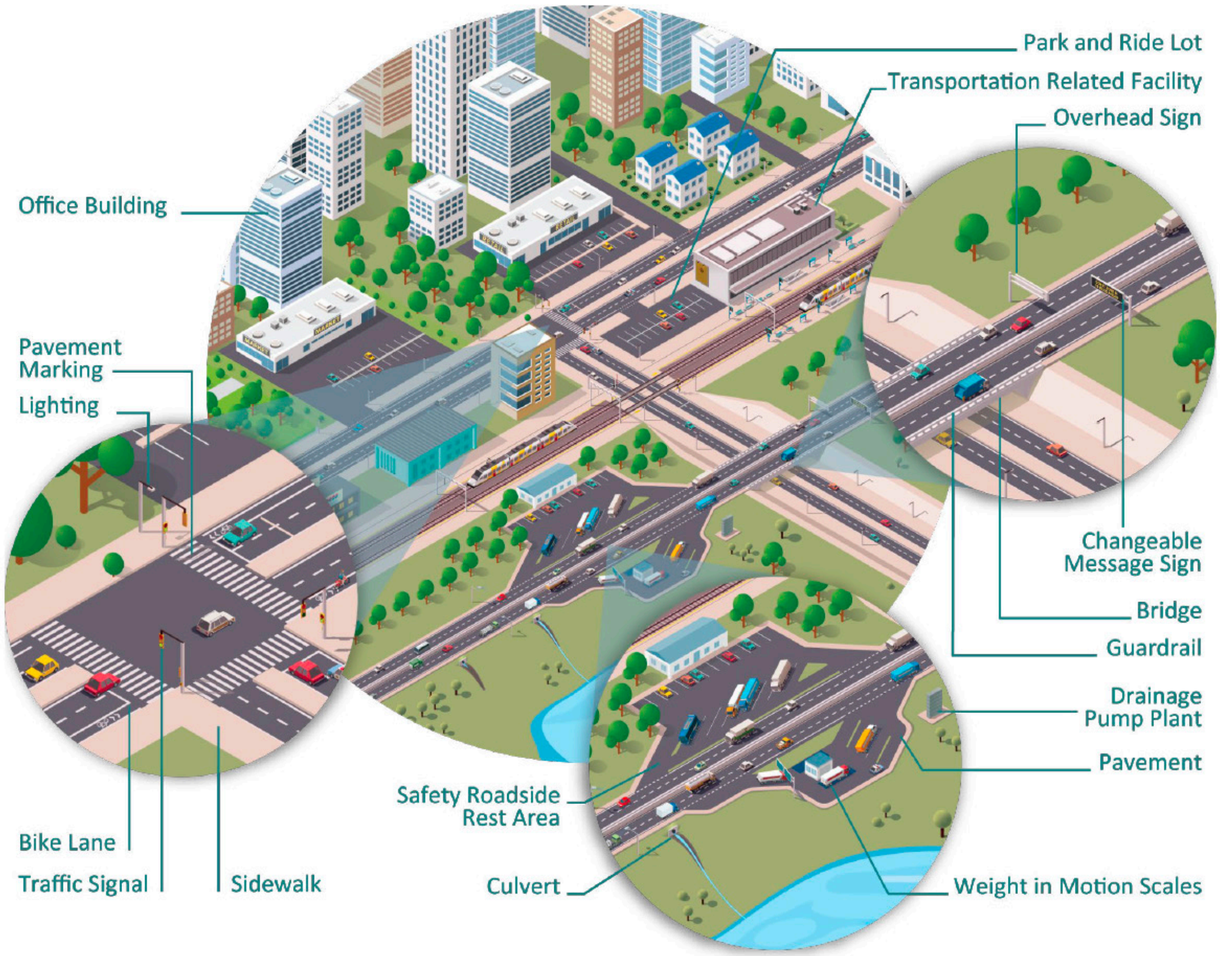


Figure 3.6 California's multi-modal transportation system faces a wide variety of threats from climate change (Source: Caltrans 2018[152], used with permission)

Mobilizing the Future: Infrastructure in the Transportation Sector

California's transportation agency, Caltrans, is responsible for multiple facets of transportation-related infrastructure including roadways, buildings, bridges, culverts, signals/ signage, safety rest areas and landscape areas (Figure 3.6). The condition of the existing infrastructure varies by type and we provide more detail on each below, but overall, the ASCE rated transportation infrastructure similarly low as the water-related infrastructure. In 2012, California's transportation infrastructure was given a low C- grade overall due to the lack of funding for operation and maintenance and new road improvements. At the time, ASCE estimated that, "There is a need for $10 billion per year more to be spent for ongoing maintenance of existing facilities and an investment of $36.5 billion in order to raise Transportation to a B grade." Additional facts about California's transportation-related infrastructure challenges were provided in 2017 (Box 3.2).

Box 3.2: Transportation Infrastructure Challenges in California

- **1,435,298,779** annual unlinked passenger trips via transit systems including bus, transit, and commuter trains;
- **$844** per motorist per year in costs from driving on roads in need of repair;
- **195,834 miles** of Public Roads, with **50%** in poor condition
- **5,295 miles of freight railroads** across the state, ranking 3rd nationally

Source: ASCE (2017)[7]

More specifically, the current situation for the different types of transportation infrastructure was recently assessed in Caltrans' own asset management plan[152] as described below.

Roadways: Caltrans is responsible for nearly 50,000 lane miles of pavement, which are exposed to various climatic stressors ranging from extreme temperatures, precipitation, wildfires, sea-level rise and storm surge. Pavements need to be replaced or rehabilitated periodically as they deteriorate from usage and climatic stresses. Per the Caltrans Transportation Asset Management Plan 2018[152], 40.8% pavement is in good condition, 53.5% is in fair condition and 5.7% is in poor condition. Caltrans has a goal per its five-year Maintenance Plan to repair 2,100 lane miles of pavement each year. In addition to maintenance of existing infrastructure, Caltrans currently constructs new infrastructure using historical climate data. However Caltrans is proactively working to develop forward-looking climate projections to assess its vulnerabilities.

Buildings: Caltrans has 13 office buildings comprising a 2.8 million square feet area, 26 equipment shops with 0.67 million square feet area, 369 maintenance stations covering a 3.67 million square feet area, and 16 laboratories with an additional 0.36 million square feet of space. Buildings are exposed to extreme temperatures and wildfires, which can lead to smoke hazards and power failures, and to extreme precipitation.

Bridges: Throughout the state, Caltrans is also responsible for 13,160 bridges which add up to 245 million square feet deck area. Bridge decks are exposed to temperature extremes resulting in stresses in joints and decks, extreme precipitation leading to higher velocities/scour on the bridge support structures, higher water surface elevations which could threaten the integrity of the bridge. Again, per the Caltrans Transportation Asset Management Plan 2018[152], 74.9% bridges are in good condition, 21.8% are in fair condition and 3.3% are in poor condition. Bridges requiring maintenance have a backlog exceeding 1,100 bridges and the Caltrans goal is to reduce the number of bridges requiring maintenance to below 1,100 bridges on an annual basis.

Culverts: There are about 205,000 culverts along state highways. Statewide, 65% of all culverts are considered to be in "good" condition, 23.5% are in fair condition, and 11.5% are in poor condition[152]. The more than 23,000 culverts in poor condition need to be replaced or rehabilitated. Culverts may be exposed to scour from coastal storms, wildfires, mudslides, and extreme precipitation events resulting in roadway overtopping, etc.

Signals & Signage: Thousands of signals and signs on state highways are susceptible to extreme weather events. Maintaining them in good working condition is critical to ensure proper traffic flows. Impacts from climate change and extreme weather events may include power failures, structural damage and functional failures.

Safety Rest Areas: Along California highways, Caltrans manages 0.24 million square feet of area and 86 rest areas. Per the Caltrans Transportation Asset Management Plan 2018, 32.6% rest areas are in good condition, 38.4% are in fair condition and 29% are in poor condition[152]. Rest areas are susceptible to extreme weather and wildfires, which could lead to power failures, flooding, smoke, failures of charging stations and failures of leach fields.

Landscape Areas: Finally, Caltrans is responsible for about 30,000 acres of landscaped areas within the right-of-way. While these areas could be susceptible to wildfires, extreme precipitation and temperature events, there is also a potential to utilize these areas as mitigation for various climatic stressors such as detention/retention for higher precipitation, greenhouse gas mitigation, rock landscaping to create fire barriers, locations for renewable energy for signals and rest areas.

Railroads: While not State-owned, railroads comprise an important part of California's transportation system and they are vulnerable to climate change. Extreme heat and cold can potentially cause a buckling of railroad tracks resulting in train derailments. As average temperatures are expected to increase (up to 100°F in some regions of the state by the end of the century under the high-emissions scenario, RCP 8.5), buckling of railroad rails (sun kinks) is expected to increase. In June 2017, a train derailment in Tulare County was caused by extreme heat, buckling the track between Delano and Earlimart along Highway 99. Nineteen cars belonging to Union Pacific derailed after the track warped in the heat (Figure 3.7).

Figure 3.7 Extreme heat can cause buckling of railroad tracks and lead – as in this example from Tulare County in June 2017 – to derailment. (Source: California Department of Fish and Wildlife, used with permission)

Union Pacific owns, operates and maintains approximately 3,400 miles of railroad tracks in California. One mile of non-constricted rail can contract or expand more than 2 ft in extreme weather. Steel rail is tempered and anchored during installation to improve the integrity of the infrastructure. But more frequent extreme temperatures as expected in the future require additional maintenance programs to inspect and repair any potential problems with the tracks[153].

Recognizing these potential challenges, Caltrans has launched a systemwide effort to assess its vulnerabilities to the impacts of climate change; this work is currently underway in addition to the agency's ongoing implementation of emission reduction and sustainability measures[154]. Impacts are already becoming evident, however. For example, the growing incidence of wildfires has had a cascading impact on transportation ranging from direct failures of infrastructure from fires to failures of infrastructure from subsequent mudslides. Fires in the El Dorado National Forest resulted in temporary closure of State Routes (SR) 50, 193 and 49 in El Dorado County on several occasions. Winter storms following the summer fires resulted in mudslides washing out segments of SR-50 and other highways in the region. Wildfires alongside SR-101 also resulted in devastation of roadways, plastic culverts and bridges, temporarily inhibiting access to local communities.

Meanwhile sea-level rise (SLR) is impacting segments of coastal highways (SR-1, SR-37, etc.) as well as airports (San Francisco International, Oakland and San Jose), sea ports and docks (see below). Coastal protection measures in the form of levees and seawalls would need to be incorporated into designs to counter the projected SLR by 2100.

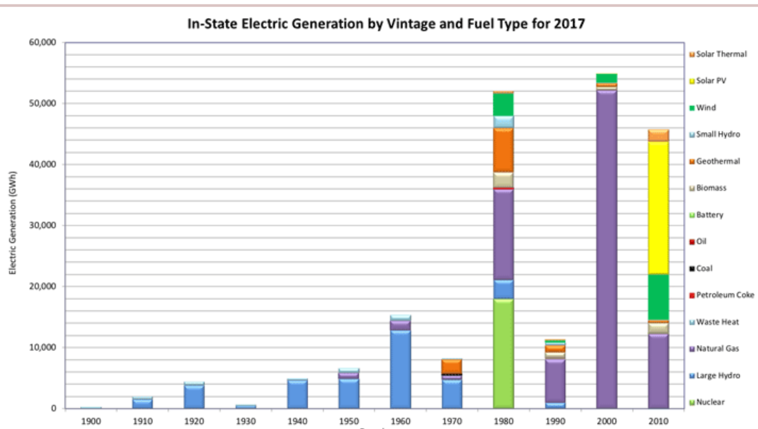


Figure 3.9 California's energy is generated in diverse types of power plants. This graphic shows the type of power generation by decade when it was built, indicating that a significant number of power plants are more than 50 years old by now (Source: CEC 2018[159], used with permission)

Energizing the Future: Infrastructure in the Energy Sector

Energy-related infrastructure in California is either publicly or privately owned, but State-regulated. It can be classified as falling into two major categories: electricity-related infrastructure and fuel-related infrastructure.

Electricity-Related Infrastructure

As of 2015 there were 66 thermoelectric power plants operational in California[155]. In addition, California has two functional nuclear reactors as of 2017 (Diabolo Canyon 1 and 2)[156]. California also had 344 hydroelectric power plants and 111 wind energy power plants in operation in 2017[157]. In-state solar photovoltaic and solar thermal generation reached 24,331 GWh that same year[158].[4]

Electricity generation takes place in plants of varying age, some now more than 100 years old, many more than 50 years old (Figure 3.10). Increasingly, energy production is adding distributed energy generation (solar roofs etc.).[4]

A highly interwoven net of transmission lines connects these power generation plants via substations to millions of users (Figure 3.10). According to the California Public Utilities Commission (CPUC), which has ratemaking and/or permitting authority over this infrastructure (built, owned or leased by private investor-owned or publicly-owned utilities), "Significant new infrastructure investments are required in order to support the state's transition to a low-carbon energy infrastructure. To realize these goals, including bringing renewable energy from remote areas of the state to urban load centers, new transmission lines have been planned and built. At the same time, significant investments to improve distribution level infrastructure are required to improve the safety, delivery and reliability of electricity and gas"[160].

Several contributions to the Fourth Assessment have specifically investigated climate change risk to the energy sector's electricity-related infrastructure. They illuminate the following risks described below.

[4] Because there is no energy generation reporting requirement for solar PV smaller than 1 megawatt, many residential and small commercial building solar installations are not captured in this figure[158].

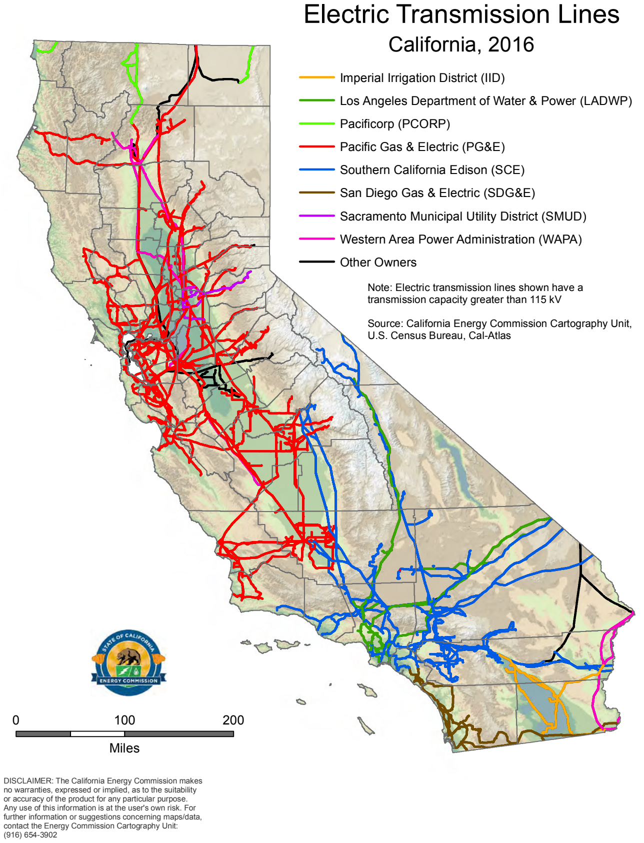


Figure 3.10 A deeply interwoven network of transmission lines connects California's power plants via substations to millions of electricity consumers. (Source: CEC 2016[161], used with permission)

Wildfire risks to the electricity's transmission and distribution grid is expected to grow. One study showed that between 2001 and 2016, a relatively small number of wildfires caused much of the damage that occurred to California's electricity grid with an estimated cost of these wildfires exceeding $700 million[162]. The study also found that the fire threat to the electricity grid in the urban fringe around Los Angeles and San Diego is presently highest but will grow fastest to the Northern California grid and that the total cost of wildfires could be 10-15 times larger than that to the grid alone.

Sea-level rise (SLR) and associated risks in San Diego Gas & Electric Co.'s (SDG&E) services territory can have cascading effects. The study explored SLR-related risks to electricity sector assets and potential impacts to customers. Using a USGS model (CoSMoS) to investigate tidal inundation, extreme (100-year) storm events and coastal erosion associated with SLR of up to 2.0 m (6.6 ft), they find that direct risks to assets are dominated by substations in low-lying areas such as San Diego Bay and Mission Bay[163]. Potential impacts associated with other assets such as underground duct banks and pole-mounted transformers would more likely come in the form of increased maintenance and repair costs rather than widespread service disruptions. Based on a low-probability, high-consequence scenario of a two-week power outage in areas served by exposed sub-stations, they find a range of $2B to $25B in economic impacts from service disruption to thousands of customers. Beyond these damages, interconnections with critical systems such as sewage pumping stations, hospitals, airports and ports could result in additional substantial impacts if they lost power. (The impact of a coincident fuel supply disruption to keep back-up generators running was not assessed but would likely drive the economic impact even higher.)

Extreme heat risks to the Los Angeles electricity grid is exacerbated by population growth. Burillo and colleagues[164] examined how increases in temperature, especially extreme heat, population growth, air conditioning penetration and changes in energy policy might affect energy demand, resource adequacy and component overloading in L.A. County. They found that "long-term service reliability is more susceptible to population growth and changes in technology than rising air temperatures due to climate change." However, "substations in the East El Monte and Pomona area were projected to be at risk of automatic outages (load factor ≥2) by 2040, which could be avoided with 200 MW of distributed solar PV and storage on the Chino and Walnut 220/66 kV systems. Calabasas to Malibu were identified at next highest risk, and lastly the southern Foothills, Pasadena, Alhambra, and East LA regions, as well as any in-basin neighborhoods that would experience population growth are also at risk of excessive loading."

Long-distance and cascading impacts from climate impacts on Los Angeles' interconnected lifeline system. Moser and Finzi Hart[165], in their first-of-its kind investigation for L.A., examined cross-sector interrelationships among infrastructure sectors and long-distance connectivity, particularly via the electric grid, which can translate extreme events occurring far away to potentially serious impacts in the L.A. metro region. The authors noted that the greatest risks from these teleconnected and cascading events not only arises from the mutual dependence of infrastructure sectors on other sectors' reliable functionality and services but from lack of cross-sectoral coordination and planning for extreme climatic events, including lack of integrated adaptation planning.

Oil and Gas-Related Infrastructure

Transportation fuels and the transmission of natural gas across the state require their own infrastructure. According to the California Energy Commission (CEC)[166], "One third of energy commodities consumed in California is natural gas. The natural gas market continues to evolve and service options expand, but its use falls mainly into four sectors – residential, commercial, industrial and electric power generation. In addition, natural gas is a viable alternative to petroleum for use in cars, trucks and buses."

In order for oil and gas to reach consumers, the state uses a largely north-south-oriented network of pipelines that crosses the state to transport natural gas. In addition, the state hosts 17 refineries, most of them located near waterways as most inputs to refineries are delivered by ocean-going vessels[167]. According to Radke and colleagues, "Refineries have long life cycles, which means that oil organizations have a tradition of investing and upgrading existing facilities rather than constructing new ones [...]. Because of permitting issues, low profit margins, and competitive markets, it is improbable that there will be any new refinery construction in the country" [or in California], as ten refineries in the state have already been closed between 1985 and 1995[168].

Again, several contributions to the Fourth Assessment focused on climate change impacts on the fuel sector.

Multiple risks from climate-related impacts to the natural gas sector in SDG&E 's service territory. Although the natural gas system in SDG&E territory is generally considered not very vulnerable to flooding, wildfire, and extreme heat hazards, Bruzgul et al.[169] noted that impacts from costs and staff time associated with restoration of service connections after fire events could be substantial; extreme heat could result in accelerated wear and tear on, and increased cooling costs for, compressor equipment; disruption to a singular transmission line between Los Angeles and San Diego – the sole source of gas service for more than 2,000 customers – is the most notable potential exposure to coastal hazards; and cathodic protection to mitigate vulnerability of pipelines in coastal areas at risk from inundation and saltwater intrusion may or may not be sufficient[5]; and, finally, water crossings are thought to be the most vulnerable pipelines to inland and coastal flooding. With at least 32 aboveground pipelines attached to or under bridges at water crossings, Southern California Gas Company recognizes (and is currently studying) risks related to scour, debris flow and buoyancy associated with flood events.

A separate, but related relevant Risk Assessment and Mitigation Phase (RAMP) report[6] by Sempra notes that the succession of extreme events as recently experienced in California – drought, followed by wildfire, flooding and mud/landslides – can cause serious damage to access roads and result in multiple exposures of high-pressure pipelines, including the risk of pipelines failing. Multiple-year projects are required involving extensive permitting and repairs to restore the infrastructure with millions of dollars in costs[171].

Wildfire and flood risks to the transportation fuel sector. Radke and colleagues[167] undertook the first-ever attempt to consider weather-related risks posed to California's transportation fuel system as a physically and organizationally connected, multi-sector network. Specifically, the research team explored wildfire- and flooding-related risks and how these risks may intensify under a changing climate. To engage transportation fuel system stakeholders, Radke et al. found that very fine (asset-level) resolution of 5-30 m is necessary to ground discussion of risks of potential disruption to operations and impact on assets. In particular, in the case of wildfire, fire behavior/intensity and consequent defensibility of assets can only be resolved by very fine-scale fire behavior models.

Subsidence and flood overtopping risks to natural gas infrastructure in the Sacramento-San Joaquin Delta. In a delta-wide update to a 2007 study of subsidence rates, Brooks and colleagues examined flood overtopping potential to the levees surrounding the islands in the interior of California's Sacramento-San Joaquin Delta. They found average subsidence rates of ~1-2 cm/year (range: 0-5 cm/year), with significant small-scale variation, including near some pipeline crossings[144]. They estimated that – depending on how fast sea level will rise and how extreme storm events (e.g., the 100-year flood) will change – Federal levee height standards (PL84-99) could be exceeded by ca. 2060 (under the fast sea-level rise scenario) or by 2080 (under the slower sea-level rise scenario), with some places projected to exceed thresholds by ~2050. At that point, the safety of natural gas pipelines could no longer be guaranteed.

[5] Radke et al.[170] note that in 2007, more than two years after Hurricane Katrina, replacement of 486 km (302 miles) of cast iron and steel pipelines with high-density polyethylene was initiated out of concern for corrosion damage associated with extended exposure to saltwater.

[6] The RAMP is the Risk Assessment and Mitigation Phase filing required of Investor-Owned Utilities (IOUs) to be submitted to the California Public Utility Commission (CPUC) with General Rate Cases (GRCs).

Building the Future: Infrastructure in the Building Sector

Figure 3.11: The building sector exemplifies the challenges of variable building stock, deferred maintenance, construction delays and cost escalation, as well as housing cost and shortage. (Photo: Downtown San Diego, Michael Seljos, flickr; licensed under Creative Commons license 2.0)

State-owned, -funded and -operated infrastructure in the building sector fall under the purview of the Department of General Services (DGS) unless directed by statute to other specific agencies.[7] DGS is responsible for buildings in the following categories of structures:

- Design and construction oversight through the Division of the State Architect for 72 Community College Districts (with 114 campuses and 244 construction projects underway in 2017-2018 for a total construction cost of $1.43 billion);
- Design and construction oversight through the Division of the State Architect for 1,084 K-12 School Districts (with 9,292 campuses and 3,119 projects in progress in 2017-2018 for a total construction cost of $6.83 billion)[8];
- Design and construction oversight through the Division of the State Architect for a variety of "essential service" buildings such as California Highway Patrol (CHP) facilities and communication towers (with 7 projects in 2017-2018 for a total construction cost of $8.03 million) (see also Widom webinar, based on submissions to the Division of the State Architect and estimates received from the Real Estate Services Division).
- Design oversight through the Division of the State Architect and relating to accessibility requirements for various state facilities including CSU, UC and Courts (for a total of 392 projects with a construction cost of $2.77 billion).
- Design and construction through the Real Estate Services Division of a variety of office and service facilities (with approximately 450 projects for a total cost of projects under construction of approximately $1.5 billion. This does not include projects in the design process which could be as high as $3.5 billion at any specific time.)
- DGS also provides other State agencies with partial building management services, serving approximately 200 State-owned buildings, such as the California Department of Corrections and Rehabilitations' leased building portfolio, selected health facilities and so on.

The challenge of a variable building stock. Each year, new construction in each of these areas adds to the existing non-residential building stock in California. This new construction varies depending on economic conditions but is a small fraction of existing buildings in the state. Nearly half of the non-residential buildings in California were built prior to adoption of the first Title 24 energy standards in 1978. Title 24 aims to address the energy use in buildings, which is principally driven by the quality of the building envelop, i.e., the degree of insulation of walls, roofs and windows. Modern building approaches that use structural insulated panels, insulated concrete forms, double-stud walls, or advanced framing can all produce more energy-efficient buildings than traditional framing methods. In older buildings, the latter approaches are common.

To compensate particularly for high heat during the hot summers, building occupants commonly use air conditioners whose energy usage is also governed by the Title 24 codes.[9] As of 2010, central air conditioning saturation in California was 45% for Low Income households (<$25,000), 53% for Moderate Income households ($25,000-$74,999) and 61% for High Income households (>$75,000)[172].

Inclusion of climate-related measures in the construction of new buildings will require, at a minimum, clearer design standards and tools as well as code requirements. Inclusion of climate-related measures in existing buildings will require that and more. For example, after Hurricane Katrina, building designers felt it essential to develop design guidelines to ensure buildings continue to provide a safe and comfortable living environment even when there is no electric power available due to a natural disaster[173, 174]. This focus on passive envelop designs – whereby buildings can maintain human comfort conditions without power – is increasingly important in the face of

[7] Many other buildings and facilities are built and operated by different departments (such as emergency response, fire or law enforcement facilities) and are not discussed here, even though challenges and opportunities may be similar.

[8] Incremental projects not included. Note also, while the State provides some construction funding, at this time the majority of funds come from local bonds.

[9] Air conditioning penetration varies by climate region. For example, in coastal and mountainous regions, air conditioning is still less prevalent than in other inland areas.

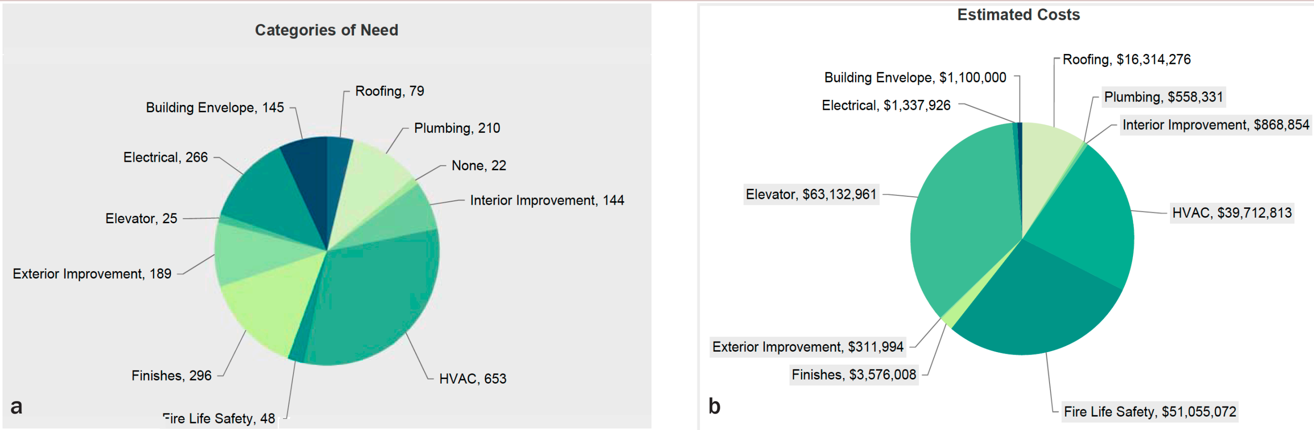


Figure 3.12 (a) California's Department of General Services estimates of the number of projects within DGS-managed buildings that fall under its deferred maintenance program. Many would improve energy efficiency, generate energy savings, and improve building occupants' health and well-being. (b) The estimated cost of a range of deferred maintenance projects (a low estimate). (Source: DGS Facility Management Division Deferred Maintenance Program for FY 2017/18; used with permission)

climate change and related extreme events in California, where summers and inland areas can reach well into the 100's°F. Other states have already incorporated building survivability guidelines in their codes (e.g., New Jersey[175]).

The challenge of deferred maintenance. Among the DGS-owned and -managed buildings alone, there are currently 224 roofing and building envelope projects seeking a total of $17.5 million of deferred maintenance needs that – if left unaddressed – will contribute to the degradation of the existing buildings with the accelerated effects of climate change. Demolition of the existing buildings and the carbon produced in the course of replacing buildings add considerable greenhouse gas emissions. Avoiding these consequences will have a positive benefit to both the current building occupants and the State's commitments to reducing the unnecessary contributions to carbon emissions.

Moreover, there are currently 653 heating, ventilation and air conditioning (HVAC) projects in DGS-owned and -managed buildings, seeking $39.7 million in deferred maintenance funds. Poorly operating HVAC systems require additional energy to maintain and contribute to the releasing of refrigerants (i.e., ozone-depleting substances that are also powerful greenhouse gases) through leaking equipment. The funding for properly retrofitting and/or replacing these systems would help reduce the state's energy use, remove sources of refrigerant releases and help reduce the state's carbon emissions.

According to the Deferred Maintenance Program for DGS-managed buildings, in addition to HVAC projects, there are significant existing needs (Figures 3.12 a-b). The estimated costs are considered low.

Significant progress in incorporating both climate mitigation and climate adaptation measures in California buildings must address the barriers associated with retrofitting existing buildings. Some of the key barriers include the following:

- The absence of a trigger that would drive a building owner to initiate a climate-related retrofit (i.e., there is no regulatory requirement to make an improvement);
- Higher costs associated with retrofitting a building versus incorporating measures in a new design (this is not always the case however while it might be less expensive on a particular element (replacing window glazing vs. new glazing, the cost of completely modernizing a facility (down to the shell and core) could be less expensive);
- Challenges in selling bonds; and
- Disruption to current building tenants during retrofits/construction.

The challenge of delays and cost escalation. In addition to DGS-owned and managed buildings, there are many more State-owned buildings (e.g., court houses, correctional facilities, Department of Motor Vehicle facilities), which are owned by their respective agencies and have their own needs for upgrades. Funding for resiliency across the entire building sector is especially impacted by the escalation of construction costs over time. Between December 2017 and April 2018 alone, the average cost of construction for K-12 and community colleges' construction was $1.0 billion per month alone and cost increases month-to-month were substantial. Construction cost escalation in California is currently estimated at anywhere from 5-10% annually. Assuming a major infrastructure project that costs $100,000,000, a monthly delay at 5% amounts to a loss of over $415,000 per month (Widom, pers. communication).

The inability of decision-makers to move swiftly on projects and for designers and contractors to rapidly build has a direct impact on a resilient society, even when the initial project includes all of the elements necessary to be climate safe. When construction is delayed, costs increase and building owners tend to eliminate "non-essential" elements from the designs to keep the costs in check. "Non-essential" sustainability or resilience-related features – i.e., non-required elements – are thus often the first things to be "value engineered" out of building projects.

The current situation – as described here – illustrates the costly uphill battle faced by the building sector in California to upgrade existing structures and build new ones. Deferred maintenance, construction delays, escalating costs and the more limited possibilities of preparing for future climate conditions through retrofitting of existing buildings illustrate the difficult starting place from which to transform toward a climate-safe building stock. The prospect involves both cost and political challenges.

The challenge of housing cost and shortage. Even without climate change, the building sector would need to add significantly to the building stock over the coming decades. Cost of housing is currently at crisis levels in some parts of the state, as is the concomitant rise in homelessness. Population growth is expected to continue, which implies that in addition to just maintaining and upgrading the existing building stock, the demand for more housing continues and is magnified in the near-term by the loss of many thousands of housing units during the recent California wildfires and subsequent floods and landslides, and in the longer-term an increasing demand for public facilities and school and university buildings to accommodate the growing number of students.

Ports, Airports and Telecommunication

While not State-owned and funded, some types of infrastructure, such as ports, airports and telecommunications-related infrastructure, are critically important to the state's functioning and economy, and often these types of infrastructure are co-located with and deeply inter-dependent on other State-owned and -managed infrastructure (Figure 3.13). We thus include them here, although a detailed assessment could not be completed in the context of the CSIWG's deliberations.

California has 190 public-use airports, rated as C+ in the ASCE's 2012 report card[176]. The state's 11 large- to moderate-sized ports were rated slightly better at B- in that same year, an improvement since the first rating. Both are critical economic engines for the state and link to the state's highway and rail system, thus serving as essential parts of the goods and people movement within and beyond the state. The CSIWG heard from the San Francisco and San Diego port as well as from the San Diego airport during its deliberations. The latter can be seen as a model for infrastructure modernization, and other ports and airports in the state have begun assessing their risks from climate change and developing adaptation plans – an indication that the owners of these important types of infrastructure recognize the need for ongoing sustainability and resilience-related improvements.[11]

Figure 3.13 Ports, airports and telecommunications infrastructure – while not State-owned – are critically important to the state's functioning and economy. Many of these infrastructure systems are increasingly at risk from flooding, sea-level rise, wildfires and other extreme events. (Photo: San Francisco skyline and Port of Oakland, Tony Webster, flickr, licensed under Creative Commons license 2.0)

Table 3.1: Selected California Airport Land Area Exposed to Sea-Level Rise Currently and by the End of the Century

Port (Enplanement area)*	2000 - 2020	% Area	2080 - 2100	% Area
San Francisco (25,707,101; 3.54 km^2)	0.84 km^2 (0.33 mi^2)	~24%	2.28 km^2 (0.89 mi^2)	~64%
Oakland (5,934,639; 7.18 km^2)	0.09 km^2 (0.04 mi^2)	~1%	3.66 km^2 (1.43 mi^2)	~51%
Los Angeles (39,636,042; 14.09 km^2)	0.4 km^2 (0.16 mi^2)	~3%	2.64 km^2 (1.03 mi^2)	~19%
Long Beach (1,386,357; 13.91 km^2)	2.39 km^2 (0.93 mi^2)	~17%	4.94 km^2 (1.95 mi^2)	~36%

* Enplanement is the number of commercial passenger boardings per year (status 2017), a figure used here to indicate the importance of the airport; airport land surface areas, pers. communication, J. Radke (2018). (Source: Adapted from Bedsworth et al. 2018)[9]

In fact, one study in the Fourth Assessment[167] illustrates why it is critical for these infrastructure operators to pay close attention to the emerging climate science. Many of them are located on flat land at or near sea level and already experience flooding during extremely high tides and storms. These challenges will increase as sea level rises (Table 3.1).

The need to address this growing flooding risk varies from airport to airport and what types of infrastructure are impacted first. While San Francisco and Oakland are already experiencing occasional flooding, Santa Barbara airport is expected to see flooding in the 2020-2040 period, San Diego not until 2060-2080[167]. Another recent study of the Los Angeles International Airport, according to the Fourth Assessment synthesis report, concluded that "no major upgrades are necessary at this point, but that the situation must be reassessed every time a major upgrade of this port takes place. Implementing adaptation measures in coordination with major facility upgrades would lower costs substantially and, in addition, new scientific information could inform the design of specific adaptation measures."

Telecommunication is not rated by ASCE, thus we have little information on the status of that infrastructure sector. The sector was also not represented on the CSIWG. The reason is that communication-related infrastructure (e.g., telephone poles and lines, data storage centers, cell towers) is typically privately owned and only minimally regulated in California by the CPUC. One study conducted as part of the Fourth Assessment, examined interconnected lifelines and noted the criticality of communication-related infrastructure and the challenge of integrating private sector entities into lifeline emergency response, recovery and adaptation planning efforts[165]. Participants in that study noted that some large data storage centers are located in flood-prone areas ("the cloud is in the ground") – a risk confirmed by a recent independent study[177] – and that cellphone towers and telephone poles are at risk to wildfire. Rules pertaining to rebuilding after disaster inhibit or disfavor adaptive switching to more robust materials, as we will discuss in later chapters.

[11] This can be tracked for various port and airports (as well as other facilities) at the Sea-Level Rise Database developed under AB 2516 (Gordon), available at: http://www.opc.ca.gov/planning-for-sea-level-rise-database/.

Old (But Still Prevalent) Perspectives and Ways of Doing Things

The physical status of infrastructure is only one of the starting conditions for considering the integration of forward-looking climate science into infrastructure planning and design. The people and organizations that plan, design, build, operate and maintain infrastructure – how they think about their work and whether there are sufficient numbers of them available – are also crucial. Thus, we close this section by pointing to a number of issues that cut across infrastructure sectors that affect what is being done now and what the starting point for investing in a climate-safe future looks like, namely: 1) the reasons why climate safe infrastructure requires new ways of managing risk and uncertainty and 2) the status of the workforce and human capital that together affect how infrastructure is built.

Beyond stationarity. Across all the sectors discussed above, one thing unites them. Engineers (including the "engineers of buildings", i.e., architects) traditionally design infrastructure to standards that are based on experimental data, such as the strength of specific materials or designs, historical conditions, such as observed rainfall or streamflow patterns, and historical trends projected into the future, such as population growth (see below). It was generally assumed that climate was stationary, meaning that the statistics of climate averages and extremes remained unchanged over time. In California, as well as many other places in the U.S. and worldwide, infrastructure designed today will need to perform in a future that will change in ways we cannot predict with accuracy. Engineers' and architects' professional code of ethics demands that structures perform to societal expectations of safety and well-being even under changing climate conditions. In fact, climate conditions are and will continue to deviate from the past. Past trends no longer will reliably continue as non-linear thresholds are approached (such as ecological conditions or demand for transportation influenced by new technology such as autonomous vehicles)[178-181].

Infrastructure designed today will need to perform in a future that will change in ways we cannot predict with accuracy.

The traditional reliance on observations and past trends is partly codified in existing infrastructure standards and associated liability norms, partly the result of traditional ways of educating engineers and architects, and partly a relic of a time when the climate was relatively stable. But for infrastructure to be climate-safe in the future, it needs to be designed to new tolerances, while recognizing that the various sources of uncertainty (discussed above) make it not always clear what degree of protection (or tolerance) will be needed. This will require a transition away from designing for static risks, e.g., the 1 in 100 storm event, to designing for dynamic conditions that may change in the future. We will return in Chapter 4 and 5 to the barriers these old ways of thinking and doing things create and suggest ways forward.

From individual structures to whole systems. The Working Group also agreed that infrastructure is more than individual physical structures such as a seawall, a water pipe, a stretch of road, a transmission line or a building. The CSIWG felt strongly that threats to infrastructure – and possible solutions – should instead be assessed through a systemic lens, using multi-disciplinary analyses that recognize the impacts of risks on infrastructure and people, and on human interests and the environment, and thus meaningfully engage and integrate the perspectives of all affected stakeholders.

Confronting a more complex and interconnected future. Infrastructure planners are used to considering future population growth as an important input into assessing future use or demand of infrastructure and the cost-benefit value of building or expanding infrastructure. In the past, to do so, historical trends were simply linearly extended several decades out to conduct such assessments. But climate change may very well cause demographic (and underlying economic) shifts that complicate this old way of doing things. For example, increased coastal storm-related and increasingly frequent nuisance flooding may cause people to move away from immediate shoreline areas[182-184], while intense inland heat may drive people toward cooler coastal regions to avoid heat-related health risks[185, 186]. Non-climatic forces such as changes in economic opportunities, affordability of housing or the attractiveness of certain areas for cultural or environmental regions may further complicate the movement of people. This migration, together with changing behavior, would determine the future economic value of different forms of infrastructure. And this, in turn, means that the economic value of making infrastructure more climate-safe depends on both projected climate risk faced by the infrastructure and its projected usage.

More constraints on and new opportunities for infrastructure systems. Over the course of the 20th century, engineers transformed California, building vast infrastructure systems to serve a population that grew over twenty times larger, from 1.5 to 34 million people.

Today's engineers will also shape California but face a new and difficult set of constraints. For example, funding for infrastructure is limited as decision-makers are faced with challenging trade-offs. This can restrict the ability to manage uncertainty with large safety margins. Moreover, environmental concerns have become more prominent and significant. And infrastructure systems must serve a diverse population equitably. Much of the land surrounding particular infrastructure projects is bespoke for private and public uses. Concurrently, rapid advances in technologies such as information, materials and artificial intelligence open up new possibilities for providing infrastructure's services. Engineers must also reckon with California residents' varied views on how to balance among these constraints and opportunities, how to use and live around infrastructure and their demands to have their voices heard.

The economic value of making infrastructure more climate-safe depends on both projected climate risk faced by the infrastructure and its projected usage.

Consider the specific example of a highway along the California coast. The key climate change concern is flooding risk due to higher storm surges as well as more frequent nuisance flooding as a result of climate change-driven sea-level rise. Projected usage of that highway in the future will depend on a) how many people live along that stretch of the coast, b) how much these residents use the highway, and c) how much it is used by non-local, longer-distance travelers for commuting or tourism. The drivers of where people live and how they use infrastructure are not well understood. This makes forecasts of usage challenging in the face of both economic and climate uncertainties. And if climatic, economic and demographic shifts are not enough yet to complicate preparing and planning for the future, profound changes in technology – as expected for example in the transportation and energy sectors – and related changes in performance of technology all create additional opportunities and uncertainties. More research is needed to understand the relationships among these factors empirically and to develop more accurate forecasts for the future.

Infrastructure planners in the past certainly considered the future and managed risks. But the future looks more uncertain now than it used to be. Financial, social and environmental pressures impose additional demands on risk management. Technology opens up new but also uncertain opportunities.

In short, infrastructure engineering will have to go through significant shifts in thinking and in the tools and approaches traditionally used (Box 3.3) to assess robust options and make decisions under conditions of deep uncertainty. We will return to those approaches and tools in later chapters.

The present and coming workforce crisis. California[187], like the rest of the United States[188-193], faces a well-documented "high risk" workforce challenge in all critical lifeline infrastructure sectors, including large numbers of retirements, lack of succession planning and consequent loss of institutional knowledge and experience; large numbers of unfilled vacancies with appropriately skilled employees, ongoing and emerging skills gaps and rapid deployment of new technologies. The problem of an aging workforce and inadequate investment in workforce development is worst in the transit sector[188, 190, 191]. Moreover, the representation of minorities and women in the engineering workforce continues to seriously lag behind (Figure 3.14). This systemic problem of lacking "people-readiness" stems from inadequate attention to "human assets" and directly impacts infrastructure safety, reliability, overall performance and productivity. Making up for the past lack of infrastructure investment, bringing up the ASCE's low grades to adequate and modern standards, much less making the additional investment to build climate-safe infrastructure cannot succeed, even if all the climate science in the world were readily available, without an adequately-sized and adequately-prepared workforce. We will revisit this serious issue in Chapter 9.

Figure 3.14 California – like the rest of the United States – faces a well-documented "high risk" workforce challenge in all critical infrastructure sectors. (Photo: Engineers at Folsom Lake, US Army Corps of Engineers)

Box 3.3: Traditional Ways of Designing Infrastructure in the Face of Uncertainty

Engineers have long addressed uncertainty and managed risks. For instance, California's current water system uses many risk strategies to manage the state's large hydrologic variability, including:

- Safety factors (e.g., building more supply than projected demand);
- Operational rules (e.g., using a demand restriction schedule during droughts);
- Infrastructure components with performance that is relatively insensitive to uncertainties (e.g., developing storage capacity, instituting demand reductions or using conveyance and inter-basin water transfers)
- Diversifying supply (e.g., drawing surface water from multiple basins; using local ground water, recycling water; rain water capture, desalinization); and
- Adaptive decision strategies (e.g., regular plan updates, near-term actions designed to create future options and dynamic short-term updating of operations).

Despite these innovative strategies, California's water systems are under increasing stress now and in the future. Engineers face the challenge of choosing the best mix of these and other options to increase the future robustness and resilience of the system in the face of large and increasing uncertainties, tightening constraints and increased demand for citizen engagement. Fortunately, better methods and tools for managing uncertainty have become increasingly available. We will return to the tools and options available for dealing with uncertainty in later chapters.

Conclusion

Together, Chapters 2 and 3 aimed to lay out the basic challenges facing infrastructure planning, design, operation and maintenance in a climate-changed world. In Chapter 2, we showed how the climate is no longer static, but now unquestionably on an accelerating warming trend. This warming has already and will result in the future in a number of effects such as sea-level rise, changing seasons and other changes in average climate parameters, but also in a more volatile climate future, marked by more frequent and/or more intense extreme events. While much of this is now understood with considerable confidence, there is some irreducible uncertainty, posing the challenge to plan for climate-safe infrastructure in new ways than engineers and architects have done in the past.

In this chapter, we showed that California's infrastructure is already not in great condition and infrastructure developers are facing significant financial, political, workforce and other hurdles to modernizing it, much less rendering it climate-safe for this warmer and increasingly volatile future. The CSIWG concluded that California stands at a critical juncture: to either risk the very foundation of its economy and its communities' safety and well-being or to make the necessary sustained investment in its infrastructure as if California's future depended on it.

It does.

Figure 3.15: California stands at a critical juncture: to either risk the very foundation of its economy and its communities' safety and well-being or make the necessary sustained investment in its infrastructure as if California's future dependent on it. It does. (Photo: Thomas Hawk, flickr, licensed under Creative Commons license 2.0)

4 A Vision for Climate-Safe Infrastructure for All

Climate Safety Through Mitigation and Adaptation: The Climate-Safe Path

Through high-level policies, executive orders and laws, California has committed to reducing its greenhouse gas emissions by 40% below 1990 levels by 2030 and by 80% below 1990 levels by mid-century. This level of commitment puts the state on a responsible path toward helping the global community achieve the targets of the Paris Accord, namely to limit global average warming to 2°C (3.6°F) or less (1.5°C or 2.7°F) by the end of this century. As discussed in Chapter 3, this is an ambitious target and will require considerable political will to achieve. Many motivations lie beneath this choice, including economic opportunity, a desire to lead politically, technologically, environmentally and morally, and enlightened self-interest. This policy orientation is also informed by the best available science that unmitigated climate change will undermine California's safety and well-being, natural resources and beauty, and crucially important economic sectors. While a 2°C (or less) warming will not prevent impacts from a warming climate (in fact, they are already being felt and more warming is inevitable), the impacts expected at that level of warming (roughly equivalent to the goals of the Paris Accord) are widely seen as considerably more manageable than those associated with greater and faster warming.

Political leaders now have an opportunity to strengthen adaptation as a political priority. They can send a directional signal that the safety of communities and the infrastructure on which they and the state's economy vitally depend is of utmost importance.

As the nearly two decades of international climate negotiations make clear, and as California's own path to increasingly stricter emissions reduction targets illustrates, stringent mitigation targets are not just a rational choice in light of potentially severe risks, but ultimately a political choice. However difficult it may be to achieve, aiming for 2°C or less is the choice that focuses the compass needle toward greater safety from some of the harmful climate impacts that would occur if emissions were allowed to further destabilize the Earth's climate system. However, the great difficulty involved in compelling the international community to make this commitment suggests that California must be prepared to contend with much greater climate impacts.

Thus, there is a parallel political choice to be made in setting adaptation targets. Over the past few years, California's political leaders and State lawmakers have laid some policy foundations for adaptation and now have an opportunity to strengthen adaptation as a political priority. They can send the same directional signal as they did with mitigation, namely, that the safety of communities and the infrastructure on which they and the state's economy vitally depend is of utmost importance. That choice is to ensure that long-lived infrastructure is planned, and may eventually need to be built, operated and maintained, to withstand future impacts from climate change associated with the "business-as-usual" emissions pathway (currently

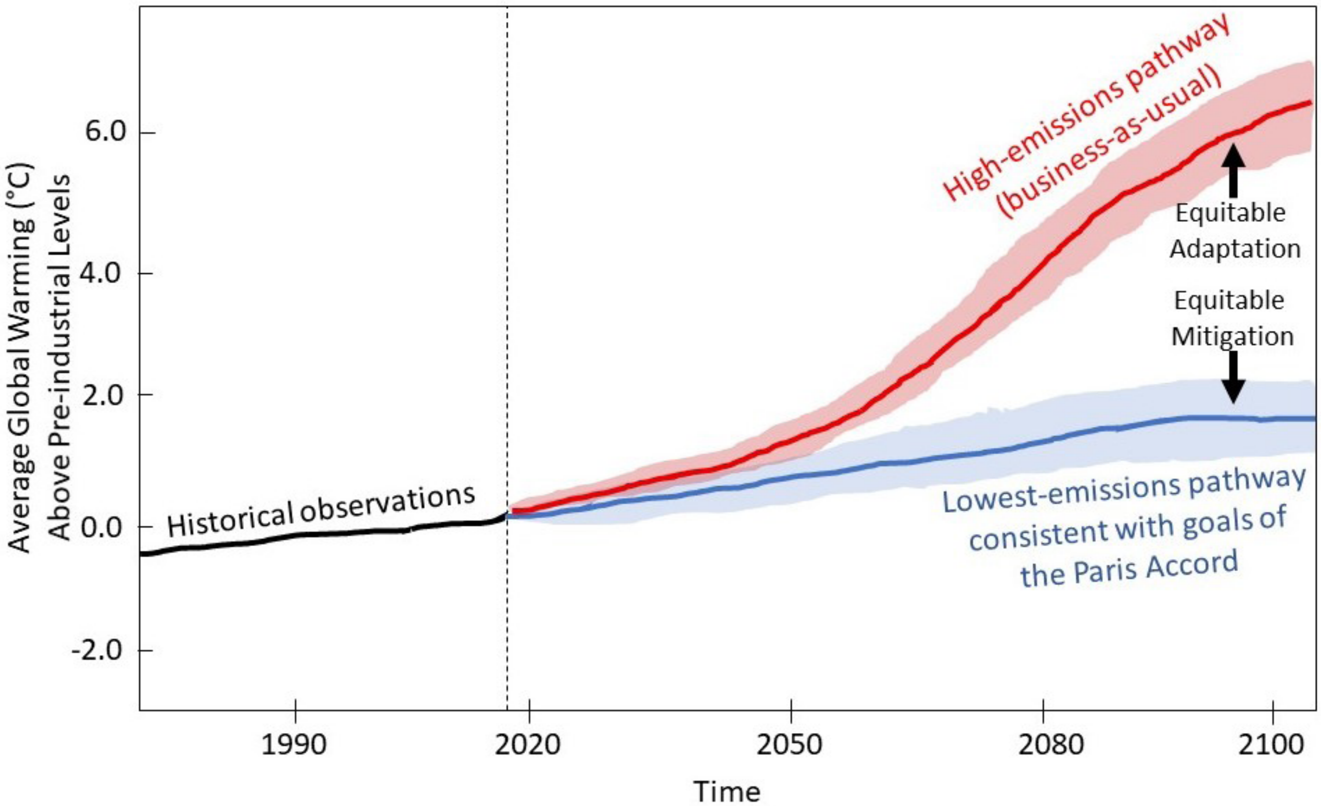


Figure 4.1 The Climate-Safe Path describes the simultaneous pursuit of stringent greenhouse gas mitigation that aims to meet the goals of the Paris Accord while charting an adaptive pathway to protect Californians against the impacts of a high-emissions scenario, both with a central focus on social equity.

the RCP 8.5 emissions scenario). Consistent with State guidance from the Office of Planning and Research (OPR), we refer to this pathway as a "high-emissions pathway" from here on.[1]

Should it become apparent over time that – globally – society has safely averted a high-emissions future, the adaptive approach promoted in this report should allow for an "off ramp" to adapt to the impacts associated with a lower-emissions pathway. However, determining the point in time when such a transition to a lower-safety threshold is indicated, is both scientifically and politically complex and requires dedicated research and public debate.

By reducing the causes of climate change through mitigation and simultaneously implementing preparedness and adaptation measures, California would pursue the safest of possible climate action pathways any state can take. We call this comprehensive strategy "the Climate-Safe Path" (Figure 4.1).

By reducing the causes of climate change through mitigation and simultaneously implementing preparedness and adaptation measures, California would pursue the safest of possible climate action pathways any state can take. We call this comprehensive strategy "the Climate-Safe Path"

[1] The emissions scenarios currently used in the Fourth Assessment, NCA4 and the Fifth IPCC assessment will be replaced with updated ones in the future. To maintain the concept without becoming obsolete when that happens, we use the more general term, which – at any one time – should be operationalized with the highest emissions scenario used by scientists to produce climate change projections.

From Guidance to Policy

Current guidance documents from State agencies on considering climate impacts recommend considering impacts associated with the high-emissions scenario within the context of specific projects. The Ocean Protection Council's (OPC) recently released updated sea-level rise guidance suggests that coastal managers consider risks from sea-level rise associated with high-emissions scenarios depending on the level of risk tolerance and potential adaptation pathways for different projects, with the highest sea levels considered for the most critical and least adaptive projects[49]. Similarly, the OPR statewide guidance for infrastructure planning *Planning and Investing for a Resilient California*, recommends that state infrastructure managers plan for impacts associated with the high-emissions scenario for all decisions with time horizons to 2050[49]. Beyond that the OPC and OPR guidance documents differ nominally from the Climate-Safe Path proposed here in that they recommend a risk assessment approach using a range of scenarios based on the criticality of the project. However, OPR's *Infrastructure Planning Guidance* does emphasize the use of the high-emissions scenario, whenever people and highly vulnerable assets may be placed at risk, if the project is more or less permanent or its failure could cause major economic impacts. Thus, the OPR guidance and the Climate-Safe Path proposed here are essentially identical. We propose a similarly adaptive and flexible approach with a stringent protective target, given the legislative intent to protect lives, the long-lived nature of most infrastructure and the continued high-emissions pathway that society appears to be on.

Guidance documents, however, are not mandatory and they will have the desired impact on decisions primarily if and when they get teeth, i.e., when they are either turned into a mandate or when effectively designed, complementary "carrot and stick" approaches ensure investment decisions protect against the impacts of a high-emissions scenario.

Realizing the Climate-Safe Path One Step at a Time

Preparing for the climate change impacts associated with the high-emissions pathway is an ambitious undertaking that has different implications for different types of infrastructure, for existing and newly built infrastructure, and for short- and long-term climate impacts. In no way does it imply that every infrastructure investment made today must build immediately to the protective level that

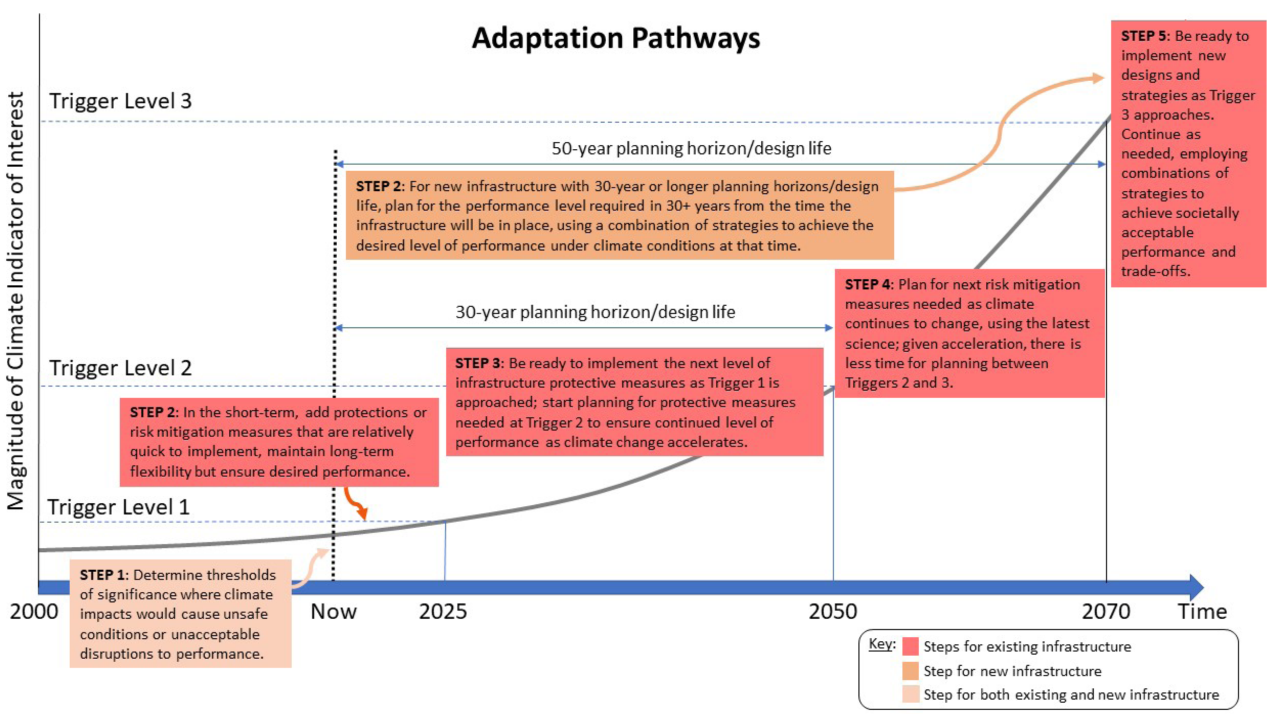


Figure 4.2 Conceptual diagram of an adaptation pathway. (Source: Adapted from Moser 2016[194], used with permission) (Explanation in text)

would be required in many decades when the impacts associated with the high-emissions pathway are beginning to unfold. In other words, realizing the Climate-Safe Path does not mean a once-and-for-all step change, but a change in many steps. This is similar to how emission reductions are achieved: not turning off all emissions at once, but successively and steadily moving toward the ultimate goal. Realizing the Climate-Safe Path means following an adaptation pathway that keeps an eye on a long-term goal but is realized through a variety of strategies in multiple stages over the course of decades (Figure 4.2).

> *Realizing the Climate-Safe Path does not mean a once-and-for-all step change, but a change in many steps.*

Such a flexible adaptation pathway begins with an agreement among relevant stakeholders as to the desired performance/service level of infrastructure. This desired performance level also has direct implications for the degree of risk aversion decision-makers might have. As climate change continues, thresholds will be crossed where the performance of the existing infrastructure as it is currently built no longer fulfills societal expectations. Where existing infrastructure is already inadequate, steps should be taken as soon as possible to augment existing levels of protection to ensure that performance can be maintained. Planning for implementing subsequent retrofits is also begun, recognizing that lead time is needed to implement them. As climate change continues and its impacts eventually exceed the projections for which infrastructure is designed to withstand, the next level of protection – using a combination of strategies – is implemented. The more flexibility is maintained each time, the better. At subsequent steps, the best available knowledge both about climate science, societal trends and performance of different infrastructure designs must be taken into account. But planning time to the next trigger level/threshold becomes shorter as climate change accelerates. These steps are continued as long as conditions change. To realize an adaptive approach to infrastructure upgrades, it is critical that money be set aside now and over time to fund the needed future changes. Otherwise, in a different future political or economic climate, support and resources for the necessary updates could lessen and thus place greater risks on communities in the future.

While we will offer more technical and tactical detail in the subsequent chapters on what is needed to implement the Climate-Safe Path, we can already say here that building and maintaining infrastructure fit for a high-emissions world will be realized through a combination of strategies, each adding a necessary but by itself insufficient dimension to "climate safety." These strategies are based on decades of experience in hazards management and mirror the definitions for climate-safe infrastructure, resilience and related terms offered in Chapter 1[181].

For newly built infrastructure, a number of interrelated but complementary strategies must be pursued to ensure infrastructure functionality and obtain desired risk aversion levels over the changing conditions that can be expected over its lifetime:

- **Robustness:** infrastructure is built to the protective level expected to be needed to ensure acceptable functionality and reliability (assuming the high-emissions pathway) over the design life of the infrastructure (e.g., 30 or 50 years); because there is inevitable uncertainty and multiple design criteria must be met simultaneously, the infrastructure would be expected to be robust over a range of uncertain conditions;
- **Resilience:** plans are developed and practiced from now on for the possibility of a situation when an extreme event exceeds the protective level and infrastructure fails, so as to improve and speed up the response and adaptive recovery to requisite levels of protection needed at that time (sometimes referred to as safe-to-fail approaches with appropriate disaster preparedness and response management); this complementarity to robustness is shown in Figure 4.3;[1]
- **Adaptability:** plans are developed and features integrated into the design now that would allow infrastructure owners to adapt the structure to a higher level of protection should it become necessary over time;
- **Redundancy:** plans are developed now and implemented over time that help the new infrastructure maintain functionality when it or parts of it fail; and
- **Avoidance:** on the basis of vulnerability assessments already in place, underway or to be conducted in the future, infrastructure development in high-risk areas should be avoided unless the infrastructure owner is willing to pay for the necessary measures to ensure functionality over the effective lifetime of the infrastructure (often considerably longer than the design life), using the above four strategies.

[2] See The L.A Metro *Resiliency Indicator Framework*[195] as an example.

For existing infrastructure, the same basic types of strategies listed above must be considered including a strategy that will become necessary when the limits of changing existing infrastructure are being approached:

- **Robustness:** as existing infrastructure undergoes maintenance, upgrades or repairs after damage, structural or material changes are made to bring the existing infrastructure to a higher protective level (if structurally possible to the level needed for impacts expected with the high-emissions scenario over the remaining lifetime of the structure) through retrofits;
- **Resilience:** because robustness and adaptability strategies may be limited with existing infrastructure, plans are developed or updated and practiced from now on for the possibility of a situation when an extreme event exceeds the protective level of the existing structure, so as to improve and speed up the response and adaptive recovery to requisite levels of protection needed at that time;
- **Adaptability:** as existing infrastructure undergoes maintenance, upgrades or repairs after damage, efforts are made to build adaptive features into the retrofit measures so as to allow further adjustments in the future (if structurally possible);
- **Redundancy:** plans are developed and implemented now that help the existing infrastructure maintain functionality when one or more parts of it fail; and
- **Retreat or Decommissioning and Removal:** assessments are undertaken to estimate the time – under the assumption of a high-emissions pathways – when the physical defense of even upgraded existing infrastructure is no longer viable and the functionality of the infrastructure can no longer be assured; based on this assessment, time-sensitive plans should be developed to either move or remove and decommission and replace the infrastructure (Figure 4.3).

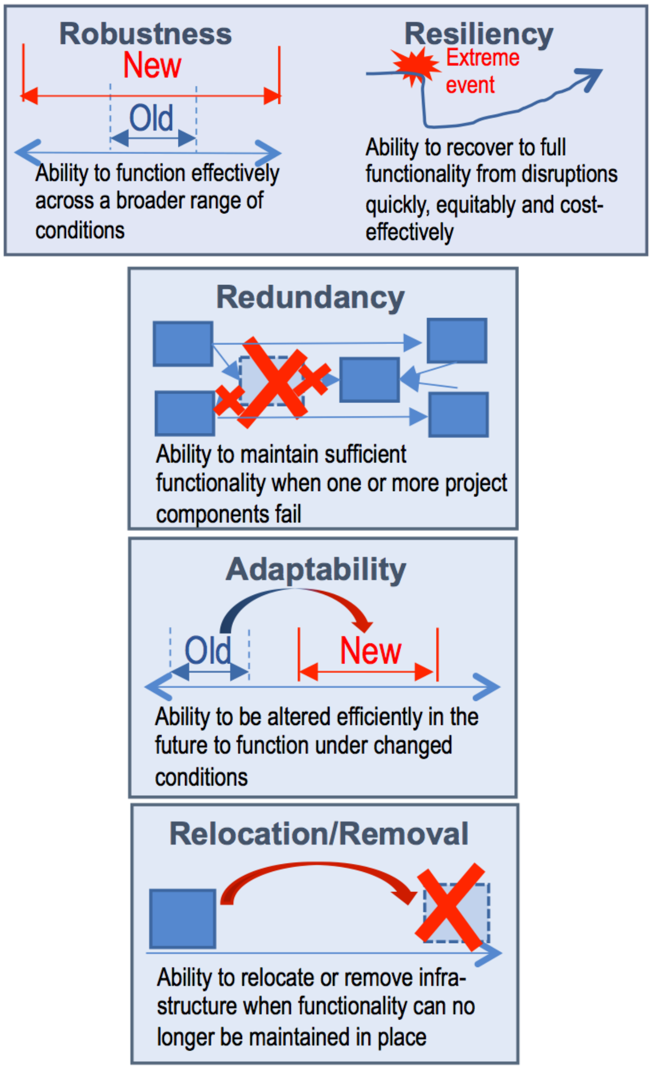


Figure 4.3 Conceptual drawings of the five basic strategies that can be flexibly combined to achieve the desired performance levels of climate-safe, sustainable infrastructure (Source: Adapted from Wallace 2017[181], original used with permission)

Over time, the dual approach of limiting greenhouse gas emissions and simultaneously investing in retrofitting, replacing and building new infrastructure that incorporates these strategies or principles will result in safer communities with more reliable infrastructure and well-practiced plans in place to recover from extreme events. This will allow infrastructure to quickly return to functionality and increased safety in the face of the trends and changing extremes experienced over time.

Importantly, designing for and working toward climate-safe infrastructure requires a shift in thinking from focusing on individual structures to thinking in interconnected and interdependent, multisectoral systems of infrastructure that can withstand not just the occasional extreme event but tightly-spaced sequences of hazardous events and complex, concatenated simultaneous events[165]. Infrastructure planners, designers, builders and operators must come to think long-term and in systems, considering both directional trends and changing patterns and characteristics of extremes.

In short, climate-safe infrastructure would be that which is designed in a way that extreme events do not lead to catastrophic failure, neither now nor across a wide range of uncertain future conditions (Box 4.1).

Box 4.1: Flexible Combination of the Five Strategies of "Climate-Safe" Design

Climate safe infrastructure would be that which is designed such that extreme events don't lead to failure, both now and across a wide range of uncertain future conditions. To achieve this goal, it would build in robustness, redundancy, be readily modifiable to adapt to the prevailing conditions and incorporate resiliency to ensure quick recovery in case of a bigger-than-expected event.

Resiliency and redundancy in particular, are useful concepts for infrastructure design because they acknowledge that events beyond design specification will happen – and maybe more often in the future than currently expected. The common preference is to build infrastructure strong enough – robust enough – that it can withstand worsening conditions. Robustness is a concept that relates to both a particular multi-factorial way of making decisions and how resulting designs will perform regardless of how uncertain future conditions play out. A robust infrastructure design would be one that remains appropriately designed in the future even if climate conditions change in ways different from our current best prediction. Achieving robustness is often accomplished by building adaptive features into the design so that the structure can evolve in response to changing conditions, i.e., it would be readily modifiable to adapt to future prevailing conditions. The complementary notion of resilience implies that infrastructure would be designed to recover (or be restored) with low effort or costs and contingency plans would be made (including redundancy) to ensure quick return to functioning or minimal disruption of functionality at all. In other words, if or when infrastructure fails, it should do so in a non-catastrophic way, fairly compensating those who experience loss or damage (the concept of "safe-to-fail", see Chapter 6 for more details).

For example, a climate-safe sea-level-rise protection scheme might include both a physical barrier designed to hold back storm surge as well as a green space that can absorb overtopping surge and thus minimize the impact of such an event. The design would also include the ability to expand the absorption capacity of the green space if future surge becomes more frequent or larger than presently anticipated. And should failure occur, plans and processes would be in place to quickly and effectively deal with the consequences should the protective features be overwhelmed by a larger-than-expected coastal storm event. Systemic infrastructure planning would also carefully assess the possibility of cascading events and the impacts of infrastructure disruption on interconnected lifelines. This multi-pronged, comprehensive approach would allow the surrounding community to efficiently regain functionality with the least possible disruption of activities and loss of life and damage to structures.

The flexible combination of multiple strategies to achieve climate safety will look unique in different localities and for different types of infrastructure. Here, hard and soft infrastructure are combined, and others could be added to protect a shoreline. (Photo: Ocean Beach, California; Dawn Danby, flickr, licensed under Creative Commons license 2.0).

But planning for climate-safe infrastructure should also involve planning for cases – which may or may not come over the course of the functional lifetime of the infrastructure – when appropriate functioning, and thus the safety of facilities and communities, can no longer be guaranteed even after all other strategies have been applied. Where climate trends are accelerating (as, for example, in the case of sea-level rise), such a time may come faster than anticipated. But if society succeeds in reducing emissions more significantly than anticipated, that time may be far out in the future.

Thus, the full set of strategies is available – in whatever combination – to infrastructure planners and designers so that they can wisely incorporate precaution, flexibility and adaptability; ensure that infrastructure can function across the wide range of plausible future conditions; and, ultimately, be taken efficiently and seamlessly out of use if necessary.

A Climate-Safe Path for All

The vision of the Climate-Safe Path outlined here is not a path just for the privileged. Instead, it is envisioned to be a path for all. Following the Climate-Safe Path must include an integral commitment to remedying past injustice in infrastructure investment so as to ensure the safety, health, well-being and opportunities of those who have borne insecurity, public health burdens and lack of economic opportunity the most and the longest.

As we described in Chapter 3, California's infrastructure – much like that of any other US state – is in many ways inadequate for current climate conditions, much less for those expected over the next several decades or more[7]. Insufficient infrastructure investment, deferred infrastructure maintenance, and a general lack of vision and political will to make the necessary long-term investments in highly functional infrastructure has plagued the state for decades (see Chapter 8). Thus, what we call for in this report is not no- or low-cost, but it is no- or low-regret because any new and additional infrastructure investment California decides to make is remedying a current problem and constitutes an investment into its future ("paying it forward"). But it will be that only if the investment is cognizant of the changing climate in which this infrastructure must serve.

The state's most outdated and dilapidated infrastructure is not evenly distributed, neither geographically, nor socio-economically. It is not affecting Californians equally. Due to decades of underinvestment and redlining (i.e., the systematic denial of various services to residents of specific areas or segments of society), low-income communities and communities of color often confront the largest potholes, the most outdated school buildings, the leakiest pipes, the worst connectivity to modern transportation, communication and other community infrastructure. The added risks arising from climate change are not going to be equally distributed either. These same communities often have the fewest resources to deal with the risks from climate change. As such, these communities are those where the State has the greatest opportunity to make a difference.

Inadequate engagement during the infrastructure planning and decision-making processes, systemic disadvantaging through decision criteria and cost-benefit requirements, long-standing institutionalized racism and narrow thinking about the role of infrastructure across multiple sectors and within a region or community are at the root of this inequitable investment in infrastructure[3,196,197].

As the Movement Strategy Center argues in its *Pathways to Resilience* report[198], "climate resilience is not about 'bouncing back.' Instead it is about bouncing forward to eradicate the inequities and unsustainable resource use at the heart of the climate crisis… [Thus,] climate resilience requires a holistic view of the challenges we face, and it calls for solutions at the intersections of people, the environment and the economy." This is consistent with the paradigm of "sustainable infrastructure" promoted since the early 2000's by the American Society of Civil Engineers[3] (ASCE) although still requiring widespread adoption.

Again, the State already promotes social equity and inclusion as one of its guiding principles for adaptation in its statewide adaptation strategy (*Safeguarding California*[199]) and through EO B-30-15. Making social equity explicitly central to infrastructure investment as a matter of State policy is not a leap, but an extension, a matter of consistency across State policies.

The Climate-Safe Path must include an integral commitment to remedying past injustice in infrastructure investment so as to ensure the safety, health, well-being and opportunities of those who have borne insecurity, public health burdens and lack of economic opportunity the most and the longest.

PolicyLink, an Oakland-based racial and economic equity advocacy group which includes a focus on infrastructure, suggests the following principles to guide equitable infrastructure planning, policy and investment[200]:

- Include residents in decision-making;
- Serve underinvested communities without pushing out existing residents;
- Improve the environmental health and quality of life for residents of disinvested communities;
- Be equitably owned, financed and funded;
- Create good jobs and business opportunities for local residents; and
- Invest in workforce training.

[3] For the full range of sustainability policies, strategic roadmaps, certificate programs and resources, see: http://www.asce.org/sustainability/.

The Working Group endorses these principles. In fact, effects of increasing impacts from climate change is a human rights issue[201]. Holding paramount the safety, health and welfare of the public is central to the code of ethics of the engineering profession. The Working Group's strong conviction is that social equity in infrastructure development should not be a last-minute adjustment of an already-decided plan, nor merely one among many criteria to guide infrastructure decisions. If the protection of lives is the goal, social equity must be considered in the beginning, middle and end of infrastructure planning and decision-making. It is the outcome that is planned for from the start, and that means a different process must prevail. As Dr. Beverly Scott put it in one of the CSIWG meetings, "Are we planning *for* communities, or *with* them?" Figure 4.4).

Social equity thus rises to an overarching priority, guiding climate-safe infrastructure planning, design and implementation. In light of the greatest need for infrastructure investment in low-income communities and communities of color, and the legislative intent of AB 2800 to ensure the safety of Californians as climate change threats to the state's infrastructure increase, equity should be included every step of the way from infrastructure planning and decision-making to implementation and performance evaluation, with clear indicators and guiding questions to show the way (Box 4.2).

Figure 4.5 illustrates how to rate infrastructure investments. The three criteria are the degree to which they would (a) reduce the state's risks from climate change, (b) remedy past lack of investment in infrastructure and (c) explicitly reduce/remedy social inequity through comprehensive approaches. This would lead to clear priority setting in favor of those regions and communities of the state that have long been neglected and are therefore in greatest need now.

Figure 4.4 To ensure the safety of all Californians as climate change threats to the state's infrastructure increase, equity should be included every step of the way from infrastructure planning and decision-making to implementation and performance evaluation. (Photo: US Army)

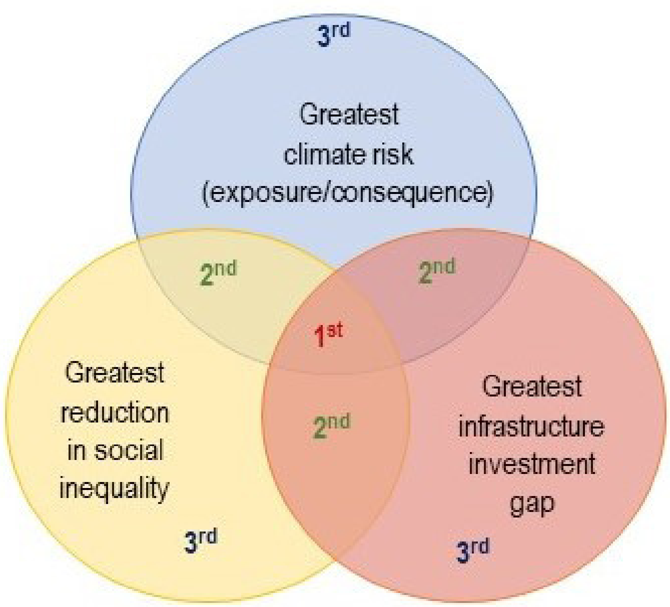


Figure 4.5 Prioritizing infrastructure investments in line with the Climate-Safe Path for All proposed here should be guided by three criteria: (1) where is the risk the greatest?; (2) where is the greatest infrastructure investment gap?; and (3) where can the investment most reduce inequality and increase opportunity? This will result in tangible improvements for long-neglected communities and regions of California.

Recommendation 1

The State Legislature should establish as official State policy "The Climate-Safe Path for All", which is a flexible adaptation pathway realized through a variety of strategies, in multiple stages over the course of decades. The Climate-Safe Path for All accounts for the full life-cycle costs of infrastructure and uses a multi-sectoral, systems approach. It prioritizes infrastructure investments based upon the greatest risks and investment gaps, as well as where investment can most reduce inequality and increase opportunity. For highly vulnerable, long-lived infrastructure, State agencies should consider climate change im-pacts associated with a high-emissions scenario while continuing to implement all applicable State laws related to stringent greenhouse gas emissions reductions.

To operationalize Recommendation 1, the CSIWG suggested the following concrete next steps:

1. All State infrastructure agencies should establish as a matter of agency-wide policy an adaptation and resilience requirement, namely that all investments in new and existing state-owned, -funded and regulated infrastructure consider and then employ an appropriate combination of the five strategies described above to work toward increasing climate safety.
2. State agencies should furthermore establish formal and readily implementable guidelines at the agency/programmatic level and at the project level as to what it means to "incorporate climate change" into infrastructure planning, design, construction, operation and maintenance. This guidance should rely on the concepts and suggestions made in this report.
3. At the program level, guidelines should address the full range of decisions related to infrastructure, including policy, planning, procurement, funding, cross-agency/cross-sector coordination to foster systemic approaches and program evaluation; and
4. At the project level, guidelines should clarify and specify agency-relevant risk and vulnerability assessment approaches, event tree analysis, full life cycle cost assessments, assessment of costs, benefits, tradeoffs as well as potential risk mitigation measures.
5. Development of guidance will often require workload and expertise beyond what is available in current budgets. To achieve this recommendation, agencies should have adequate funding and efficient ways to leverage similar activities from other agencies and solicit outside scientific and technical expertise.

To operationalize the social equity dimension of Recommendation 1 specifically, the CSIWG suggested the following critical next step:

1. State legislation, propositions and state agency policy directives related to infrastructure should direct infrastructure investment where it is needed most as determined by a screening of climate risks (see Climate-Screening Tool in Chapter 6), the infrastructure investment gap and the potential to reduce social inequities. This would prioritize infrastructure upgrades, repairs and new investment in long-neglected communities and regions of the state.

Box 4.2: An Equity Indicators Framework

Demographics:
Who lives in the region and how is this changing?
- Racial/ethnic diversity
- Demographic change
- Population growth
- Racial generation gap

Economic vitality:
How is the region doing on measures of economic growth and well being?
- Is the region producing good jobs?
- Can all residents access good jobs?
- Is growth widely shared?
- Do all residents have enough income to sustain their families?
- Is race/ethnicity/nativity a barrier to economic success?
- What are the strongest industries and occupations?

Readiness:
How prepared are the region's residents for the 21st century economy?
- Does the workforce have the skills for the jobs of the future?
- Are all youth ready to enter the workforce?
- Are residents healthy?
- Are racial gaps in education and health decreasing?

Neighborhoods:
Are the residents of [the region] prepared for and connected to the region's opportunities?
- How are demographics changing?
- How are residents doing on measures of economic opportunity and readiness?
- Are residents connected to opportunities?

Connectedness:
Are the region's residents and neighborhoods connected to one another and to the region's assets and opportunities?
- Do residents have transportation choices?
- Can residents access jobs and opportunities located throughout the region?
- Can all residents access affordable, quality, convenient housing?
- Do neighborhoods reflect the region's diversity? Is segregation decreasing?
- Can all residents access healthy food?

The National Equity Atlas has developed an equity indicators framework, along with several regional profiles to illustrate how it would be applied (examples for the San Francisco Bay, Sacramento and Los Angeles regions and Fresno County are available, see PolicyLink and PERE[200,202-205]. The guiding questions and associated quantitative indicators, especially disaggregated data on each of the indicators, offer a tangible way toward improving, tracking and evaluating social equity over time. (Source: Adapted from PolicyLink and PERE (2017)[202], p.13, used with permission)

From Vision to Action: A Framework for Action

In order for this vision of climate-safe infrastructure to be realized, integrating the best available forward-looking science (of climate change as well as demographic, socio-economic, technological and ecological changes relevant to infrastructure investment decisions) is necessary, but insufficient. Publicly accessible data and information inputs, as well as high-quality analytics such as risk and vulnerability assessments, are essential both to set standards and guidelines and for ongoing operation and maintenance. But they are only one part of an action-oriented framework that will result in the ultimate intent of AB 2800, namely that infrastructure investments get made and that climate-safe infrastructure is actually built so that lives are protected and the foundation for a prosperous future is built and maintained.

We therefore propose the following framework that places the integration of forward-looking science into infrastructure planning and design in the context of additional necessary steps and areas for improvement in order for climate-safe infrastructure to be implemented on the ground (Figure 4.6).

The five core components of this framework mirror key needs of any infrastructure planning and design process, and we dedicate a chapter to each in the remainder of this report.

- **Data and Analytics (e.g., risk and vulnerability assessments, along with the necessary tools)** Infrastructure planning and design requires many types of data, model simulations and forward-looking science – appropriately used and interpreted. This is a central focus of AB 2800, and we will discuss in greater detail what information is needed, what information is currently available or should be produced in the future in Chapter 5.

- **Project Pipeline (e.g., project planning and pre-development, standards for prioritization, project management flow)** Infrastructure projects are often years to even decades in the making. Where and what to prioritize, to what standards of performance climate-safe infrastructure should be built, and planning and deciding about them in a transparent and inclusive fashion requires effective project management and coordination. A well-developed project pipeline is a necessary pre-condition to attract infrastructure finance and involves successful stakeholder engagement, efficient progress through the permitting process, multi-sectoral alignment and other processes, which we describe in chapter 6.
- **Governance Structures (e.g., at various scales)** Many types of infrastructure involve engagement of multiple levels and different kinds of jurisdictions and can include multiple State agencies or sectors, for funding and financing, review and permitting, oversight, operation and maintenance. Appropriate and effective governance structures and processes are required for complex partnerships and financing but may be lacking or need clarification and streamlining for efficient functioning. Governance also involves the rules, codes, standards and guidelines that govern where and how infrastructure is built. We discuss these needs in Chapter 7.
- **Financing Tools (e.g., funding/revenue, financing/loans, innovative instruments incl. insurance)** Federal and State funding sources alone are widely seen as insufficient to catch up on past inadequate infrastructure investment, resulting in a call for private sector involvement and innovative partnerships and financial tools to generate the necessary funds. In addition to familiar tools such as bonds, taxes and fees, a number of innovative tools are currently being piloted. We review these trends, needs, related obstacles and opportunities in Chapter 8.
- **Implementation Aids (e.g., training, professional development, M&E, public engagement)** None of the above will be realized at the rate and quality needed without engineers, architects, planners, procurement officers and on-the-ground operations personnel having the necessary professional training and know-how to appropriately use available scientific data and tools. They must also be able to understand different planning or financing options and be capable of navigating complex governance challenges. Thus, to enable climate-safe infrastructure to be built, relevant staff require professional development opportunities, accountability mechanisms, and a cyclical, iterative approach – informed by ongoing monitoring and evaluation of the performance of infrastructure – to periodically reassess climate risks and adjust infrastructure planning and design approaches accordingly over time. We will discuss critical needs in this category in Chapter 9.

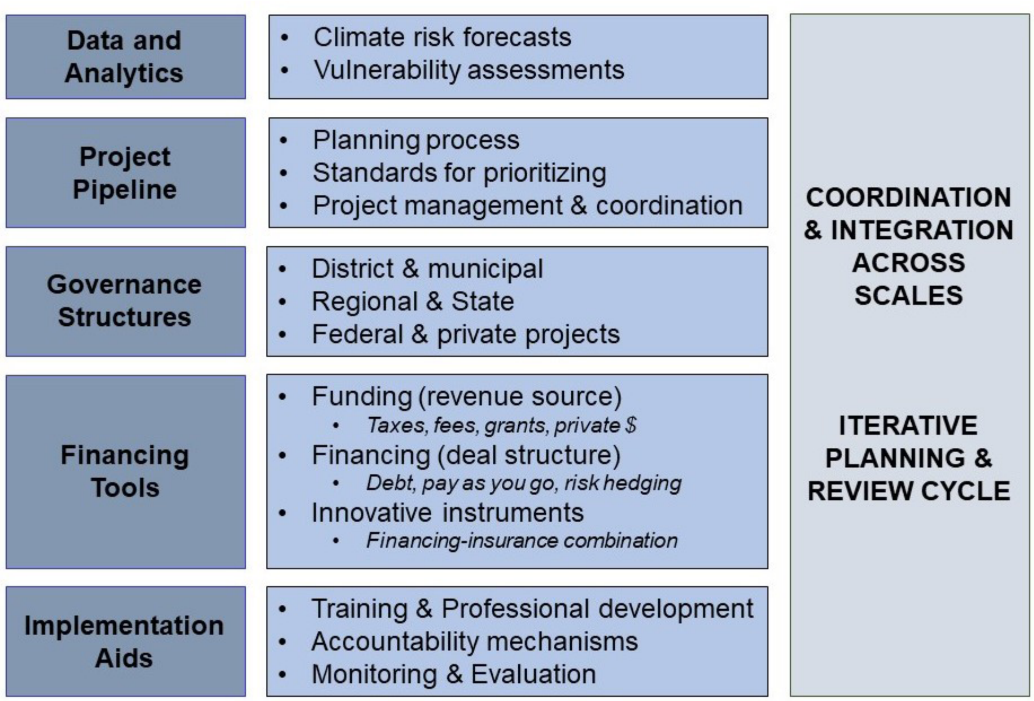


Figure 4.6 A strategic, integrated framework for action is needed to ensure that the vision of Climate-Safe Infrastructure for All gets realized. It includes data and analytics which inform infrastructure planning and design to generate a prioritized list of projects that can be implemented with the help of appropriate governance structures, financing tools and implementation aids. (Source: Adapted from Cleveland 2018 webinar; original used with permission)

It is clear from the discussion so far, and from what will be explained in much greater detail in the following chapters of this report, that the integration of forward-looking climate science alone will not "solve" the problem of the state's infrastructure being ill-prepared for the current and coming climatic conditions. A systemic, iterative approach must be developed that links climate and other forward-looking science to planning, governance, financing and the appropriate conditions for project implementation.

To ensure strategic advancement toward realizing the Climate-Safe Path for All, and to make implementation more likely, future State legislation and programs developed by the Strategic Growth Council and individual State agencies (as well as other entities interested in or charged with climate-safe infrastructure planning and design) should adopt an "it takes a system" approach as a foundation for building climate-safe infrastructure.

To ensure strategic advancement toward realizing the Climate-Safe Path for All, and to make implementation more likely, future legislation and programs should adopt an "it takes a system" approach

The following five chapters take on each of the framework-to-action elements in greater detail, beginning with the data and analytics in Chapter 5.

Figure 4.7 At "The Longest Table" event in Howard County, Maryland, 320 residents sat a a 320-foot long table and shared their respective vision for their community. This type of socially inclusive engagement ensures equitable respresentation; everyone had a seat at "the table." (Photo: Howard County (Md.) Library System, flickr, licensed under Creative Commons license 2.0)

5 Data and Analytics: Meeting Forward-Looking Science Needs

Introduction

Two important mandates of AB 2800 are to consider and investigate:

1. The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design; and
2. The critical information that engineers and architects responsible for infrastructure design and construction need to address climate change impacts.

In this chapter we summarize what the Climate-Safe Infrastructure Working Group (CSIWG) found in terms of climate information currently used in infrastructure planning and design and what forward-looking climate science needs exist, along with barriers to using it. Throughout the discussions, the CSIWG identified other sources of forward-looking information beyond physical climate science. Those are presented here as well.

Identification of Climate-Sensitive Infrastructure

Perhaps the most important immediate outcome of AB 2800 is to demonstrate the State's commitment to understand the barriers that until now have limited agencies' ability to incorporate forward-looking climate information.

Following the mandate of AB 2800 and using the ASCE (2015)[178] report recommendations, the CSIWG identified the infrastructure that should be addressed as part of this study. It then assessed the information required to implement existing standards, guidelines and regulations, which determine how infrastructure is planned, designed, built, operated and maintained. Working Group members also identified relevant standards that come into play in building and maintaining infrastructure. Only those codes, standards and guidelines that cannot accommodate a changing climate must eventually be updated with forward-looking climate information (for a fuller discussion see Chapter 7). While some State agencies have begun to do so, not all have.

CSIWG discussions focused on State-owned, -funded and -regulated infrastructure in the building, energy, water and transportation sectors (with an emphasis on infrastructure for which members had expertise), with lesser attention to infrastructure such as correctional and healthcare facilities, State parks and related green or nature-based infrastructure.[1] CSIWG members identified which weather/climate impacts their respective infrastructure assets currently face and those they expect to face more of in the future (Table 5.1).

One of the most important immediate outcomes of AB 2800 is to demonstrate the State's commitment to understand the barriers that until now have limited agencies' ability to incorporate forward-looking climate information.

[1] For the purposes of this report, we use a very broad definition of green infrastructure that can include both already existing or restored natural features, such as beaches, wetlands or habitat corridors, as well as human-made but nature-based infrastructure that is intended to serve a protective function or provide other ecosystem services to a community such as storm water management, groundwater recharge or greater tree cover in urban areas.

Table 5.1 CSIWG-Identified Climate Impacts to Assest Categories For Each Sector

		Temperature		Wildfire		High Winds		Precipitation		Flooding/ Run-Off		Debris Flow / Mudslides		Coastal Flooding / Waves / Storm Surge		Sea Level Rise		Erosion		Drought	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Transportation	Culvert Design	✓		✓	✓			✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Transportation	Pavement Design		✓	✓				✓	✓	✓	✓			✓		✓					
Transportation	Bridge Design	✓	✓				✓	✓	✓	✓	✓		✓		✓		✓				
Transportation	Signal & Signage Design	✓	✓	✓	✓		✓	✓	✓	✓	✓		✓				✓				
Transportation	Caltrans Buildings	✓	✓	✓	✓				✓	✓	✓										
Transportation	Safety Rest Areas	✓	✓	✓	✓					✓	✓										
Transportation	Landscape Areas	✓	✓	✓	✓			✓	✓		✓									✓	✓
Transportation	Roads & Bridges	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓				
Transportation	Rail System & Busways	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓								
Transportation	Bust & Rail Mainte-nance	✓	✓			✓	✓	✓	✓	✓	✓										
Transportation	Electrified Fleet	✓	✓			✓	✓	✓	✓												
Transportation	Rail Cars & Buses	✓	✓																		
Transportation	Ports					✓	✓	✓	✓	✓	✓			✓	✓		✓				
Transportation	Coastal Roads & Railroads					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Energy	Hydro Dams							✓	✓	✓	✓	✓	✓				✓		✓	✓	✓
Energy	Power Plants		✓					✓	✓	✓	✓	✓	✓		✓		✓		✓		✓
Energy	Electrical Transmission Lines	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓		
Energy	Electrical Transformers	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓		
Energy	Natural Gas Compressor Stations	✓	✓							✓	✓				✓		✓		✓		
Energy	Natural Gas Pipelines														✓		✓		✓		✓

Table 5.1 (Con'd) CSIWG-Identified Climate Impacts to Assest Categories For Each Sector

		Temperature		Wildfire		High Winds		Precipitation		Flooding/ Run-Off		Debris Flow / Mudslides		Coastal Flooding / Waves / Storm Surge		Sea Level Rise		Erosion		Drought	
		Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Buildings	Energy Demand for Space Cooling	✓	✓																		
	Energy Demand for Space Heating	✓	✓																		
	New Buildings	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
	Existing Buildings	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
	Parking Lots	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
	Garages	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓		✓		✓		
Water	Dams			✓	✓			✓	✓				✓								
	Pipelines / Tunnels							✓	✓	✓	✓	✓	✓	✓					✓		✓
	Canals	✓	✓					✓	✓		✓						✓		✓		
	Levees					✓		✓		✓	✓			✓			✓				
	Sewage Treatment Plants							✓	✓	✓	✓			✓	✓		✓		✓		
	Sewage Pipes / Septic Fields							✓	✓	✓	✓			✓	✓		✓		✓		
	Pumping / Generating Plants	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓		✓		✓

It is immediately apparent from Table 5.1 that the impacts of temperature, wildfire and high winds, as well as the combined impacts of precipitation and associated flooding present immediate challenges to existing infrastructure, and these are expected to be exacerbated with a changing climate. Impacts from sea-level rise, coastal flooding and coastal erosion are important in specific locations where critical infrastructure is located along the coast.

Information Currently Used for Infrastructure

Fulfilling the mandate of AB 2800 to identify information needs and any barriers to information uptake requires: (1) an understanding of the information that is currently available and that is regularly being used by engineers and architects now; (2) identifying the perceived gaps in currently existing information; and (3) identifying future climate-science (and other forward-looking science) needs. Appendices 4 and 5 provide summaries of the information currently used in infrastructure design and maintenance and identify future climate-science needs broken out by infrastructure sector. These tables in the appendices belie the complexity of the conversations, however, about what information is really needed and the level of detail required to continue to decrease risk in infrastructure design, planning and implementation. We address this greater complexity in the sections below.

Forward-Looking Climate Science Needs

Chapter 2 of this report identified what is currently understood about climate trends and projections into the future. However, engineering studies and planning often require information at a parcel- or project-level scale, and at time scales not always currently available from global climate projections (e.g., precipitation rates on an hourly scale versus monthly or annual averages). If that level of detailed information is available, it is usually accompanied with high degrees of uncertainty and wide ranges of possible future climates, which are themselves dependent on the even less predictable behavior of humans and future global greenhouse gas emissions. This disconnect between what is available and credible on the one hand and what is needed by engineers and architects on the other has stymied much effort to incorporate forward-looking climate information into existing design standards, guidelines and principles.

The CSIWG does not believe, however, that this disconnect creates an unworkable impasse. Instead, the CSIWG identified an adaptive process by which infrastructure planning can continue with the information that is currently available, while also highlighting climate information needs that would be useful moving forward. This entails using the information that is currently available, while allowing for more refined information to be incorporated in the future (see the adaptive pathway described in Chapter 4); when possible, using adaptive designs for planning infrastructure (discussed more fully below); while developing sustained funding source to advance climate and social science as well adaptive engineering research to fill identified gaps (see research needs below and in Chapter 8). To prioritize achieving this latter step, the CSIWG identified critical information needs for each sector (Appendices 4 and 5). Table 5.2 provides selected examples of some of the information needs – typically requiring additional research to fill them – while Appendices 4 and 5 provide a more complete list for each sector.

Figure 5.1 An important component to adaptive design entails monitoring and observing how the infrastructure responds to current environmental conditions, as well as monitoring global emissions, how climate is reponding and whether adjustments are needed to ensure existing infrastructure is climate-safe (see also Chapter 9) (Photo: U.S. Army Corps of Engineers)

As we highlight these climate information needs, it is important to recognize that most of these data are already available, just not at the level of granularity thought to be needed by the engineering community. Where the desired granularity cannot be obtained, decision-analytic frameworks such as decisions scaling[146,206-208] and robust decision making (see Chapter 6) can be used to arrive at climate-safe infrastructure designs despite lack of adequate or uncertain data. In fact, many of the forward-looking climate data needs are in fact climate research – and research capacity – needs. For instance, the CSIWG called for more detailed information on increased capacity to model precipitation and storm water flows in urban areas in a changing climate. There has been some pioneering work in this area by CSIWG members and other researchers[56,58,209-213], however most studies are limited in geographic scope and require time and investment to apply to other locations (see Chapter 2 and Box 5.1 below). Detailed analysis of the concurrence of different flood contributors is equally time- and resource-consuming[56]. Thus, research is needed to identify less computationally-expensive methods to develop these flood projections; this is, in turn, dependent on funds to ensure adequate research capacity.

The perceived lack of sufficiently high-resolution data and too much uncertainty in the projections already available may not be solved by more research, but rather requires a new approach to planning and design. The CSIWG accordingly grappled with the consistent challenge of ensuring that "the perfect not become the enemy of the good." The applied research question then becomes: where is the higher-resolution information actually needed and when/where does this higher level of resolution imply a false sense of precision about what we can expect in the future? Can infrastructure systems be designed to be adaptive and be able to withstand a range of possible climate futures, rather than be tied to one particular future, which may or may not ever become reality. In Chapter 6, we will discuss probabilistic risk management and adaptive design approaches, and in Chapter 7 ASCE's Manual of Practice. Both provide concrete steps by which engineers and architects can do exactly this.

The perceived lack of sufficiently high-resolution data and too much uncertainty in the projections already available may not be solved by more research, but rather requires a new approach to planning and design.

Table 5.2: Examples of Forward-Looking Climate Information Needs, Requiring Additional Research, for Selected Infrastructure Sectors (see also Appendix 5)

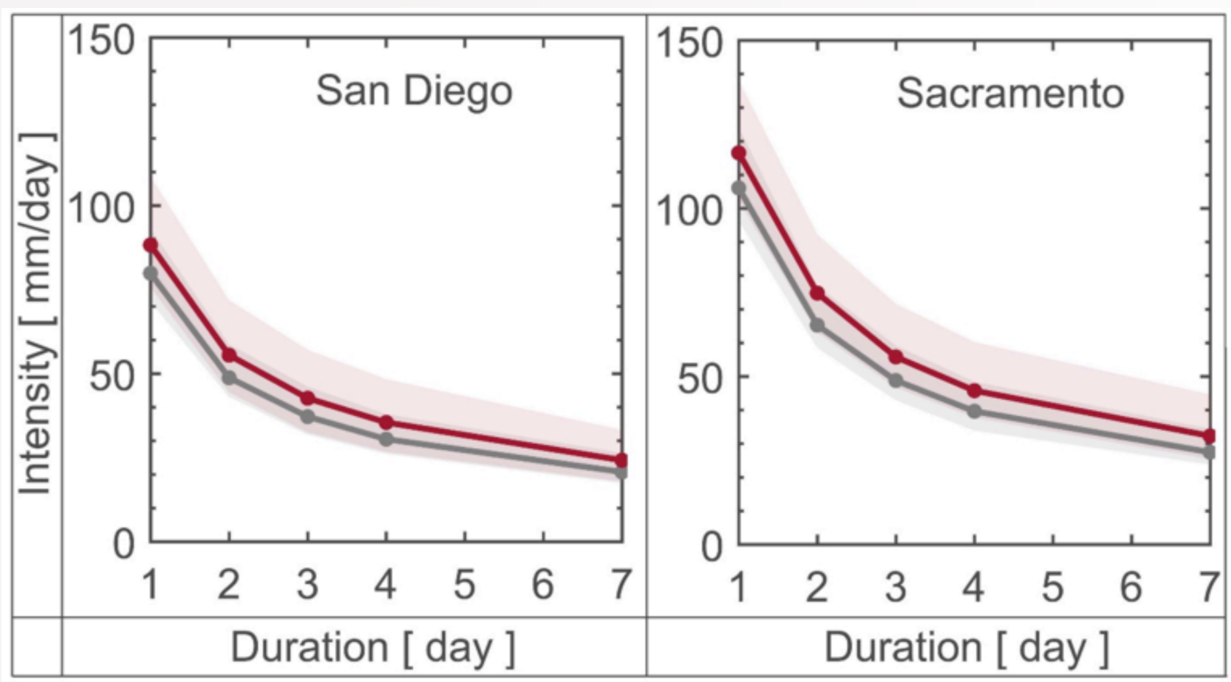
Water Infrastructure • Flow rate (hourly) data for urban water systems • Increased capacity to model flow in urban areas • Continuous and reliable runoff information • Sub-hourly precipitation measurement • Spatial/temporal resolution (varies for different types of infrastructure and depends on size/scale)
Transportation • Rain intensity, downscaled to highest spatial resolution possible • Sea level rise downscaled to highest spatial resolution possible • Extreme wind prediction • Change in storm surges • Change in temperature • Frequency of extreme temperatures • State developed flood plain maps • Regional maps identifying areas susceptible to wildfires (i.e., infrastructure within areas susceptible to wildfires) • Regional maps identifying areas susceptible to mudslides (following wildfires)
Energy/Buildings • Downscaled global climate model data at smaller temporal scales (i.e., from daily [6 hour] to hourly data needed for building energy modeling [e.g., dry/wet bulb temperatures, solar radiation, wind speed and direction]) • Sea-level rise impacts on groundwater levels • Different spectrums of radiation for material and surface light of building components • Future projections and variability of outdoor air quality

Box 5.1: Example of How to Fill Specific Climate Science Needs

Experts at the University of California, Irvine, have prepared rainfall Intensity-Duration-Frequency (IDF) curves using projected precipitation data. These projected precipitation IDF curves have been prepared for 14 major cities in California[58]. Members of the CSIWG noted that forward-looking IDF curves need to be developed for the entire state. Such IDF curves are used in design of storm water systems, levees, bridges, culverts, etc.

At present, IDF curves are based on historical data, using data tables from NOAA Atlas 14. Not having IDF curves for future climate conditions limits incorporation of climate change into the design of these types of infrastructure. Data would need to be developed at a resolution of 0.06 degree (dividing the state into ~11,800 grid cells). This would amount to having data representing 3 to 4-mile square cells statewide. To complete this task could take 1-2 years and additional resources but is entirely achievable and would benefit water and transportation agencies and other State agencies for design and planning projects.

A recent paper[214] assessed how out-of-date state design manuals are, given extreme rainfall occurrences and projected changes in extremes. It shows that California is one of eight states where updates of this sort should be a high priority.



IDF curves using forward-looking climate projections (RCP 8.5, red curve) for a rainfall event in San Diego (left) and Sacramento (right) that has a 25-year recurrence interval), with a 90% confidence interval (pink-shaded area), compared to the historical IDF curve (black curve) (Source: Adapted from Ragno et al. 2018[58]; used with permission)

Beyond Climate Science Information

While the scope of AB 2800 can be read to be limited to physical climate science information, the phrase “climate impact science” opens up a much larger body of work, ranging from physical impacts to ecological and social impacts. In the course of the CSIWG’s deliberations, many other information needs were identified that extend beyond traditional climate, geophysical or meteorological information that are not even just “impacts science.” These data needs spanned from traditional social scientific information such as projections of future land use, demographics and social vulnerabilities, to the economics of adaptation and cost-benefit analyses of different infrastructure concepts and plans (which then ultimately drive final design decisions), to shifting infrastructure technologies and associated energy demands as communities electrify transportation and move from fossil fuel-based energy sources to renewables throughout California. Such information is as critical to making infrastructure decisions as climate information: if future transportation is electrified, how and where should charging stations be built to be safe from climate impacts? If the energy system is reliant on a greater share of microgrids and distributed energy sources, should existing energy infrastructure be retrofitted or decommissioned? And so on.

Land Use, Demographic, Socioeconomic and Ecological Information

Many types of critical infrastructure have a 20 to 30-year design life cycle, with a useful life that can extend an asset’s life for several more decades if it is well maintained and built appropriately. The communities dependent on, and hosting, these long-lived assets can – and do – change dramatically over these years. In California’s major urban centers, urbanization continued unabated, involving rapid population growth with concomitant increased economic activity – albeit with increasing income disparities, gentrification, housing costs and homelessness. Conversely, in the early 2000s, a number of communities went bankrupt or experienced serious declines in their budgets, either due to population declines, shifts in the economic bases, the 2007-08 recession or other fiscal challenges (e.g., in California, the City of San Bernardino and City of Stockton had to declare bankruptcy). As urban sprawl continues its growth along the edges of the major metropolitan regions, land use patterns shift and infrastructure needs and vulnerabilities change[215-217]; J. Thorne presentation to the CSIWG, 2018). If income disparities persist or increase further, the number of people living below the poverty level would increase (see the equity profiles highlighted in Chapter 4). These economic disparities are a key contributor to social vulnerability. Implementation of the Climate-Safe Path for All, as argued in the previous chapter, should be informed by such socioeconomic data as much as by climate data.

When determining whether to retrofit existing or build new infrastructure such social and economic data points must be considered. However, reliable projections of land use, population growth and economic activity are inadequately understood (as discussed in Chapter 3). Climate change also causes significant (and uncertain) change in the environment. However, major infrastructure projects must mitigate their impacts on the environment and thus need reliable ecological information to inform those environmental mitigation efforts (J. Thorne presentation to the CSIWG 2018). In the past, California has supported some research that has considered various interactive (social, physical and ecological) drivers of climate impacts[84,218], but more such work is needed to cover all of the state.

Figure 5.2: As urban sprawl continues its growth along the edges of California’s major metropolitan regions, land use patterns shift and infrastructure needs and vulnerabilities change. Planning climate-safe infrastructure should be informed by forward-looking socioeconomic data as much as climate data. (Photo: Interstate 805 in San Diego, Wikimedia Commons, licensed under Creative Commons license 2.0).

Recommendation 2

In the past, the State's financial support for its various climate science efforts and decision-support tools has been uneven and insufficient. At a minimum, the State Legislature should provide a permanent source of funding for the State's mandated Climate Change Assessment process, the State's ongoing Climate Change Research Program, and decision-support tools and other assistance that disseminate their findings, so as to meet the needs for improved understanding and forward-looking science information.

There are several critical next steps that the State can take to operationalize Recommendation 2 and fill the identified information/research gaps and place California's climate research and assessment efforts on a stronger foundation (see also Table 5.2 and Appendices 1-2):

1. The State should convene a follow-up panel or process to prioritize the full range of information gaps (bio-physical, engineering, and socio-economic) identified by the CSIWG into high, medium and low priority. For those gaps identified as high priority, the State budget should provide a level of funding and staffing commensurate to fill these gaps—utilizing resources both internal and external to State government – within five years, where scientifically feasible. State agencies should furthermore establish formal and readily implementable guidelines at the agency/programmatic level and at the project level as to what it means to "incorporate climate change" into infrastructure planning, design, construction, operation and maintenance. This guidance should rely on the concepts and suggestions made in this report.
2. With the help of the Strategic Growth Council, the Natural Resources Agency and the California Energy Commission, future renditions of the Climate Change Research Plan should prioritize research needs identified in this report, including identification of the most appropriate agency and outside partners capable of addressing them, and look at all relevant climate, emergency planning and infrastructure-specific funding sources to support these needs.
3. For water infrastructure information needs in particular, the Department of Water Resources (DWR), working with other State agencies as well as a diverse group of stakeholders, has recommended formally establishing and funding a California Climate Science and Monitoring Program in the *Draft California Water Plan Update 2018*. Should this finding be included in the final version of the 2018 update, the State should implement and fully fund this recommendation.
4. The State Budget should provide modest and stable additional funding to expand the State Climatologist Office, in order to realize the full potential of the State Climatologist to engage the climate science community and in turn advise State government on climate change issues.

5. The State need not begin from scratch, but rather can leverage and expand on already ongoing (and in some cases, state-funded) research throughout the state by both public and academic researchers to ensure forward-looking climate science is available at high resolution for use by state and regional or local infrastructure owners. With expected benefits to various State agencies and to projects across the state, the Legislature should provide funding for research in the following areas:
    (a) Produce statewide IDF curves with associated uncertainty for future climate conditions (especially the high-emissions scenario, to be consistent with the Climate-Safe Path for All described in Chapter 4);
    (b) Continue to invest in high-resolution climate modeling to better define spatial and temporal structure of extreme events;
    (c) In addition to studies focusing on future projections, traditional knowledges and paleoclimatology should also be included as funding priorities;
    (d) Building on the State's previous investment in USGS's CoSMoS model for sea-level rise and storm surge, determine where exactly in the state even more fine-scaled hydrodynamic modeling is needed and focus additional resources there; and
    (e) Because extreme events are particularly critical to climate-safe infrastructure design, invest in research that merges case studies, ensemble modeling, forecast experiments and sophisticated uncertainty analysis approaches to investigate the likelihood, mechanisms, joint probabilities, predictability of climatic extremes, including worst-case events, that pose significant threats to California's infrastructure.

In order then to further implement Recommendation 2, the CSIWG identified critical social science information needs that should be filled through State agency-supported research and in partnership with external experts. Some of this information may be available in existing academic research but is not widely known or available to infrastructure planners and familiarity with such information is often lower than with physical science information:

1. Fine-spatial scale historical demographic information to identify vulnerable populations and to more fully understand the factors that drive social vulnerability;
2. Fine-spatial scale historical information on infrastructure use and detailed understanding of the factors that drove those use patterns;
3. Transit-dependent population information;
4. Projections of demographic shifts under different economic and climate conditions;
5. Projections of climate change impacts (e.g., ecological) that combine climate, economic, demographic and other drivers; and
6. Projections of changes in technology and infrastructure use (e.g., electrification and related changes in energy infrastructure needs and energy use).

Adaptive Design and Related Economic Analyses

With climate change, the impacts that infrastructure will have to withstand will change over time, but both the rate and extent of change are uncertain. Most infrastructure incur a large upfront cost that is fixed and sunk. It is fixed in the sense that it is required even before any usage can begin. A highway needs to be built before anyone can use it. It is sunk in that once built, one cannot really recoup this cost by selling it. Once a highway is built, the concrete cannot easily be repurposed for something else that has value. Because of these features, most standard infrastructure projects are not very flexible. They are built for a particular design requirement and cannot easily be adjusted if requirements change in the future.

As we discuss in this report, however, there are a number of ways to ensure even during construction that infrastructure can withstand future conditions, which cannot be fully known. Traditionally, designers required infrastructure to be built with "safety buffers" (see Chapter 3). For example, if sea level is projected to rise 1 ft by the middle of the century but there's a 10% chance it rises by 2 ft, the uncertainty could be addressed by requiring a structure to be built with a 2 ft clearance. This is costly as it is building for a lower-probability event but, if it occurs, can be a high-impact event. An alternative approach is to require that infrastructure is built with some degree of modularity so that it can be adaptively adjusted in the future, if needed. In the example above, engineers could design the highway today such that it meets the near-term needs of accommodating just 1 ft of rise, but has the option to build it higher in the future if the 2 ft rise becomes reality. This might involve a stronger base to elevate protective measures or the ability to raise the structure or space to move it back (Figure 5.3). In the first (safety buffer) approach, infrastructure is fixed now to deal with the "worst case" of what is known about the future today. In the second (adaptive) approach, infrastructure is built in a modular fashion to allow for adjustment if it becomes necessary at some point in the future.

Neither adaptive design choices in different infrastructure sectors nor cost estimates of these options – compared to traditional design choices – are well understood at this time. While the shift in this direction has begun (B. Ayyub, presentation to the CSIWG 2018; see also discussion in Chapter 6), questions arise as to whether traditional cost-benefit analyses adequately capture the value gained for such construction, despite potentially higher initial cost outlays (see Chapter 8). How to incentivize adaptive design approaches is insufficiently understood and there is still a paucity of research on what cost-benefit methodologies

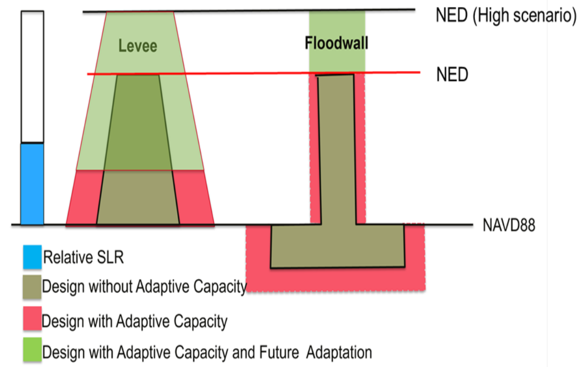


Figure 5.3: Cross sections of a levee and a seawall built with foresight and adaptive capacity so that the protective structures can be enlarged in size later if or when sea-level rise requires additional protection. (Source: Kate White webinar 2018, USACE)

might be best. Research is therefore needed to improve economic models and cost-benefit analysis methodologies to better model the true life-cycle costs of adaptive design. This may entail a paradigm shift as future resilience is not currently prioritized in traditional analyses.

More fundamentally, there are profound knowledge gaps as to how much it might cost to adapt California's infrastructure to the changing climate. The State should invest in economic research to better understand the growing fiscal risks (and opportunities) from climate change impacts and adaptation, particularly in the context of an integrated infrastructure investment strategy (Chapter 8).

Tools, Platforms and Processes to Support the Exchange between Scientists, Engineers and Architects

AB 2800 mandated that the CSIWG review and include recommendations on tools and "a platform or process to facilitate communication between climate scientists, infrastructure engineers [and architects]." CSIWG members discussed their experiences with existing tools, platforms and processes, the strengths and weaknesses of those, and what they see as the most useful path forward for the State.

Existing Efforts

The CSIWG emphasized the importance of recognizing that there is already ongoing work at various State agencies to facilitate discussion among climate scientists, engineers and architects. During in-state conferences, California's climate change assessments and research activities, professional association meetings (e.g., annual meetings of the American Geophysical Union (AGU), which in the past were regularly held in San Francisco) and in other venues and activities, state engineers have actively engaged with climate scientists for many years. In turn, these exchanges have informed the direction and usefulness of climate science for practicing engineers. While difficult to measure, such interactions have led to the formation of lasting and valuable personal relationships and the creation of trust between individual climate scientists and state engineers, providing for informal, two-way consultation on a variety of scientific matters (Box 5.2). Within California, state engineers have also worked closely with state-based climate researchers in several research studies included in the Fourth Assessment (see also Chapter 2), and such collaboration in future research and assessment activities should be continued and enhanced, starting with the development of user-oriented research agendas to ensure that the science that gets funded fits the most pressing state needs.

State agencies also have made dedicated efforts to bring together climate scientists and state engineers for focused projects and outcomes. For instance, DWR has twice formally assembled a Climate Change Technical Advisory Group (CCTAG), the first to specifically advise the *California Water Plan Update 2009*, and the second – which involved CSIWG member, Dr. Dan Cayan, and Project Team member, Guido Franco – to provide advice on the use of planning approaches and analytical tools in DWR project management. In 2015, this collaboration, chaired by DWR climate scientist Elissa Lynn, produced a widely cited final report, *Perspectives and Guidance for Climate Change Analysis*[219], which directly informed the state's Fourth Climate Change Assessment[220]. This process of bringing together scientists and engineers was also the subject of a poster at the AGU meeting in 2016 (Appendix 6).

Yet, while DWR's CCTAG is an excellent example of interdisciplinary coordination, these types of efforts are still not commonplace, largely because they require significant resources (money, time and people) and sustained commitment from the lead agency and the participating scientists to ensure a continued effort and actionable outcomes. Moreover, the purview of the CCTAG was focused on just one sector; but this level of effort needs to be replicated across all critical infrastructure sectors (transportation, energy, buildings, telecommunications etc.) in order to advance climate-safe infrastructure across the State's assets.

The challenge is also bigger than "simply" bringing together climate scientists, engineers and architects. Throughout the CSIWG's discussions, it became evident that big sources of uncertainty or lack of knowledge are not only about climate change but are related to the subject matters of other disciplines, such as economics, land use, demographics and behavioral science as discussed above. Similarly, discussions on policy design, governance, implementation of new methods through workforce development and training, and concerns of ensuring social equity, are also critical to the discussion. Thus, there may not be a single platform or process, and for any to be effective, the engagement must include representatives from all of these disciplines and areas of expertise. It will take time for participants to understand each other's language and concerns, thus sustained efforts will actually be more cost-effective than one-off engagements (Box 5.3).

Box 5.2: Unsung Heroes

While mostly unsung, there is a long and rich history of the state's engineers communicating and working with climate scientists. In 1987, Mr. Maury Roos, Chief Hydrologist for DWR, presented a paper entitled "Possible Changes in California Snowmelt Patterns" at the Fourth Pacific Climate (PACLIM) workshop in Pacific Grove, California – one of the early investigations into the effects of a changing climate on California's water resources. Another example is Guido Franco, a licensed mechanical engineer with the California Energy Commission (CEC). Mr. Franco has played a major role in each of the state's four climate change assessments (2006, 2009, 2012 and 2018), mandated by former Governor Schwarzenegger's Executive Order S-3-05. State engineers, including Mr. Franco, are also members of the editorial board for California's Fourth Climate Change Assessment. Mr. Franco is a key contributor to the state's Climate Change Research Program, as is Dr. Michael Anderson, a licensed civil engineer with DWR, who also serves as California's official State Climatologist.

Clockwise from left; Marty Ralph, Scripps Institute of Oceanography, Michael Anderson, State Climatologist with DWR, Jay Jasperse, Sonoma County Water Agency, and Jeanine Jones, Interstate Resources Manager at DWR, during a break at an October 2016 workshop on drought vulnerability in southern California. (Photo: Kelly M. Grow, DWR, used with permission)

Box 5.3: California and the Sustained National Climate Assessment Process

During the development of the Third National Climate Assessment (NCA3, delivered in 2014), a new concept was developed – namely, the idea of a sustained national climate assessment[221]. The idea of a sustained assessment was in part a response to the "stop-and-go" approach to previous national climate assessments, mandated by federal law since 1990 to be delivered to Congress every four years, but for a number of reasons not delivered with this regularity[222]. At the same time, many information users and decision-makers increasingly ask for state-of-the-art data and usable, actionable knowledge syntheses, which were not being delivered through the national assessment reports.

Since then, the notion of a sustained assessment has been significantly developed further (see also Moss 2018 webinar). While assessments in California typically involve the production of new research, more commonly assessments serve to synthesize existing science and critically assess the state of knowledge so as to provide reliable guidance to decision-makers on what is well understood and what is less well known at a given point in time (examples of this approach include the NCA and the IPCC assessments).

The sustained assessment idea (although still evolving) describes an ongoing platform for interactions between researchers and science users, drawing heavily on partnerships of federal agencies, research institutions, science-based non-governmental organizations, professional societies and others to provide knowledge syntheses and assessments that are driven by user needs. If traditionally assessments focused only on the state of science, a sustained assessment could also include assessments of the state of practice that is of interest to practitioners (e.g., to support the search for innovative or best practices). Similarly, the traditional sector or regional focus could be augmented with an emphasis on implementation challenges (such as updating codes, assessing financial risks of different adaptation approaches or design challenges).

California could greatly benefit from actively participating in shaping and implementing the sustained assessment process. Opportunities include the following:

- **Active participation in the sustained assessment process:** As the sustained assessment consortium of civil society and State/local/tribal groups is launched, California should be actively represented in the consortium and process. The consortium will identify, develop and evaluate sources of reliable, relevant and actionable information to support action, and to contribute to integration of knowledge and scientific understanding. California will benefit both from ensuring its own research is included, thus illustrating its national leadership, and from learning from the work done by others.
- **Convene sustained conversations (e.g., communities of practice involving scientists, engineers and architects) about the challenges, opportunities and benefits of applying climate change science (broadly defined) in infrastructure design:** This could also involve direct engagement with professional societies to ensure a direct link into entities that shape standards and guidelines at the national level.
- **Foster innovation in the applied science/engineering community:** As this report shows, the engineering community is not only challenged to adopt new scientific information into its traditional ways of doing things, but – over time – to transform its ways of doing business. There are many dimensions of these novel practices and engineers and architects across the nation can and should learn about and from them. The sustained assessment process is one way to track and share innovative practices initiated in California and elsewhere.
- **Improve linkages between state-level assessments and NCA reports:** Many states are undertaking their own assessments, but when they are not aligned in time with the national assessment report cycles, much of what is being learned at the state level is not shared nationally and vice versa.[2] Thus, coordinating timing, ensuring regional representation and reducing overly burdensome demands on researchers participating in both assessments would improve state-national assessment linkages.

[2] California's Fourth Climate Assessment is concluded and released publicly one month after the deadline for inclusion of papers in the Fourth National Climate Assessment, resulting in hundreds of thousands of dollars of State-funded research not being able to be included in the NCA4. The Fourth Assessment reports that were accepted for publication prior to June 15 and personally brought to the attention of NCA4 author teams are an exception.

What Makes Platforms Successful?

Based on a literature and web review and meeting discussions, the CSIWG identified the following five interconnected criteria that both build on each other and are equally critical to developing effective science-practice processes in support of building climate-safe infrastructure.

1. **Establishing clearly defined goals and priorities.** Before commencing discussion via any means (tools, process or platform), the CSIWG felt that the critical first step is to identify the goals and priorities for the discussion and to have these bounded by specific outcomes. Working Group members agreed that any effort to create a Climate-Safe Infrastructure platform should have one or more specific products to work towards (see, e.g., discussion on a California-specific Manual of Practice below).
2. **Engaging the right participants.** The CSIWG highlighted the importance of careful curation of platform participants and discussants. Experts from various disciplines must be included, as well as participants who are knowledgeable on the technical or practical details as well as those who can work well across areas of expertise and who can help facilitate conversation (these might not always be the same people). It is also important to ensure that all participants recognize that they both contribute to and get something out of the process (see discussion below on continuing the work of the CSIWG).
3. **Sustaining a deliberative process and the funds to support it.** Identifying the process and requirements for developing climate-safe infrastructure is not something that can be accomplished in a handful of sporadic, ad-hoc meetings. The science is ever-evolving as are engineering methodologies. Thus, as goals are set, consideration of the timeline required to meet those goals should be commensurate. For ultimate success, these discussions must also include a sustained source of funding, which is especially important to ensure equitable social inclusion and participation for all relevant voices (see social equity discussions in Chapter 4 and implementation needs in Chapter 9).
4. **Being able to form robust and trusting relationships.** In the most successful examples, CSIWG members identified the development of trust among participants one of the most important components of successful collaboration, resulting in useful products and outcomes. This requires having the opportunity to engage with others on a consistent basis for a specified period of time, which will likely require commitment of funding from agency budgets, NGOs, philanthropic organizations, private sector, professional or academic societies, or ideally some combination of all (Figure 5.4).
5. **Prioritizing transparency.** Transparency builds trust. To many engineers, climate models are black boxes they do not understand. To many scientists and non-governmental outsiders, the same is true for government decision-making processes. As a result, data and decisions are suspect and less likely to be used or accepted. Transparency and trust-building in the co-creation of actionable scientific information for application in infrastructure design and planning is thus a critical pre-condition for use of data and tools.

The success of the DWR CCTAG example described above highlights many of these criteria[220]. DWR prioritized this work and provided some financial support via travel stipends for CCTAG members. The CCTAG members were also committed to the process and were willing to donate their time and effort to help advance the goals of the group, which were well-defined from the inception. Additionally, DWR highlighted the identification of the "right" mix of experts who developed a trusting relationship due to the sustained nature of the effort, which spanned three years.

The Working Group reviewed a number of existing platforms that have the goal of linking science to practical applications. Examples are shown in Table 5.3, yet none resolve the challenges discussed during the CSIWG deliberations. There was consensus among the CSIWG that continued opportunities for scientists, engineers and architects to interact was critical to advancing climate-safe infrastructure in California, but that development of a new platform was not necessary. Indeed, the CSIWG preferred building on existing platforms that could be bolstered to include dedicated time, effort and funding to address the recommendations identified in this report.

Figure 5.4: Developing trust among diverse participants with different types of expertise and knowledges is one of the most important components of successful collaborations. (Photo: DWR, used with permission)

Table 5.3: Sample of Platforms Available for Exchange Between Scientists, Engineers and Architects

Data portals • Cal-Adapt • USGS Coastal Storm Modeling System/Our Coast Our Future • Climate Model Intercomparison Project (CMIP) • WeatherShift™
Tools platforms • Digital Coast • Resilience Toolkit
Interactive forums • Thriving Earth Exchange • Resilience Dialogues • Professional Society Meetings (e.g., AGU, ASAP, ASCE regional meetings) • California Adaptation Forum • National Adaptation Forum • National Academy of Sciences – Disasters Roundtable
Interactive forums • California Adaptation Clearinghouse • Georgetown Climate Center Adaptation Clearinghouse

While there are an increasing number of scientists who speak at professional society meetings and practicing engineers and architects who address scientific audiences, the CSIWG did not find any standing science-engineering/architecture platforms dedicated to addressing the infrastructure design challenges arising from climate change. Some of the data portals and platforms listed in Table 5.3 were not known to or are not regularly (if at all) frequented by engineers and architects, including Cal-Adapt. Thus, they should be viewed as opportunities that could be used to foster better and more frequent interactions across the science-practice interface. In addition, scientific data must be brought to those data portals that engineers and architects already use.

One example is to make better use of the California Adaptation Forum (CAF). That conference already attracts local and regional practitioners as well as a range of consultants grappling with many of the climate adaptation considerations the CSIWG discussed, but engineers, architects and climate scientists do not attend that event in significant numbers. Similarly, practitioners on their part, do not usually attend the technical conferences generally convened by professional societies and academic organizations. Yet, as witnessed by the important discussions elicited during Working Group meetings and webinars that engaged a wide range of external experts with deep experience of working on the ground – this type of transdisciplinary dialogue is needed and critical. During future CAFs, the State could hold workshops specifically focused on discussions among state engineers and architects, physical and social climate scientists, local practitioners and professional societies to increase such transdisciplinary interactions and exchanges.

Deliberate, enhanced and sustained engagement of scientists with professional societies is a critical area on which to focus.

Deliberate, enhanced and sustained engagement of scientists with professional societies where engineers and architects already gather is another area on which to focus. Sharing the experience and process as well as outcomes of California's CSIWG will be of great interest to professional societies and other states. As we described in Chapter 1, this type of engagement has begun during the life of the CSIWG, but should be sustained and deepened over time.

Tools in Support of Climate-Safe Infrastructure

In response to the AB 2800 mandate to "consider and investigate the information and institutional barriers to integrating projected climate change impacts into state infrastructure design," the CSIWG also discussed available tools – both throughout California, as well as nationally and globally – that provide climate science information. Tools identified during Working Group meetings and through external data-gathering are listed in Appendix 5.

There are indeed many tools that have been developed that aim to connect practitioners to climate science, with the hope of advancing climate adaptation. As with the discussion on platforms and conferences from the previous section, however, these tools may not be the ones that state engineers and architects are likely to use. Moreover, there is at this point an overabundance of different types of tools that are variations of each other, with slightly different intended audiences and information. For instance, K. Baja pointed out during the webinar on tools that there are 4,300 green infrastructure tools and resources available to practitioners. Additional common challenges with regard to tools include:

- Most practitioners are unaware of available tools;
- Tools are ill-designed, difficult to use and there is typically no online or in-person support available to help practitioners use the tools effectively;
- Tools do not meet the specific needs of users (e.g., answer cost of action/inaction questions);
- Information available through tools does not connect to existing processes or reporting requirements;
- Tools do not help practitioners address real-life complexities;
- There is no way of knowing which tools are reliable or preferable to use over others; and
- Tools are for single purposes, without helping practitioners connect to the next step in the planning or design process.

While there remains considerable discussion on which data are available and if they are at the right scale for engineering projects (see Chapters 2 and 3), there was consensus among the CSIWG that development of new tools that are specifically focused on the climate science/engineering interface is not necessary, and maybe not even desirable. Rather, CSIWG members felt that existing tools could be modified and/or expanded to incorporate the level of information that would be most relevant for infrastructure-scale projects. One option is to modify Cal-Adapt to answer engineers' and architects' information needs.

Critical to the development and updating of any tool, however, is ensuring that tools meet the needs of end-users. To achieve this goal:

- Tools must be co-designed with the intended end user;
- There must be direct support and step-by-step guidance for using the tool appropriately; and
- The tools must effectively integrate social equity.

Existing tools could be modified and/or expanded to incorporate the level of information that would be most relevant for infrastructure-scale projects.

Summary: Platform, Tools and Data to Support the Climate-Safe Path for All

As described above, with important State policies in place, the tremendous breadth of research that has been funded through the state's climate assessments, as well as the conferences, platforms and tools already available or under development, key elements of an innovative and effective data and analytics system to support the building of climate-safe infrastructure are already in place and now must be tied together and augmented, not reinvented or replaced. Recommendation 3 intends to help the State put the pieces together.

Whether it is through a national scale connection to the Sustained Climate Assessment, or through augmentation of the state's adaptation clearinghouse, including its Technical Advisory Group, or the better use of gatherings such as the CAF, formalized processes should be developed in which state engineers and architects have deliberate and sustained interaction with physical and social climate change scientists from diverse research institutions, as well as professional organizations and other experts and stakeholders (see, for example, Chapter 8 for the engagement of financial experts).

Recommendation 3

Because of the diversity of State agencies, types of infrastructure and their vulnerabilities, and the specific needs for climate science, there cannot be a one-size-fits-all recipe for State agencies to engage with the climate change science community. That said, the State budget should provide full funding to State infrastructure agencies so they can dedicate time and support to their engineers and architects to substantively and collaboratively interact with climate scientists and other relevant experts in the creation of useful advice, guidance and tools on a regular and ongoing basis, in a way and at a level appropriate to their needs.

There are a number of steps the State can take in operationalizing this recommendation, including:

1. Expand timely options for state engineers and architects to travel outside of California to participate in professional conferences. The knowledge and talent to address the complex issue of global climate change often lies beyond the borders of California.
2. Develop a prioritized and expedited process for State agencies to leverage the expertise at universities and other research institutions in order to engage climate scientists on specific projects and studies.
3. Building on emerging efforts, Cal-Adapt should become more useful to sectors beyond the energy sector. Through an engaged, user-needs driven and broadly inclusive process, Cal-Adapt – and sister tools – could be updated to provide California-specific physical and social science information at the scale and resolution needed by state engineers and architects. Concerted outreach will be needed to raise awareness of this information among state engineers and architects. In addition, common data portals used by engineers should create links to Cal-Adapt to further raise awareness of available data in those places that engineers and architects already frequent.
4. In addition, relevant international and national science products and data sets should be more easily accessible (i.e., linked to) through Cal-Adapt to bring them to the attention of California data users.
5. All state geophysical research results should be consolidated into a single location (e.g., the State Open Data Portal and mechanisms should be created to regularly update these geophysical data (see Glossary). This would entail developing active data integration and consolidation policies and procedures to ensure users have access to all the state's best thinking on our changing geophysical environment. This should begin with linking all state-generated data sets and providing a common library to access and manage data. In the future, open data, data sharing and data quality policies should be developed that brings scientists' research results into the common platform, thus making continuously-updated information available to users.
6. Equally important to the quality of the data served up on Cal-Adapt, once the tool is established, tool developers (within academia, consultancies, or State agencies) should provide training to end users to help them become familiar with and supportive of innovation and best practices related to sustainability and resilience, including support for collaborative processes. This will be essential to its success and use by the engineering and architectural community.

6 Project Pipeline:
Pre-Development and Prioritization

Introduction

There are a number of critical steps that must be taken to develop a single, linked or bundled set of projects (i.e., a "project pipeline"), that can attract financing from lenders or investors. Only well-advanced ("shovel-ready") and clearly-prioritized projects get implemented on the ground.

To realize the vision of The Climate-Safe Path for All introduced in Chapter 4, it is important in the pre-development process to take forward-looking climate science, social equity and systems thinking into account. Calls for improvements in the pre-development phase are becoming widespread[223], but the approach we rely on here was proposed by re:focus partners in their Re:Invest Guide[224] [1] and has been adopted and recommended in the Financing Guide to project teams involved in the San Francisco Bay Area Resilient by Design competition[225]. While none of the analytical, design, financial planning or legally required steps (e.g., permitting, environmental review) are omitted in the re-envisioned approach, the sequence of steps and the systemic approach taken is far better aligned with the Climate-Safe Path proposed here than traditional approaches (Figure 6.1).

Pre-development is more than a technical planning and design exercise. If one broadens the focus from a single project to a statewide, sectoral or cross-sectoral and

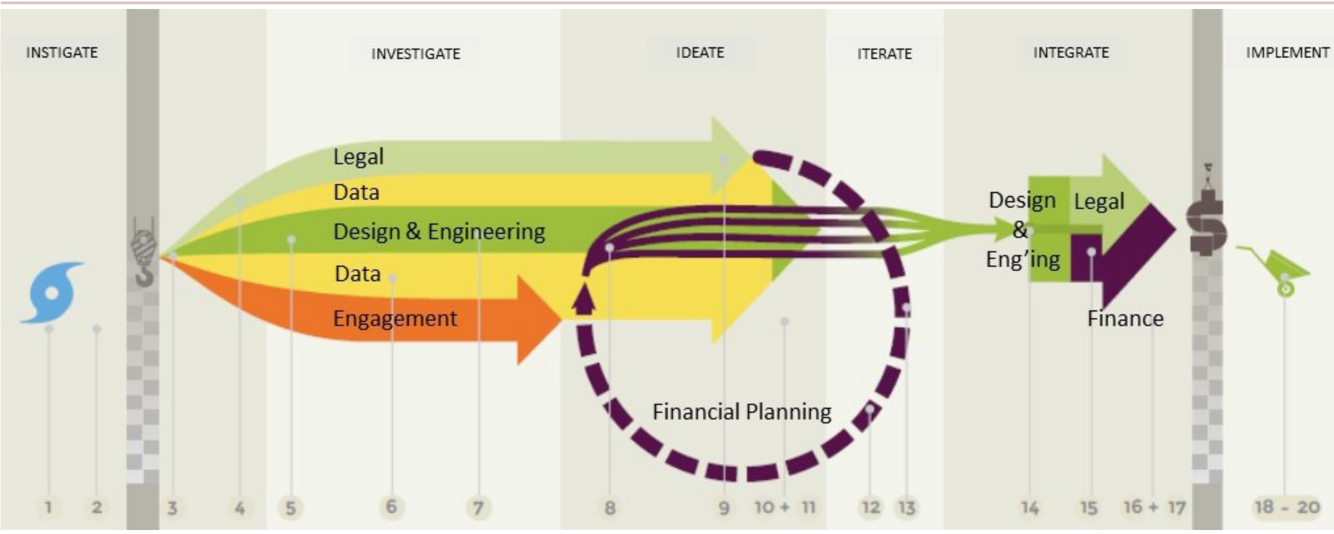


Figure 6.1: The six phases of the pre-development process are far better aligned with the systemic approach proposed in this report compared to traditional project development approaches (individual steps explained in re:focus partners 2015) (Source: adapted from re:focus partners 2015[224]; used with permission)

[1] Readers interested in the full report and a detailed treatment of the steps in the proposed approach including case examples can access the guide at: http://www.reinvestinitiative.org/wp-content/uploads/pdf/RE.invest_Roadmap-For-Resilience.pdf.

systems-oriented infrastructure investment strategy that will be implemented in stages over time, with deliberate movement toward upgrading existing infrastructure and adding new infrastructure that accounts for climate change, then a prioritized line-up of well-integrated projects needs to be developed. And, if the goal is to create climate-safe infrastructure for all as this report proposes – a perspective that takes social equity seriously – then stakeholder engagement is not an add-on late in the project development process, but an integral part of pre-development from the conceptual start in meaningful and creative ways all the way to construction. The difference lies in what questions drive the planning and design process and what problems are being solved. The questions we ask either focus us narrowly or open up to more creative possibilities of solving infrastructure and related problems.

Similar opportunities exist for state infrastructure planning. Traditional single sector-driven projects tend not to be able to take advantage of multi-sector benefits; roles and responsibilities cannot be shared; financing opportunities are more limited; and communities tend to benefit less. While more complex and potentially more time consuming (especially when this approach is still new to participants), doing more of the same will result in more of the same: underinvestment, a high risk of negative unintended consequences and political resistance from those most directly affected. There are, in short, risks involved in both approaches, but only the former is aligned with the Climate-Safe Path for All.

Recommendation 4

During the all-important pre-development phase, projects are conceptualized, planned and designed. The State budget should improve this process by building staff capacity and greatly increasing project funding to better account for a changing and uncertain climate, by addressing social inequity, and by assessing and accounting for the true costs and benefits of integrated projects across their full life-cycle.

Below we note the emerging shift in thinking in the engineering and architecture communities already underway that points to climate-conscious building in support of this overarching recommendation, then describe ways to operationalize it through a more systems-oriented project development process that takes stakeholder engagement and social equity seriously. In the latter part of this chapter we introduce and recommend that engineers and architects use a number of more sophisticated methodologies increasingly available to:

- Better account for the true costs and benefits of infrastructure over the entire life of the infrastructure along an adaptive but uncertain pathway;
- Screen for climate risks so as to determine the best assessment approach to use;
- Assess risks probabilistically and – where that is not possible – still arrive at a robust decision; and
- Design infrastructure in the face of uncertainty.

Infrastructure Planning in a Changing Climate

There is consensus among climate scientists that weather and climate stationarity is no longer a good predictor for the future (as discussed thoroughly in Chapter 2). All types of infrastructure in California (and in many other places) are now being exposed to record high temperatures, prolonged and more extreme heat waves, droughts, wildfires, unpredictable deluge rain events, sea level rise (SLR) as well as mud and debris flows. While these are acute extreme events, they serve as exemplars of what infrastructure in California will experience more frequently and for longer periods of time in the future. Existing and new infrastructure must be able to withstand this new future – a future that was not planned for previously. At a minimum, it is thus critical for forward-looking climate information to be included in updates of existing standards and guidelines while new standards are being developed so that new infrastructure can be designed to be climate safe, as we described in Chapter 4.

At a minimum, it is critical for forward-looking climate information to be included in updates of existing standards and guidelines while new standards are being developed.

In recent years, there has been a growing recognition within the engineering and architecture community that, despite challenges with using forward-looking climate information, it is important to develop methodologies and practices for doing so. In 2015, the American Society of Civil Engineers (ASCE) published a report entitled *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*[178]. In this report, the society provides four recommendations to start moving in this direction:

1. Engineers[2] and climate scientists must engage in cooperative research;
2. Practicing engineers, project stakeholders, policy-makers and decision-makers should be better informed about uncertainty;
3. Engineers need a new paradigm for a world in which climate is changing; and
4. Critical infrastructure most at risk should be identified.

There is still, however, considerable resistance to, and questions about, doing this. A U.S. Government Accountability Office (GAO) report from 2016, entitled *Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications*, identified several of these challenges. As the GAO[226], pp. 18-19, notes:

> "[Representatives from standard setting organizations indicated that] technical challenges include difficulties in identifying the best available forward-looking climate information and incorporating it into standards, codes, and certifications. For example, representatives from one organization said that climate models provide a wide range of possible temperatures that is difficult to use in their standards..., that they need forward-looking climate information for a site-specific project area rather than at the country or state level, which is what is available from climate models..., or that they needed additional detailed information, such as whether any projected increased precipitation would occur evenly throughout the year or in concentrated bursts."

Moreover, as discussions among CSIWG members revealed, many engineers and architects do not feel confident enough to be able to defend climate science in debates with skeptical project sponsors.[3] Because cost is always an issue, arguing for potentially higher upfront outlays to protect against an uncertain (climate) future requires not only solid understanding of climate science but a considerable degree of mastery of approaches for decision-making under deep uncertainty, neither of which are standard components of engineers' and architects' professional education.

Many engineers and architects do not feel confident enough to be able to defend climate science in debates with skeptical project sponsors.

Below, we address some of these challenges (beyond the climate science already discussed in Chapter 2) to equip engineers and architects with concepts and tools that help address these obstacles.

[2] While the ASCE report is geared primarily to licensed engineers, we view these recommendations as transferable to architects.

[3] In early 2018, the ASCE published Policy Statement 556, which recommends that public and private infrastructure owners incorporate sustainability principles (including resilience) into infrastructure projects; the policy also advocates for owners to become more aware and better educated about the need for sustainability with the intent to lessen climate and sustainability skepticism.

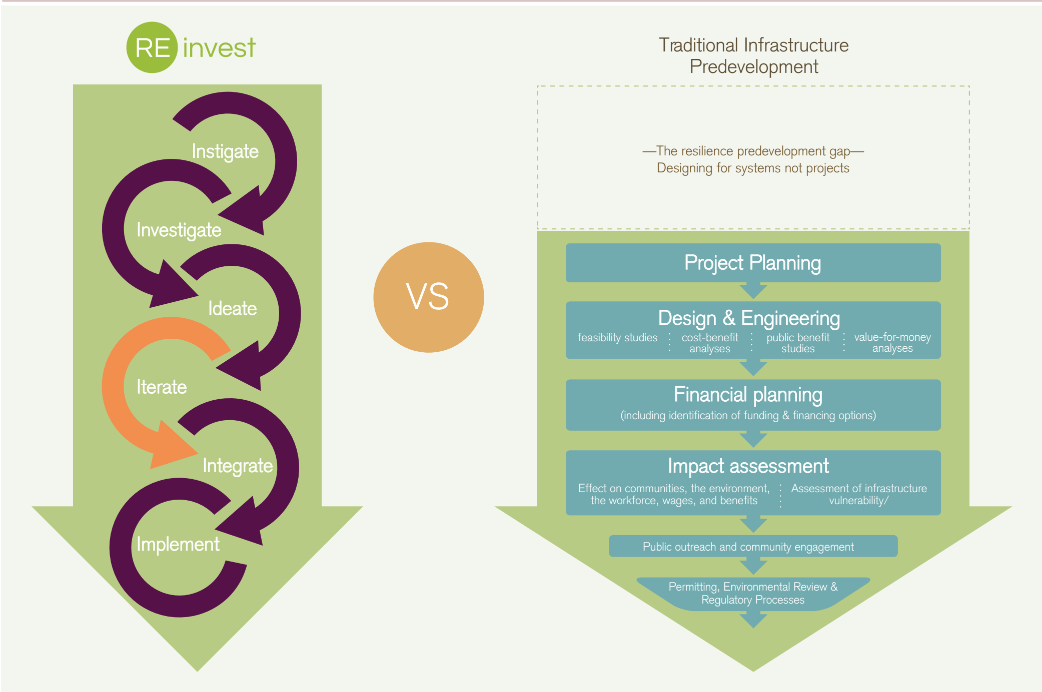


Figure 6.2: Comparison of a traditional versus Re:Invest's 6 I's infrastructure pre-development process (Source: re:focus partners 2015[224], used with permission)

Pre-Development

During pre-development, infrastructure projects go from being just an idea to being well-laid plans and designs ready be built. Often supported by short-term funding from general funds and grants, pre-development determines the goals of the project, assesses their economic and technical feasibility, explores and decides among different design options, and involves all necessary components of project planning – including developing financial plans to make projects investor-ready. As Figure 6.2 illustrates, traditional approaches to project development tend to be narrowly project or sector-focused and do not make room for design choices with broad, multi-sector benefits. Stakeholders come late into the process, and typically only after design choices have been made.

The modified step-by-step process proposed by re:focus partners[224] reshuffles the order of steps, remains open to reiteration to ensure greater stakeholder engagement and satisfaction emphasizes cross-sector integration to solve multiple problems at once, opens up additional funding sources and reaps more benefits. "Examples of this approach include integrating broadband or fiber networks into water system upgrades, running utilities through new sea water berms, or finding ways to create new energy or water efficiencies. These approaches bring conventional revenue-generating infrastructure into a larger portfolio of resilience solutions to help fund project implementation"[225].

Effective Stakeholder Engagement

This reworked pre-development approach emphasizes the early building of "communities of benefit" as a source of ideas, funding and political support. Some partners will be directly affected, for example through job opportunities, environmental co-benefits of infrastructure investments, improved property values in neighborhoods with upgraded infrastructure (i.e., measurable benefits) and greater safety from climate-related risks (i.e., the absence of damages, a calculable benefit). In widening circles out from the direct beneficiaries, other partners may benefit in indirect, but still tangible ways such as from greater economic activity and hence greater tax revenues.

During the Climate-Safe Infrastructure webinar series, numerous speakers reiterated the importance of engagement. Similarly, subject matter experts invited to CSIWG meetings emphasized this point. While the arguments are well known and often repeated, the fact that they were made so frequently suggests that early, repeated and meaningful stakeholder engagement is not common or sophisticated practice yet. Dr. Beverly Scott (presentation at CSIWG meeting, June 2018) in particular emphasized the importance of engagement of communities most directly affected by infrastructure projects. She emphasized that social equity should not be thought of as an "initiative" or an "add-on" to projects but as the heart of any project and the underlying policies and programs that drive them. Benefits to communities is what

Recommendation 5

Difficult decisions will have to be made and the impacts of potential policies or decisions on different stakeholder groups are complex and challenging to assess. It is critical therefore to engage all affected stakeholders in a meaningful way, from early on and throughout any decision-making process, using the seven principles of equitable planning and decision-making.1 The Strategic Growth Council is well positioned to take a range of steps to encourage, improve and provide guidance on effective stakeholder engagement in the context of infrastructure development.

Central components necessary to operationalize this recommendation to advance effective stakeholder engagement in state infrastructure projects include the following:

1. Create opportunities for timely and meaningful engagement by a wide range of stakeholders to help develop and evaluate potential policies and programs;
2. Develop guidelines (or even requirements) for effective stakeholder engagement in infrastructure projects;
3. Encourage agency staff to attend relevant conferences and meetings to make their constituents aware of proposed guidelines and to solicit comments;
4. Hold trainings for stakeholder engagement facilitators; and
5. Track progress on social equity (e.g., by using the questions and indicators proposed in Box 4.2).

infrastructure should be about. In her words, "If you do not center what is important, it will not happen later." She considered this necessary shift in thinking a "culture shift" in engineering.

If equitable climate safety is the outcome of the Climate-Safe Path for All, achieving it requires, as Chione Flegal put it, "shared decision-making that is rooted in transparency and a commitment to changing inequitable policies and practices, intended and unintended." Engineers and architects and their project partners must thus see community leaders as experts in and of their communities. Failing to include them can result in unintended harm, while inclusion can create buy-in. She warned, however, that "community engagement and partnerships are necessary vehicles towards achieving equity, but in and of themselves, do not achieve equity." To achieve equity requires tangible changes in policy, projects, decision-making processes and outcomes.

Identification of relevant project outcomes – through meaningful engagement – thus must begin by co-creating a shared, community-endorsed vision that is at once broad enough to matter and specific enough to shape decisions. Defining needs, identifying shared priorities, assessing opportunities and availability of resources as well as obstacles to access necessary resources, and joint setting of priorities (different ones for different scales of action) are critical steps in the process. Starting small as part of bigger projects can satisfy immediate needs and build trust. Effective communication to link initial steps and small successes with the goals of the larger pathway to the shared visions is equally important as any one project alone may not achieve the shared priorities and vision, but multiple projects together can.

Public participation in State planning processes can be very time consuming and impact work and family schedules. In the development of the 2017 Safeguarding California Plan Update, the Natural Resources Agency benefited greatly from organized input from a coalition of environmental justice and community-based organization that were supported by philanthropic funding. The State should build on this model by both funding its own representatives to prioritize stakeholder engagement and by working with philanthropic funders to support funded participation of these organizations in infrastructure policy and project development. These external organizations often also provide the added and immeasurable benefit of being trusted by the impacted communities, which can lead to more efficient and effective engagement.

Importantly, training will be required on each of the above-mentioned principles and approaches to ensure that practitioners are employing these strategies appropriately.

Climate-Screening Tool

In Chapter 4 we articulated a way to prioritize infrastructure projects (Figure 4.6). One of the prioritization criteria was exposure to climate risks. How should this get operationalized?

It begins by requiring an assessment of how future changes in climate might affect the infrastructure. In some cases, it is relatively straightforward to assess the potential effects of climate and account for this in the design of infrastructure. For example, warming temperatures are not likely to cause a significant increase in additional heat stress of existing road materials in the coastal areas of California over the next 20 years (at which time they will be resurfaced and the assessment would be repeated). In other cases, the effects of climate may be complex, and the infrastructure design could be particularly sensitive to potential changes. Flood control infrastructure, for example, can be highly sensitive to changes in hydrology. Recognizing that different infrastructures need different climate vulnerability evaluations, we recommend that California develop a screening process that can be used to guide how much climate analysis is necessary in order to design climate-safe infrastructure in an efficient way.

Drawing on other screening processes in the literature and in practice[227-230], the CSIWG proposes a simple, straight-forward three-tiered approach (Figure 6.4).

The first level – Initial Screening – consists of two steps: (1) defining a performance threshold for infrastructure and (2) assessing qualitatively whether current or future climate change – both the average changes as well the potential projected extremes (particularly on the high-emissions scenario) - might degrade performance beyond thresholds. The result of a Level 1 evaluation could be a simple check-list indicating that different aspects of the infrastructure as designed would not be sensitive to plausible changes in climate over the lifetime of the infrastructure (i.e., lifetime = design life + reasonable period over which well-maintained infrastructure is expected to function). If the qualitative assessment reveals potential sensitivity, then the evaluation would move to Level 2.

The second level – Climate Stress Test – would involve some quantitative analysis. First, it would evaluate quantitatively the system performance over a wide range of plausible current and future climate parameters (again, averages and extremes from a range of global climate models), with particular emphasis – in concordance with the Climate-Safe Path – on climate impacts under a high-emissions pathway. Second, the analysts would compare any identified vulnerabilities to available climate information to ascertain how plausible the identified vulnerabilities are. If the identified risks appear low, then the evaluation would stop with a climate risk statement documenting the findings. If the risks are found to be high, then the third level of assessment would be required.

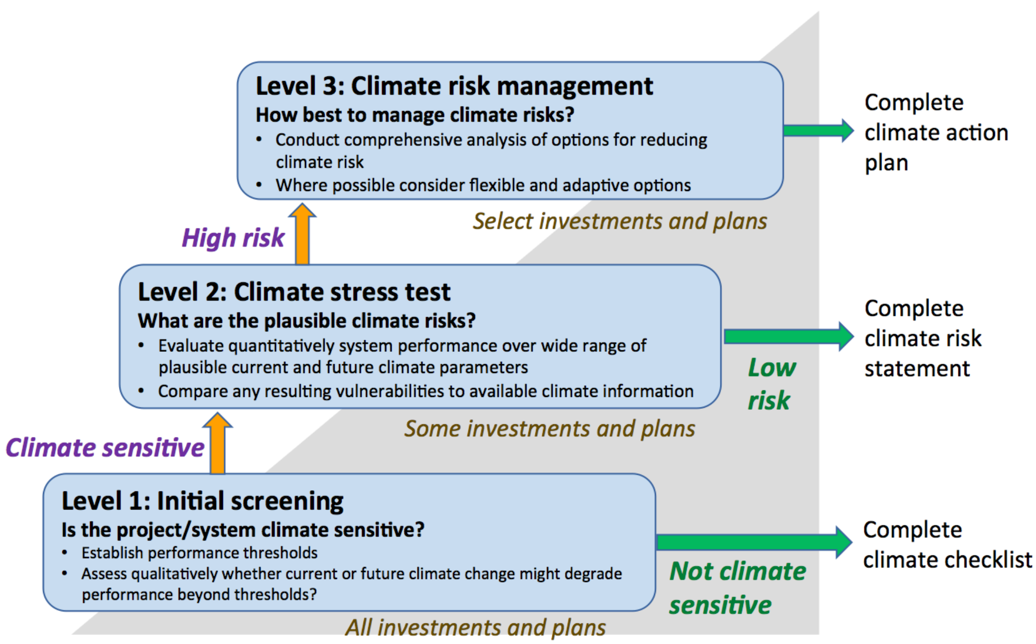


Figure 6.4 The proposed three-tiered screening process (Source: Robert Lempert, used with permission)

The third level – Climate Risk Management – requires a comprehensive evaluation of options for reducing the identified risks, including alternative designs that are flexible and adaptable (see further discussion below). As future climate is deeply uncertain, i.e., it is not easily described through probability statements, alternative methods for the analysis of options are required (see Box 6.1 below on decision-making under deep uncertainty). The results of the third level of analysis would be a climate action plan that describes a modified infrastructure design that is shown to be climate-safe through the combination of a number of different strategies (Box 4.1 in Chapter 4) over a wide range of plausible climate futures.

To further operationalize how California can move toward climate-safe infrastructure – both at an agency and at a project level, the CSIWG recommends that infrastructure planners, engineers and architects employ this climate screening tool to identify assets that require an extensive climate action plan. Together with the other prioritization criteria outlined in Chapter 4 (infrastructure investment gap and potential to reduce social equity), this will help move toward a priority list of projects that will make a significant contribution to realizing the Climate-Safe Path for All.

Project Feasibility: Calculating Cost Effectiveness of Climate-Safe Infrastructure

Assessing the economic feasibility of infrastructure projects is often the first step after a project has been proposed. As we argued earlier, the traditional approach has been too narrow, and often predetermines certain "solutions" before a more comprehensive analysis has been undertaken.

Over the course of the work of the CSIWG, members discussed and learned about a number of ways in which traditional benefit cost analysis (BCA) is limited. For example, BCA:

- Focuses on easily monetized costs and benefits, but externalizes or ignores many more difficult-to-assess benefits and costs;
- Often is carried out only for the initial cost (capital outlay) and does not consider operations and mainteance (O&M) costs over the entire lifecycle of the infrastructure;
- Significantly discounts the future (a values choice, often reflected in signals from capital markets);
- Is not well suited for infrastructure using adaptive design approaches over the course of many decades in order to better deal with uncertainty in scientific projections; and
- Is often narrowly project-focused, rather than system-focused and typically does not account for costs and benefits that accrue to other sectors.

Taken together, these problems result in upfront costs of protective measures being overstated while the systemwide benefits of taking them are underestimated.

There are better tools available, but these are not always widely known or appropriately applied. Over the course of CSIWG deliberations and webinar presentations, the Working Group learned of several more sophisticated alternatives:

- The life-cycle cost and benefit assessment tool developed by the Zofnass Program for Sustainable Infrastructure at Harvard University (a compliment to the increasingly commonly used ENVISION tool[4] (see also[231]);
- Real Options Analysis – an economic cost-benefit approach that operationalizes the notion of adaptation pathways from an economic perspective by combining decision tree analysis with BCA;
- Robust decision-making – an iterative analytic process, often used in engagements with stakeholders, designed to support decision making under deep uncertainty by trying to identify strategies that work cost-effectively over a wide range of climate futures and other decision-relevant factors; and
- Triple bottom line analysis, which evaluates cost effectiveness based on social, environmental and economic criteria.

While by no means a complete list, these alternative approaches complement and enhance traditional BCA and illustrate that more sophisticated economic tools are available but not commonly used – to the detriment of the ultimate choices made and outcomes achieved. These tools must be brought to engineers', architects', and project managers' attention, and those individuals must learn when and how to use such tools appropriately.

The CSIWG sees an important opportunity for the State to improve the benefit-cost assessment approaches it uses. Instead of conventional BCA, the State should use more sophisticated methods that account for:

- The full infrastructure life-cycle, not just initial capital outlays;
- The cost of inaction;
- The deep uncertainty in both climatic and non-climatic aspects of the future;
- Adaptation pathways and the adaptive implementation of design choices;
- Benefits and costs to systems, not just projects; and
- The social costs and benefits to ensure that equity is explicitly accounted for.

[4] For more information, see: http://economictool.zofnass.org/ and: http://sustainableinfrastructure.org/envision/.

Probabilistic Risk Management

In Chapter 2, we explained the fundamental sources of uncertainties in making climate change projections. We also explained (see Box 2.2) that probabilistic climate change projections as developed for the Ocean Protection Council's (OPC) SLR guidance[49] or the Fourth Assessment are only conditional probabilities: they provide the odds for particular outcomes under the assumption of a particular emissions pathway that society may or may not follow. OPR's State guidance[230] urges planners and decision-makers to consider projections using the high-emissions scenario for decisions with time horizons up to 2050; beyond that, OPR suggests assessing risks under both a mid-level and the high-emissions scenario, but emphasize the latter for high-risk infrastructure. In this report, we similarly urge the State to consider the high-end emissions scenario across all projects to be consistent with the legislative intent of AB 2800.

But even with just that one, high-emissions scenario, considerable uncertainties remain that must be accounted for. While probabilistic projections are increasingly being made available for this scenario at the temporal and spatial scales needed by engineers and scientists (see Chapters 2 and 5), how should engineers and architects use that information in project development?

Probabilistic risk management approaches are increasingly common and widely recommended for climate change planning, but many are not yet deeply familiar with them. The typical arguments for employing such approaches, include the following:

- The magnitude of potential hazards from climate change are both diverse and potentially large, but there is irreducible uncertainty as to their timing and likelihood of hazardous events;
- Risk management seeks to eliminate or reduce hazards, and then to mitigate the hazards that remain. For cases when hazardous events occur, risk management also involves absorbing or resisting damage, and when the magnitude is too great, accepting and spreading the burden from the harms that result;
- Risk-based approaches weigh the likelihood of a hazard and the severity of the potential consequences against a defined set of criteria that can be used to make high-level decisions about how to act; and
- The goal of a managed risk approach is to quantify the potential hazard severity and the likelihood and frequency of its occurrence to enable an agency to rank all the risks it faces and to make reasoned decisions as to where to focus efforts and limited resources.

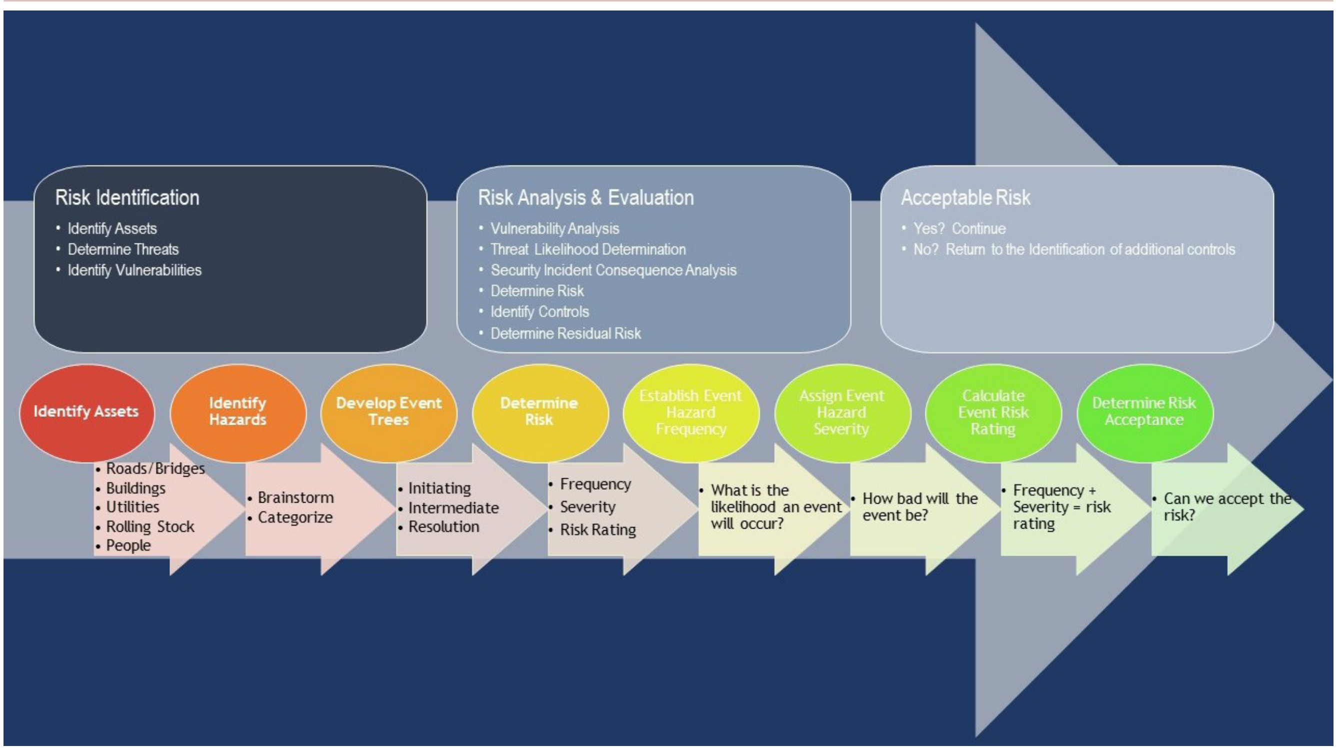


Figure 6.5 Steps in a probabilistic risk management approach to climate adaptation (Source: Image courtesy of James Deane, California High-Speed Rail)

The process to assess risk involves five critical steps (the complete process with additional steps is shown in Figure 6.5 using eight circles), to: identify hazards; determine frequency; assign severity; assign event risk ratings; and evaluate risk acceptance in light of the ratings. This basic approach has been used in a variety of contexts and cases; a useful one related to developing a climate risk management approach for infrastructure design is the assessment undertaken for New York City[232]. We include a case example of probabilistic risk assessment and management in Appendix 7. The Working Group believes that the basic risk assessment approach illustrated by these examples is a helpful approach to infrastructure decisions and related risk management for time horizons of 20-30 years. Over time, infrastructure planners and operators should monitor and update their risk assessment to ensure observation and updated science continue to inform the risk calculus and needed updates to the risk management strategy.

Given the limits to providing probabilities for climate change impacts with confidence, however, particularly over long time horizons (i.e., for infrastructure expected to be functional past 2050), other approaches can be employed in tandem with traditional probabilistic risk management, helping to identify ideal project designs, given multiple sources of deep uncertainty (Box 6.1). Appendix 8 offers a simplified example of considering climate change impacts when upgrading existing infrastructure.

Innovative Design Choices

Toward A New Paradigm for a Changing World

With actionable climate science in hand, improved approaches to project development that include deliberate and enhanced stakeholder engagement, more sophisticated economic feasibility analyses and risk analysis and management approaches, including those developed for DMDU, the final question during the project design phase concerns how to design for uncertainty.

As the ASCE noted in its 2015 report on adaptation[178], there is growing recognition within the infrastructure community that "engineers [and architects] need a new paradigm for a world in which climate is changing." While still (and necessarily) rooted in the world of standards, codes, regulations and guidelines, there are efforts underway now to transform traditional standard-setting processes. Many of the concepts that are starting to gain resonance across the engineering community today have already been circulating for years to decades, but in different disciplines. Concepts such as "adaptive design" have emerged from the theory of adaptive management first proposed in ecology in the 1980s[240,241]. Core risk management concepts such as "safe-to-fail" versus "fail-safe" have long been established in areas ranging from environmental safety to hazardous materials management, from handling lawn mowers to operating big infrastructure projects like the Thames River Estuary barriers[5] (Box 6.1), and increasingly in the context of climate change[242-244]. The necessity to move to "safe-to-fail" becomes notoriously obvious when things go wrong, i.e., when things thought to be safe do fail (such as the BP oil spill or the Fukushima Daiichi nuclear power plant disaster)[245, 246]. We define these concepts below and provide recommendations for what California can do to implement the best of these approaches in developing climate-safe infrastructure.

Adaptive Design

With the recognition that a changing climate will lead to not just one type or level of impact but shifting impacts to existing and new infrastructure over time, the engineering community is increasingly embracing the concept of adaptive design, or adaptive, flexible infrastructure. As most recently defined by Chester and Brady[247], p.10):

> An adaptive infrastructure is one that has the capacity to perceive and respond to perturbations in such a way as to maintain fitness over time. Adaptive infrastructure have the capacity to recognize that stimuli or changes in demand are occurring or will occur including the effects of these stimuli, and have the socio-technical structures in place to change quickly enough to meet future demands.

Some examples of adaptive design can include:

- Levees with adjustable crests;
- Seawalls with adjustable heights;
- Structures that can be dis- and re-assembled;
- Floating structures;
- Non-permanent structures such as long-term campgrounds or temporary housing; and
- Movable structures.

While the ideas of adaptive management have been used by planners for decades, transferring these principles to infrastructure design and implementation by engineers and architects is still in the early days. While this may initially slow adoption of adaptive pathways and design, more research on effective adaptive design principles will help advance the field and provide information for wider support of this methodology. Important questions to examine include (among others):

- How and when should adaptive designs be applied?
- How should uncertainties in future climate projections be included in the context of adaptive design?

[5] In some cases, safe-to-fail approaches can be made adaptive in that failures serve as triggers to move to the next adaptive measure(s). This is the case with the Thames River Barrier.

Box 6.1 : How to Make Good Infrastructure Decisions When Future Climate Change is Hard to Quantify with Confidence?

Traditionally, engineers and others manage risk by quantifying hazards such as flooding with a probability distribution. For instance, transportation engineers might look at historical records and observe the magnitude of the 100-year storm. Based on the resulting probability estimate, engineers would size culverts for a road to most cost-effectively meet desired performance goals. Such risk management approaches are called predict-then-act, because they start with predictions about the future and then recommend actions based on those predictions.

Engineers recognize that probability distributions may not be accurate, so sometimes they add a safety margin (see Box 3.3). But this can get expensive when, as described in this report, the imprecision in the probability distributions is large. For instance, OPC's *2018 Updated Sea-Level Rise Guidance for California*[49] provides a probability distribution that suggests an average of 2 ft of SLR by 2100 as well as an "extreme" sea-level rise scenario of 10 ft that has no probability attached. In most instances, the design of coastal infrastructure systems would be significantly different for 2 ft vs. 10 ft of SLR. State guidance recommends considering many contextual elements of projects in qualitative terms, but how should engineers develop a single approach that quantitatively addresses these different numbers?

AdaptLA Regional Sea Level Rise Planning Project stakeholders play Decisions for the Decade, a role-playing game developed by the World Bank, in partnership with RAND Corporation, to help practitioners learn how to make decisions under deep uncertainty. (Photo: Holly Rindge, used with permission)

In recent years, new risk management approaches have come into use that address this type of challenge. The approaches, which go under the broad label of Decision Making Under Uncertainty (DMUU), or more precisely, Decision Making Under Deep Uncertainty (DMDU)[227], view the future as inherently uncertain, identify a wide range of plausible futures, and use this information to craft infrastructure designs and systems that perform well no matter which future comes to pass.

A variety of such DMDU approaches are commonly used but all share the following common elements. Rather than starting with predictions, they: (1) begin with a proposed infrastructure design; stress test that design over a wide range of futures, including projected extremes; (2) use this information to identify potential vulnerabilities in the design; and then (3) identify modifications to the design, or new designs altogether, that significantly reduce these vulnerabilities.

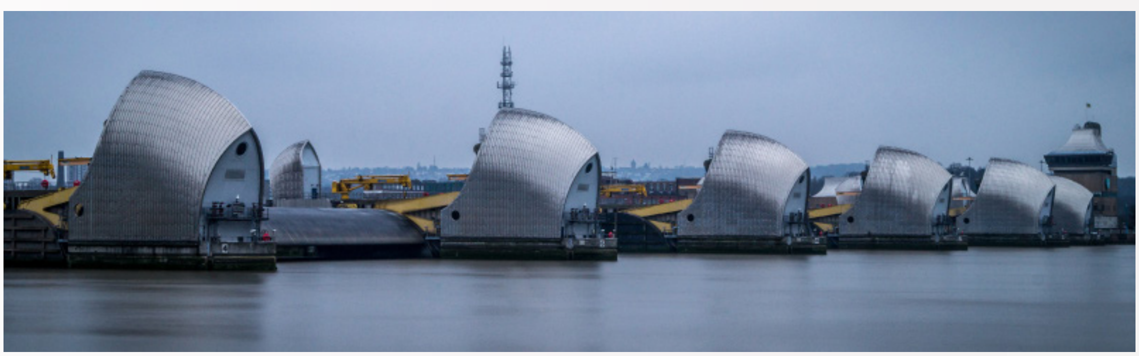
For instance, engineers might modify the design of a levee, making its base larger than currently needed so it might be more easily raised if needed in the future. An example of choosing an entirely new design, engineers seeking reliance against hurricanes of hard-to-predict future intensity, might replace a bridge over a river with bollards. The latter would flood more often, but only for a short while, and could not be destroyed by even the largest storm. We discuss these newer, non-traditional strategies in greater detail below.

What are some of these alternative DMDU approaches? The most common include:

- **Scenario planning,** the most widely used DMDU approach, develops several internally consistent descriptions of the future[233], often using participatory stakeholder processes or expert opinion to choose the scenarios. Engineers can seek designs that perform well in each of the selected scenarios;
- **Robust Decision Making (RDM)**[234-236] is a simulation model-based approach that combines scenario planning with more quantitative risk analysis and is often used in deliberative stakeholder engagements. RDM stress tests proposed infrastructure systems over myriad plausible paths into the future and then uses the resulting database of model runs to identify policy-relevant scenarios and robust adaptive strategies. As one important product, RDM and related approaches such as Decision Scaling[206, 237], often generate scenarios that identify specific vulnerabilities of infrastructure systems due to climate change;
- **Adaptation (or adaptive) pathways**[238] provides a framework for developing, visualizing and evaluating plans that can adjust over time. The approach links the choice of near-term adaptation actions with identifying pre-determined threshold events. Observation of such threshold events would trigger subsequent actions in the planning or implementation stages of adaptation strategies. Often an adaptation pathway includes low-regret near-term actions that preserve future options to adjust if necessary; and
- **Flexible engineering design analysis**[239] uses tools such as real options analysis (see above) to help designers of complex, long-lasting projects – such as communication networks, power plants or hospitals – to abandon fixed specifications and narrow forecasts and build infrastructure system that can be easily adjusted as conditions change.

DMDU methods do use any probabilistic information that scientists can provide. But rather than start the design and planning process with probabilistic forecasts, DMDU methods use them to adjudicate among alternative designs. For example, imagine engineers designing infrastructure systems in a watershed in which the historic 500-year flood is becoming more frequent. With an RDM or adaptive pathways and design approach, the engineers identify two (or more) combinations of flexible design, green infrastructure and land use options that would meet performance goals. The first combination might meet those goals if the historic 500-year flood occurred as frequently as once every century. The second, more expensive than the first, would meet those goals if the historic 500-year flood occurred as frequently as once a decade. The engineers would then work with climate scientists to determine if there is any evidence that the historic 500-year flood could occur once a decade and, ideally, if there were any trends in climate indicators engineers could observe that would signal whether and when such storms are becoming more frequent in the future.

The use of these DMDU approaches is becoming more prevalent. For instance, the *2018 California Sea-Level Rise Guidance*[49] recommends communities choose a near-term coastal adaptation strategy consistent with current probabilistic SLR projections and also develop adaptive pathways that include contingency plans appropriate for the extreme SLR scenario if in fact, actual SLR turns out to be larger than projected.



While a massive structure, the Thames River Estuary Barrier uses failures to protect London from the growing risks of coastal flooding as triggers to deploy the next adaptive measures. (Photo: Phil Dolby, flickr, licensed under the Creative Commons license 2.0)

- How should multi-model and multi-scenarios simulations be incorporated into adaptive design concepts?
- How should a cost-benefit analysis be conducted that accounts for the true costs today and in the future with these modular types of designs?

There are two important steps forward for the State to take in order to support the greater adoption of adaptive design:

1. To support applied research and testing of adaptive design for different types of critical infrastructure as well as developing rigorous economic methodologies for determining true cost and benefits of implementing adaptive design; and
2. Design policies that allow and encourage infrastructure which is either sufficiently "modular" or built with sufficient "safety buffer" to accommodate changing climate change risks over time.

Safe-to-Fail

Traditional engineering design accounts for risk by including safety factors (also referred to as factors of safety, see Box 3.3). Given known and predictable conditions, safety factors provide the load carrying capacity of a system beyond the expected or actual loads. The goal is to make structures fail-safe – in that the safety factor presumably predicts accurately what can go wrong, and accounts for it, thereby reducing the risk that a structure will fail entirely. In a changing climate, where the past is no longer a reliable predictor of the future and the future has large uncertainties, the fail-safe paradigm may not be as dependable as before.

Safe-to-fail is an emerging design principle that assumes that the safety factors may not adequately protect an asset, and the structure is thus developed so that if some part of it fails, the damage is controllable or minimized. In fact, safe-to-fail "recognizes that the possibility of failure can never be eliminated"[195], p.9]. As described by Kim et al. (2017)[248], safe-to-fail infrastructure embody these characteristics in the following ways. They:

- Focus on maintaining system-wide critical services instead of preventing component failure[249];
- Minimize the consequences of the extreme events rather than minimize the probability of damages[250];
- Privilege the use of solutions that maintain and enhance social and ecosystem services[251];
- Design decentralized, autonomous infrastructure systems instead of centralized, hierarchical systems[250]; and
- Encourage communication and collaboration that transcend disciplinary barriers rather than involving multiple, but distinct disciplinary perspectives[251,252].

Modularity is one potential mechanism to design for safe-to-fail. As described by LA Metro in its 2015 *Resiliency Indicator Framework*[195], modularity can be achieved by:

- System components having enough independence so that damage or failure of one part or component of a system has a low probability of inducing failure of others; and/or
- System components being constructed in a 'modular' manner that facilitates rapid rebuild/restoration following failure.

As with adaptive infrastructure design, this is a new concept with few implementation examples from which to draw best practices. However, LA Metro's *Resiliency Indicator Framework* includes two safe-to-fail indicators (one for design approach and one for design guidelines) to assess a project's potential resilience[195]. Given the newness of the approach, case examples presented in their indicator framework do not yet include safe-to-fail features. The framework, with guidance on how to use it, is a good example, however, of how to measure and track features that make infrastructure more robust and resilient in the face of greater demands, change and uncertainty.

It is also critical to apply a social equity lens with these new and adaptive approaches to ensure that any decisions are just, fair and equitable to all. With safe-to-fail, for instance, some part of the system may be down for the sake of preventing more widespread failure. Clear procedures must be developed to help infrastructure operators and regulators choose equitably which part will be planned for disruption or even failure, and how to compensate those affected in a fair manner.

With Safe-to-Fail, clear procedures must be developed to help infrastructure operators and regulators choose equitably which part of a system will be planned for disruption or even failure, and how to compensate those affected in a fair manner.

In Chapter 7 we turn to governance, which should provide this sort of guidance and lay out requisite processes.

7 Governance:
Changing the Rules to Enable Climate-Safe Infrastructure

Introduction

How infrastructure is built is in large part determined not just by the available science, tools, assessment methodologies and design paradigms prevailing, but also by the rules that govern how infrastructure should be built. In this chapter we turn to these rules and how they need to change in order to accommodate a changing climate and create the conducive environment that supports the movement toward climate-safe infrastructure.

We use the term "governance" to capture these societal rules because governance consists of all the processes of interaction and decision-making that create, reinforce, change or maintain the affairs of society. Besides governments, governance is carried out through markets, networks and social systems (such as formal and informal organizations) using laws, regulations, standards, guidelines and less formal, but often powerful societal or professional norms, incentives, market signals and so on.

How infrastructure is built is in large part determined not just by the available science, tools, assessment methodologies and design paradigms prevailing, but also by the rules that govern how infrastructure should be built.

Following the mandate of AB 2800, we focus first on the existing standards and non-standard-based approaches that govern how infrastructure to date is being built. We describe how standards are developed and changed and to what extent existing standards and guidelines help or hinder the ability to use forward-looking climate science. We close with exploring how current advances in engineering methodologies (professional paradigms, norms and principles) can be incorporated into infrastructure governance to support the transition to climate-safe infrastructure.

Existing Approaches to Infrastructure Design

Traditional Approaches of Governing Engineering Design

Assuming a stationary world in which historic weather and climate patterns were good predictors of the future, the traditional approach for infrastructure design has generally yielded reliable infrastructure that provided the necessary functions, while also protecting life and safety. Engineers, architects, designers and contractors have an extensive suite of engineering standards upon which to design all different types of infrastructure (Box 7.1). Conforming to these baseline standards decreased the risk of catastrophic failure of a specific type of infrastructure and reduced the liability to the engineer, architect, designer or contractor.

Below, we discuss the traditional approach to standard-setting and then discuss how the field is already beginning to shift its practices to accommodate a non-stationary climate future. In Appendix 9, we present a specific case example of the information needs required to update California's Building Energy Standards.

The Standard-Setting Process

Generally, standards are developed at the international or national levels through various standard-setting organizations. The most commonly recognized are the National Institute of Standards and Technology (NIST), the International Organization for Standardization (ISO), the International Code Council (ICC), and the American National Standards Institute (ANSI). Professional organizations for individual sectors, such as the American Society of Civil Engineers (ASCE), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), or the American Association of State Highway and Transportation Officials (AASHTO) can also set new standards within their own organizations or initiate the updating of existing national and/or international standards. State or local agencies typically adopt these international, national or sector-specific professional standards as minimum standards and codify them in design guidelines, manuals and codes. Both states and local jurisdictions can – and often do – adopt more stringent codes and standards above and beyond those prescribed by the minimum standards developed at the national and international levels (Figure 7.1).

Figure 7.1 Generally, standards are developed at the international and national levels through standard-setting organizations and states and local jurisdictions adopt them. Sometimes, states and local governments develop more stringent codes and standards that go above and beyond minimum standards. (Photo: Pipe installation at Jones Tract levee break in 2004; DWR, used with permission)

Box 7.1: Definitions of Key Terms and Examples of How Infrastructure Design is Governed

- **Design Standards:** Office of Management and Budget (OMB) Circular A-119 establishes policies on the federal government's role in development and use of standards. It defines "standards" to include the common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods. For example, the American Society of Civil Engineers (ASCE) issued a design standard that specifies minimum structural load requirements under various types of conditions, taking into account factors such as soil type and potential for floods, snow, rain, ice and wind.
- **Building Codes:** Building codes are laws or regulations that specify minimum safeguards to ensure public health, safety and general welfare of the occupants of new and existing buildings and structures, according to the International Code Council (ICC), a standards-developing organization. For example, building codes may ensure that exterior walls and roofs are resistant to the weather, such as by including flashing and drainage. Building codes may reference one or more design standards.
- **Specification:** A set of conditions and requirements of precise and limited application that provide a detailed description of a procedure, process, material, product or service for use primarily in procurement and manufacturing. Standards may be referenced or included in specifications. For example, a particular government agency may have specifications as to what type of material is to be used (and not used) for culverts.
- **Technical Regulation:** A mandatory government requirement that defines the characteristics and/or the performance requirements of a product, service or process.
- **Voluntary Certifications:** Voluntary certifications assess infrastructure across a spectrum of key criteria, including environmental performance, and recognize those that go beyond minimum code compliance. For example, the U.S. Green Building Council (USGBC) developed the Leadership in Energy and Environmental Design (LEED) certification, which offers four ratings levels - certified, silver, gold and platinum - depending on how many points a project earns in various categories.

(Source: Based on GAO (2016)[226])

Updating existing standards, or creating a new one, generally follows a deliberately slow, empirically-tested and consensus-based process. To provide more detail beyond what is shown in Figure 7.2, the process can be described as following these general steps:

1. An entity suggests the need to update or create a new standard;
2. A standard-setting policy body initiates a committee and selects a chair;
3. The chair selects the committee membership from volunteering association members and obtains approval from the standard-setting policy body;
4. The Committee meets periodically – this could be either a public or private meeting process depending on the standard-setting body's rules;
5. Committee deliberations include seeking out necessary research or data or advice, which can take considerable time to conduct and be reported back to the committee;
6. The Committee drafts the standard;
7. When the draft is ready, the committee holds a consensus vote to release for public review;
8. The standard-setting policy body approves release, which can be followed by public review process (again depending on the standard-setting body's rules);
9. The Committee holds a consensus vote to publish the finalized standard;
10. The standard-setting policy body approves the publication/adoption of the finalized standard;
11. The standard is published;
12. The standard is disseminated or sold;
13. In some cases, a standard written in code-intended language is adopted into code by various jurisdictions; and, finally,
14. The standard is either put on continuous maintenance or a committee is periodically reconstituted to revise the standard, at which point the process repeats.

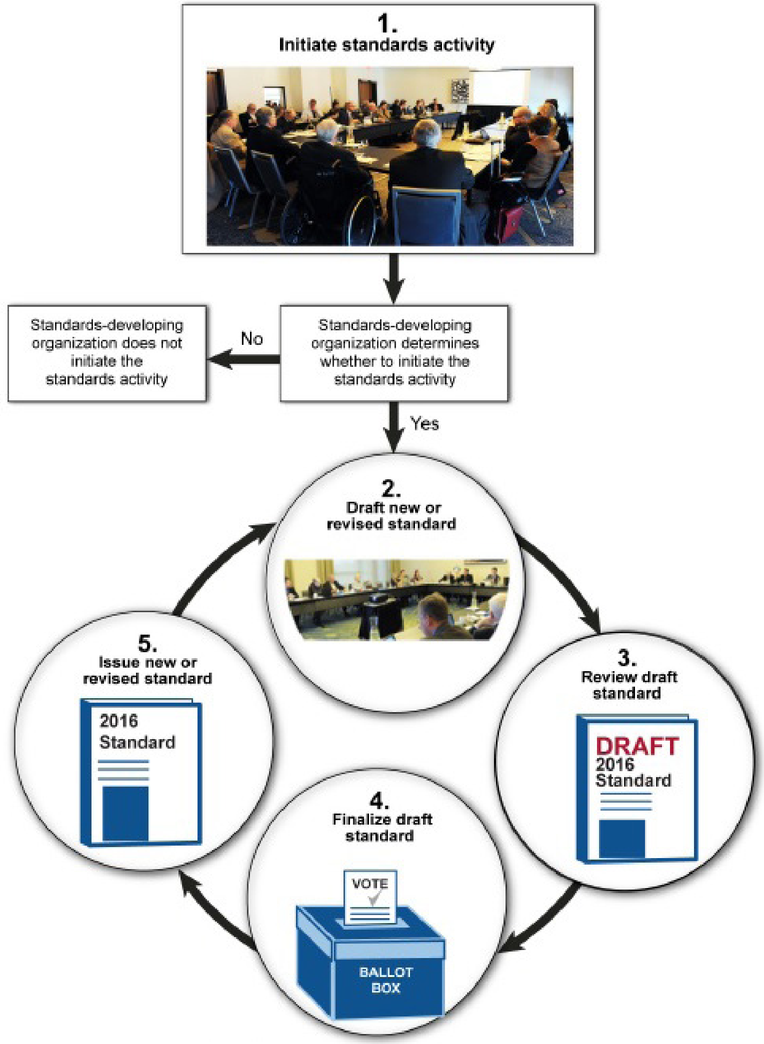


Figure 7.2 Generalized standards-developing process (Source: GAO 2016 [226])

Some standards take 20 years to develop or change; others have been changed in much less time (1-2 years) but given the significant implications of changing the way things are built all over the world or in a particular nation, the approach is methodical and often time-consuming. Often, in addition to research, years of testing and in-the-field observations are required before a standard can be advanced to a vote with voting rules depending on the rules of the standard-setting organization. Engineering standards setting is recognized as being a very conservative process that is resistant to change, since the potential for failure resulting from a poorly developed standard can have costly and – sometimes – tragic consequences.

Information utilized in developing climate-sensitive standards traditionally has relied on historic weather and climate information. Over time, the historical period used has changed, even if the basic standard did not. But as a general rule, structural standards have relied on backwards-looking data, not forward-looking climate projections. To address the gaps in the observational record and deal with the natural variability (i.e., uncertainty in historic information), engineers and architects have been trained to use and thus have methods for factoring in these uncertainties, through "safety factors" (see Box 3.3).

Non-Standard Based Approaches

If standards – turned into prevailing code, rules and regulations – are the most stringent ways to ensure infrastructure is built a certain way, State and local jurisdictions can establish more ambitious guidelines if they see a necessity or if they wish to take leadership and action before a higher standard is adopted nationwide or internationally. California has a long history of doing just that. The State's energy efficiency standards have and still lead the nation and have demonstrated that such higher standards do not restrict the economy or well-being of its people and the environment. Some local jurisdictions, too, have chosen to go beyond minimum standards, by either adopting higher voluntary standards or by establishing other local guidance that those building infrastructure locally must adhere to.

The success, and eventual wider adoption, of these beyond-minimum approaches typically depend on being able to illustrate that the more stringent approach works, exceeds performance and is cost-effective. This requires establishing frameworks, indicators and metrics of "success" that can be tracked over time to make that convincing case. LA Metro offers a good example.

In 2015, LA Metro published its *Resiliency Indicators Framework*[195], a guidance document that explains how the transportation agency understands resilience, what principles guide its work, what factors it sees as contributing to transportation resilience and how indicators of organizational and technical readiness can be tracked and combined to produce a quantitative and qualitative sense of progress toward greater resilience (Figure 7.2).

California's Infrastructure Design Standards

As part of the work of the Climate-Safe Infrastructure Working Group (CSIWG), members compiled lists of standards, guidelines and other frameworks that guide how infrastructure in the state must be built (Appendix 10).[1] This compilation illustrates that there are dozens of standards, design manuals, bulletins, plans and specifications, design guidance, design criteria and references to rely on in any one infrastructure sector.

Simply identifying which standards need to be updated – and doing so – will not get the job done on its own, however. There is much more to building climate-safe infrastructure than simply updating standards, though that is an important process. The real change will come from using different types of standards and deploying them in practice throughout the infrastructure planning, design and operation and maintenance (O&M) process.

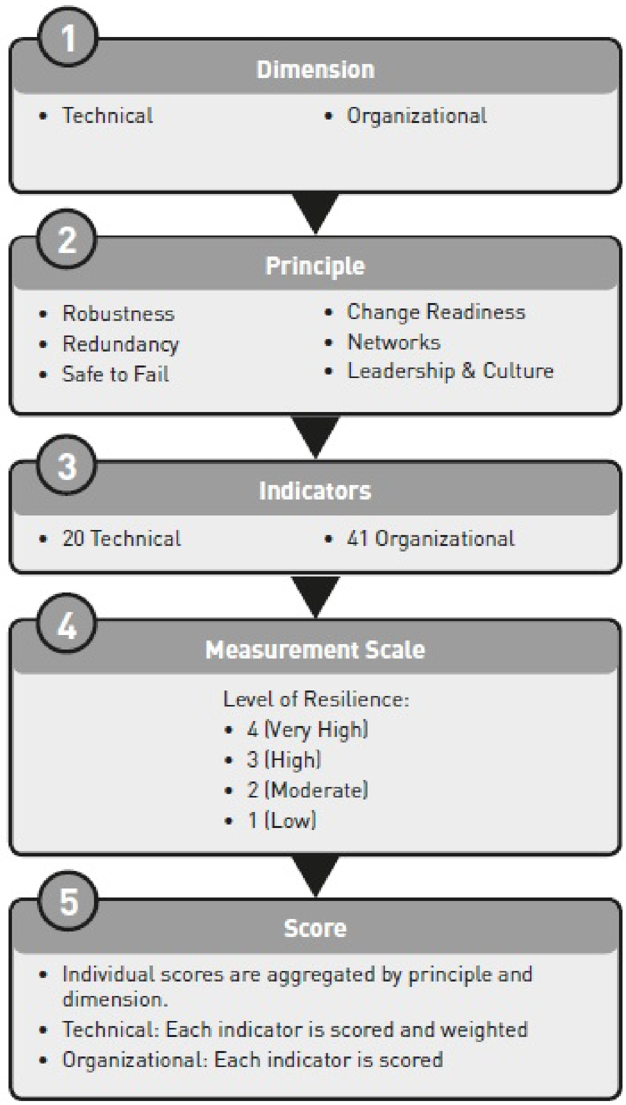


Figure 7.3 The process by which key dimensions and principles of resilience identified by LA Metro in its *Resiliency Indicators Framework* result in specific indicators and scores (Source: LA Metro, 2015[195], used with permission)

Standards and other guidance and governance mechanisms used by State agencies are updated at different intervals (some annually, some once per decade, others irregularly) to reflect changes in codes and standards set elsewhere and experience with existing codes. In some instances, these standards and guidelines are adopted from national and international standard-setting organizations; in others, the State sets its own standards and guidelines. As described above, updating these standards can take considerable time, but the State has opportunities to take steps immediately (Box 7.2).

Box 7.2: Small Steps Toward Climate-Safe Infrastructure: The California Building Code

The California Building Code does not yet require that building envelope designs be capable of maintaining healthy indoor environments over a wider range of expected future climate conditions even when there is a power outage (see Chapter 3). To address this type of shortcoming, one step could be to direct the California Building Standards Commission to clarify its criteria that guide code development and updates. One of these criteria currently states that proposed standards must serve the public interest, including environmental considerations. To operationalize the overarching mandate to update State codes and guidance, this criterion could be clarified to state that proposed standards must also address climate resiliency, to the extent possible. The first and most important first step then is to direct State agencies to prioritize these types of efforts in all infrastructure-related planning with the goal of achieving Recommendation 6.

Clarifying the criteria that trigger standard and code updates can be an effective small step toward initiating updates to existing codes and advancing on the path toward climate-safe infrastructure for all. (Photo: Lawrence Scarpa, LEED-certified building in Hollywood, Wikimedia Commons, licensed under Creative Commons license 2.0)

The exercise of compiling the codes, standards and guidelines used in state infrastructure construction and O&M (Appendix 10) revealed many institutional barriers to integrating forward-looking climate science (even if it were available). We compiled those barriers in Appendix 11. The exercise also offered a number of overarching lessons for the State, if it wishes to update its State-based standards above and beyond national and international minimum standards in order to enable the transition to climate-safe infrastructure:

1. **A plethora of standards of varying stringency.** While potentially confusing, having more stringent standards in California than elsewhere, and/or more stringent standards at the state than at the local level in order to account for climate change, has precedent: already, there is a plethora of standards and codes in play. Side-by-side infrastructure built at varying times was built to the prevailing codes at the time of construction. There is nothing fundamentally new or more difficult about that if California wishes to update its standards now to account for climate change. However, structures built to standards and codes no longer sufficient for a changing climate constitute potential weak spots in infrastructure systems.
2. **More stringent State codes can pave the way for more stringent local and national codes.** Often infrastructure systems under State ownership or regulation is placed in local contexts or involves local and/or federal partner agencies that have different prevailing codes than the State. State policy changes, translated into design standards and guidance can have a strong influence on what others do. It sets precedent, provides a model, and – through appropriate mechanisms – can incentivize others to follow suit.
3. **Varying degrees of ease to change standards.** In some instances, standards and codes can – with appropriate policy guidance from above – be updated relatively easily. Updating base years on a rolling basis, moving the range of years forward over which averages and patterns of extremes should be assessed, extending the design-life length from 20 to 30 or 50 years, are examples that fall into this category. In other instances, the shift to using forward-looking climate science faces greater obstacles. Some code and standard changes require regulatory action, others can be implemented through administrative processes within agencies.
4. **Standards and guidelines that are there vs. that aren't there.** Sometimes, existing standards present a barrier to the use of forward-looking science; other times they are agnostic, and ideally, they should allow, support or mandate the use of forward-looking science. But sometimes the barrier lies in the fact that relevant standards or guidelines are absent (see Chapter 10 for a summary and Appendix 11 for a detailed overview of these types of barriers).
5. **Resources and technical capacity to change standards vary across State agencies.** While CSIWG members agreed that standards, codes and guidelines should be updated to help create the enabling environment for climate-safe infrastructure, State agencies differ in their technical capacity to make these changes themselves vs. awaiting standard-setting organizations to provide those updated standards, which the State would then adopt. Thus, while policy guidance should be unambiguous, the way to implement it at the level of standards and codes would need to be flexible to reflect this range of in-house capacities.

Recommendation 6

Consistent with Executive Order B-30-15 and AB 1482, State agencies should update all relevant (i.e., climate-sensitive) infrastructure standards and guidelines that they can directly affect. Alternatively, or in addition, they should develop new state-specific guidelines where there are gaps to address climate resiliency by incorporating forward-looking climate information in those standards and codes. Where State agencies rely on standards developed by standard-setting organizations, state engineers and architects should work through the relevant professional organizations to advance development of climate-cognizant standards. Until new standards and codes are in place, State agencies should develop guidelines that go above and beyond minimum standards and codes to meet the goals of the Climate-Safe Path for All. Where agencies don't have resources to fulfill this workload, they should be fully funded in the State budget.

Moving from Structural Design Standards to Different Kinds of Standards

Internationally and nationally, standard-setting organizations are exploring different approaches to standards that can accommodate the adaptive infrastructure and safe-to-fail approaches described above and build in flexibility in a heretofore very prescribed and inflexible process. The essence of what a standard is, and what guidance it should contain, is an equally important and active area of discussion and testing. Examples include performance-based standards and standards for professional practice.

Prescriptive vs. Performance-Based Standards

In common prescriptive standards, the goal is to specify required elements in a system design, assuming that if something is built with these elements, it will perform adequately in order to achieve policy goals for the standard. This often leads to a "least common denominator" approach to the design, using what is well known, tried and tested, including historical data. Less certain scenarios are not addressed, controversial or innovative measures are not included and changing climate conditions are not accounted for. Prescriptive standards are valuable in that they provide a simple approach to achieving desired policy outcomes. However, prescriptive standards are limited in that they discourage innovation. As integration of climate resiliency in design standards is an emerging issue, both prescriptive standards and performance standards will be useful. Prescriptive standards will allow the integration of basic climate resiliency measures broadly in standard practice (the "no-regrets" opportunities), while performance standards will give designers the flexibility to devise the best way to achieve the desired outcome for a particular application without the State prescribing how to get there. California's Title 24 Building Energy Code is an example of this. Title 24 includes a "prescriptive path", in which mandatory measures are specified, along with a finite list of optional measures that can be traded off for one another, to accommodate different applications. This approach is simple but not frequently used, since it does not give the designer much latitude.

Performance standards, in contrast, identify a performance objective, and leave it to the designer to identify a particular design that will deliver that performance. Some of the advantages to performance standards are that they allow designers to innovate in their designs and be rewarded for clever designs. They also can be more successfully applied to non-typical situations. For a future that will not mimic the past, the flexibility inherent in performance-based standards is particularly promising.

The challenges to this approach are in defining performance metrics and mechanisms for demonstrating performance. Ideally, performance can be demonstrated through observation or measurement of actual system operation (i.e., not just performance of the asset, but reflecting the goals of the larger, integrated system of interest; see Chapter 6). This can have limited usefulness because system compliance cannot be evaluated until after the system has been operating in the field for some period of time, at which point it may be too late to make modifications or deny approval. So, in practice some performance standards evaluate designs for their "potential" to perform adequately. The availability of modeling tools that capture a range of operating scenarios and accurately predict how a system with a given design will perform in the real world enables setting these kinds of standards. In those cases, ongoing monitoring and evaluation over time are critical, so that such performance standards can be updated on the basis of actual performance data.

Ongoing monitoring and evaluation over time are critical so that performance standards can be updated on the basis of actual performance data.

Future standards are now being contemplated that will provide an even deeper level of performance assessment. For example, air conditioner efficiency is reaching a theoretical maximum, so many of the remaining measures to implement in standards (such as unique operating modes or system configurations) must be carefully targeted toward specific applications. To support improvement to these existing standards, sophisticated modeling algorithms are being developed and validated so that a range of quite different system approaches can be used to meet a performance standard.

The CSIWG recognizes that performance standards are more complex to establish and to enforce, however, the sophisticated measures that will be needed to ensure system resiliency in the future may demand these types of approaches. As the State moves to implement Recommendation 6 above, the CSIWG urges that it consider performance-based standards, as opposed to narrowly targeted prescriptive design standards.

Standards for Professional Practice

Another category of standard that should be considered are Standards for Professional Practice. Examples of this kind of standard are ASHRAE's Standard 180 (standard for quality maintenance of HVAC systems) and ASHRAE's Guideline 0 (standard for the building commissioning process).

As described above, simple prescriptive technical standards will likely not be sufficient to achieve the State's goals for climate-safe infrastructure, and more sophisticated approaches may be needed in the future. ASHRAE Standard 180, for example, provides a lengthy checklist of items that a technician should check on a mechanical system (Figure 7.4). Because it is impossible to know ahead of time which of these items will be necessary in a particular building, however, the teeth of the Standard are in the provisions that establish the process for selecting the tasks and the accountability for carrying out the process. In this case, the process requires establishing performance objectives and identifying indicators of failures to perform. Once this has been completed, it is relatively straightforward to define the necessary observations, measurements and tests. Similarly, ASHRAE Guideline 0 identifies the process for commissioning a building or building system, including stating the Owner's Project Requirements, developing a Commissioning Plan, developing Functional Performance Tests and Construction Observations and documenting the requirements for ongoing operation and maintenance of the commissioned system.

Figure 7.4: ASHRAE's Standard 180 for quality maintenance of HVAC systems is a good example of a professional standard of care. It provides a lengthy checklist of items a mechanic must check and ensures accountability for carrying out the process. (Photo: Aaron Plewke, flickr, licensed under Creative Commons license 2.0)

Box 7.3: Example of a Performance Standard

The ASCE is currently in the process of developing a Sustainable Infrastructure Standard, which will be a performance standard (Proposal to the ASCE Codes and Standards Committee by the ASCE Committee on Sustainability 2018; pers. communication by Cris Liban).

Achieving sustainability in an infrastructure project requires the balance of environmental, economic and social conditions – conditions that are unique in every project; as a result, the way sustainability is achieved will be unique to every project. Rather than develop a standard with prescriptive provisions, the standard currently in development will provide performance objectives which, when met, will result in sustainable infrastructure projects. The performance objectives will be written such that they are applicable across all infrastructure sectors.

Existing performance requirements (through various federal Executive Orders or voluntary standards such as the LEED Rating System) do not address infrastructure systems for communications, energy, transportation, and water, sewage and storm water and civil infrastructure projects that benefit the economy, environment and society. Thus, the ASCE standard that is currently being developed is anticipated to provide coherent and consistent performance objectives that can be included in procurement documents by owners, regulators, stakeholders, and policy makers committed to enhancing the sustainability of infrastructure projects.

Approaching sustainability from a performance-oriented perspective facilitates implementation of sustainability measures that are unique to projects; involve owners in establishing the "triple bottom line;" encourage the use of rating systems or tools to monitor and measure sustainability; foster creativity and innovation by the design and construction community to meet the performance objectives and provide for flexibility in how – sometimes conflicting – objectives can be met.

Furthermore, some of the common elements of these standards for professional practice involve the owner or end-user in defining the ultimate objectives, establishing a plan, and identifying how the plan will be adapted over time. These steps ensure that the process has buy-in and will go beyond simply running through a checklist. Providing accountability for developing and applying the process is essential: codes or programs that apply these standards must recognize that the standards provide a measuring stick and they will only have an impact if accountability is enforced through the code or the program. Buy-in and accountability ensure that the standard generates ongoing and permanent savings.

Building to More than One Number: The ASCE's Manual of Practice

Building on its *2015 Roadmap*, ASCE is currently developing a Manual of Practice (MOP) for infrastructure that provides guidelines for how engineers – and architects – can incorporate forward-looking climate information in their infrastructure plans and designs[253]. The MOP is not a standard *per se* but helps those needing to account for future climate change in infrastructure design absent any standards doing so.

While still under review at the time of this report, the MOP provides guidance on how engineers can bolster the use of historic information with climate model-based future projections to get a more robust assessment of future risks. Rather than selecting one number as the definitive value to which to build and thus to measure the success of a particular piece of infrastructure, the MOP recommends adopting a range of numbers that capture the full complexity of risk. Using risk management and adaptive design principles, the suggestion is to build infrastructure for a particular design load (based on observations or future projection) but such that it can be adapted in the future upon observing changes in statistics of extremes. The ASCE MOP provides an important suite of implementable stepping stones for how engineers can begin to incorporate climate science into their practice.

California can build on this pioneering work by adopting the principles within the ASCE's MOP and modifying or extending them to be California-centric. This would entail tailoring the suite of climate information included to address the state's specific climate regimes and changing patterns of extreme events common across the state (with emphasis on the high-emissions scenario, particularly for vulnerable assets) and addressing all of the infrastructure categories outlined in this report.

Thus, another concrete step the State can take in moving toward climate-safe infrastructure is to:

1. Appoint a working group of relevant technical experts that develops a California-specific Manual of Practice. This Cal-MOP should build on the ASCE's MOP and
   - address all relevant infrastructure sectors in the state;
   - reference the climate science information that is most relevant to California, produced by and for the state; and
   - include experts on the various approaches described in this chapter, such as adaptive design and pathways, as well robust decision making under uncertainty, social scientists, economists, as appropriate.

2. Adequately support the work of this working group with in-house staff, external experts and commensurate funding.

Advancing Standards in Support of Climate-Safe Infrastructure

Leadership Through Voluntary Standards

The discussion above presumes that creating new or updating old standards are the only – or maybe the most important – methods by which the State can ensure climate-safe infrastructure gets built. Through Working Group discussions and the webinar series, the CSIWG also explored non-standard-focused approaches for building resilient and climate-safe infrastructure. Because climate adaptation measures will frequently involve incorporation of incremental measures or strategies that may add cost to a project design or retrofit (see Chapter 8), and because changing standards and codes will take some time, incentivizing voluntary approaches that go above and beyond existing minimum standards would be a way to rapidly start moving in the direction of climate-safe infrastructure.

Examples of voluntary programs in the building sector that might be appropriate candidates are LEED certification, Cal Green Tiers 1 and 2, Title 24 and various certifications from ASHRAE, Uniform Building Code (UBC), Unified Mechanical Code (UMC), Building Research Establishment Environmental Assessment Method (BREEAM), the Living Building Challenge, and others (Box 7.4). Meister Consultants Group (2017)[254] compiled an overview of the different voluntary "resilience" standards currently available in the building sector and rated them on a four-point matrix from facility-specific to community-level and from technical (usually focusing on just one hazard and one type of infrastructure) to holistic (generally focusing on multiple hazards and applicable across a system) (Figure 7.5).

The combined use of mandatory standards and voluntary standards can help advance the development of climate-safe infrastructure. Indeed, in our webinar series, the US Green Building Council (USGBC) provided an example of how the push-and-pull interplay of voluntary measures and building codes have served to increase the resilience in both (Figure 7.6). In this instance, as the LEED voluntary certification raised its standards, one observes the raising of the minimum building codes over time. The voluntary standards essentially provide field testing of nontraditional approaches; after demonstrated success, this allows time for the more conservative mandatory minimum standard-setting process to gain comfort and acceptance with these new approaches, which eventually become the new standard operating practice. Incorporating climate resiliency measures in voluntary standards such as LEED or Cal Green Tiers, will serve as a motivation for design engineers to incorporate climate resiliency in their building design because there are other benefits to them in achieving these levels of voluntary compliance.

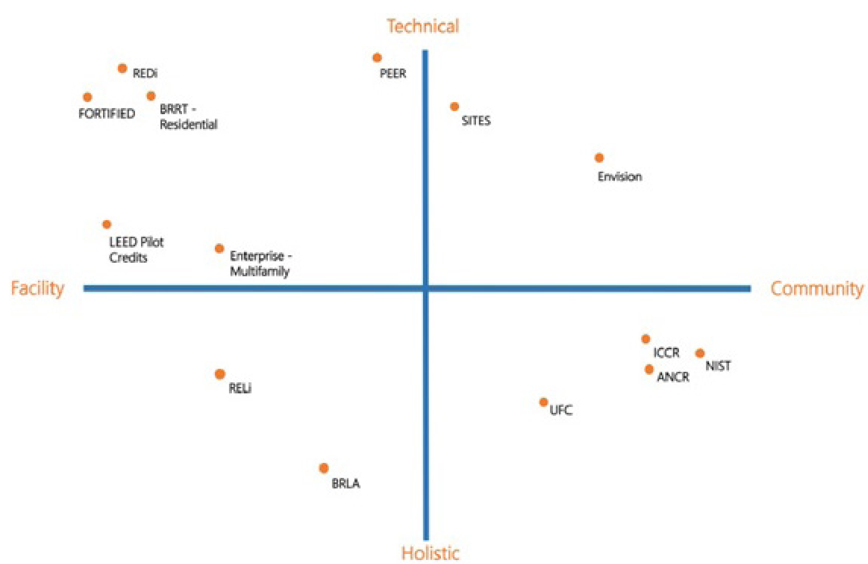


Figure 7.5: Voluntary standards in the building sector fall into a number of categories, here classified by whether they are technical or more holistic in focus, and whether they focus on a single facility or a community (Source: Meister Consultants Group 2017[254], used with permission)

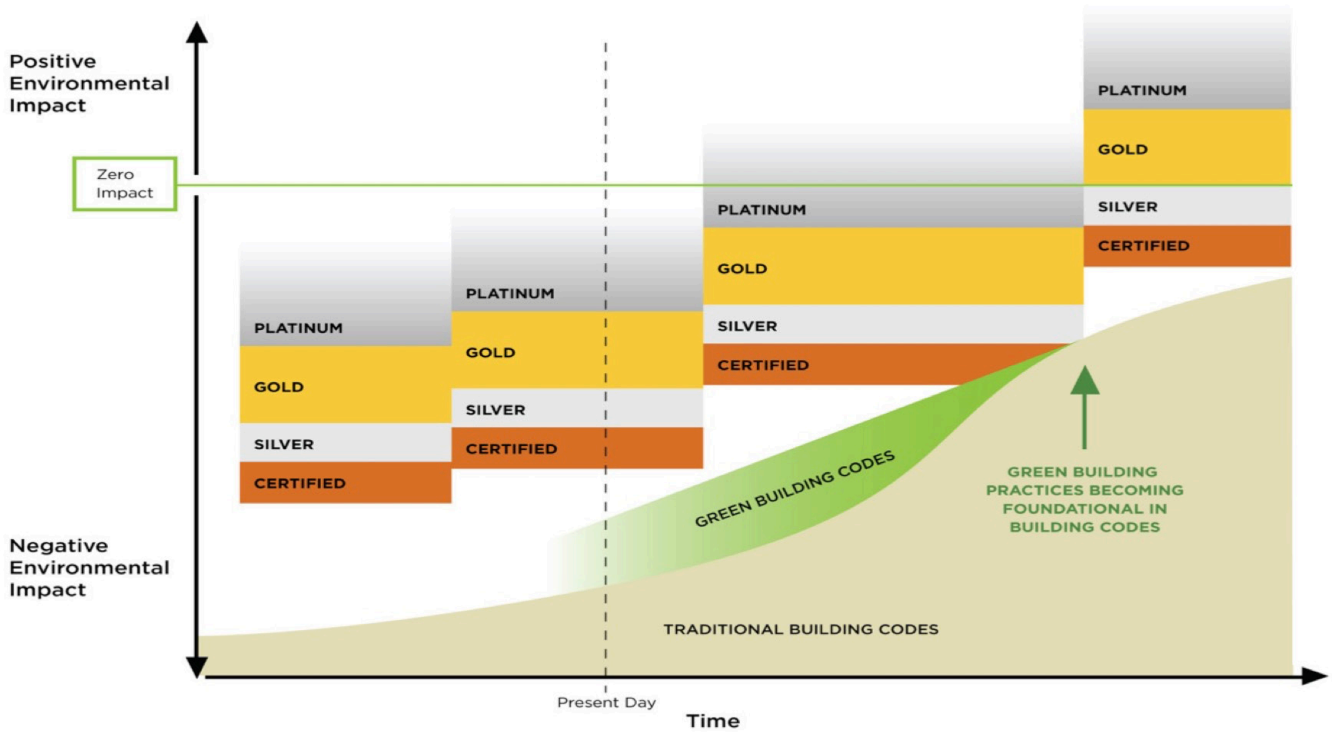


Figure 7.6 States can lead through adopting aspirational voluntary standards that over time raise the floor of mandatory/minimum standards (Source: adapted from US Green Building Council, used with permission)

Box 7.4: Examples of Voluntary Resilience Standards

- The US Green Building Council's Building Resilience—Los Angeles Project (BRLA)
- The Insurance Council of Australia's Building Resilience Rating Tool (BRRT)
- The Institute for Sustainable Infrastructure's Envision Rating System
- The Insurance Institute for Business and Home Safety's FORTIFIED Standards
- The US Green Building Council's LEED program
- The US Green Building Council's Performance Excellence in Electricity Renewal (PEER) program
- The RELi Resilience Collaborative's RELi Resiliency Action List & Credit Catalog
- Arup's The Resilience Based Earthquake Design Initiative (REDi)
- Sustainable Sites Initiative (SITES)
- Enterprise Community Partners' Enterprise Green Communities Certification
- Alliance for National and Community Resilience (ANCR) (and its resilience benchmarking system, currently under development
- The Department of Homeland Security's Interagency Concept for Community Resilience (ICCR)
- The National Institute of Building Sciences' Unified Facilities Criteria (UFC)
- The National Institute of Standards and Technology (NIST) Community Resilience Assessment Methodology (CRAM)
- Cal Green Tiers 1 and 2

The Need to Address Liability

One important governance issue – requiring further study – is liability and the protection against liability for building structures in certain ways, namely design immunity. Climate change will affect liability issues. There is a more general and a more specific issue at hand. The first and broader issue has to do with liability for climate change impacts in the first instances, in an attempt to link specific local impacts and the financial damages and costs incurred to local communities to those bearing significant responsibilities for greenhouse gas emissions. This has been the subject of a number of court cases, including one involving several California cities against several international oil companies. That particular case was recently dismissed on the grounds that such liability issues should not be decided in the court but in legislative bodies at the state and national levels (and through international law).

The second, and more specific issue, of considerable concern to the matter at hand in this report, is the liability of individual engineers, architects, developers, project sponsors, contractors, realtors and insurance agents for designing structures with or without accounting for climate change, and to what level of climate change. These liability concerns are the subject of a recent publication by the Environmental Law Foundation and should be taken very seriously[255].

Licensed engineers and architects in private practice must carry professional liability insurance, which is tied to the requirement to adhere to prevailing professional standards and codes, which – after all – reflect consensually determined, best professional practice and widely-accepted professional ethics.

Deliberation with subject matter experts over the course of the CSIWG meetings pointed to the ways in which liability concerns among practitioners can stymie innovations that would go beyond well-established practice. It can also lead infrastructure designers to pass liability on to project owners, in that the engineering consultant might inform the project owner of the state of science and the range of design options, but then leave the decision as to which design to choose to the project owner, thus disavowing responsibility (i.e., liability) for that decision. This practice raises critical questions, including what the impacts of such transfer of responsibility has on coordinated planning and coherent levels of protection if infrastructure owners vary in their level of risk aversion. It is, at the very least, challenging to imagine how this approach would lead to coherent implementation of the Climate-Safe Path for All.

There is relevant case law[256] in California that could not be assessed at the level required in the course of this project, but liability and design immunity have critical implications for whether and in what ways infrastructure will be designed and how climate change can be accounted for from a legal standpoint (see also[255]). The CSIWG recommends that to further operationalize its recommendation on updating standards, State agencies work with legal experts and insurance experts to address these concerns.

Ultimately, establishing professional standards of care that affect liability and convey a responsibility to safeguard infrastructure and the people that depend on it in the face of climate change may be the most powerful influence on how practicing engineers and architects carry out their work. To enable professionals to carry out their work to appropriate levels of care, enhanced training, professional development and certification programs can support the effective implementation of this recommendation (see Chapter 9 for additional detail).

Liability issues constitute a large and complicated enough challenge that a separate panel may need to be convened to address all the nuances and complexities; this group could then provide guidance and recommendations to infrastructure agencies.

Figure 7.7: Establishing professional standards of care that affect liability and responsibility in the face of climate change may be the most powerful way to influence how practicing engineers and architects carry out their work. (Photo: Dave Rauenbuehler, Chase Center, flickr, licensed under Creative Commons license 2.0)

Institutions for Integrated Infrastructure Systems

The governance of climate-safe infrastructure discussed so far was mostly concerned with the rules that govern how infrastructure is built. But the governance challenge is in fact bigger than that. The current approach to infrastructure planning, design, financing, construction, O&M, and eventually decommissioning is siloed by sectors and frequently isolated, narrowly focused agencies within sectors.

As we discussed in the Chapter 6 on pre-development and as we will discuss in Chapter 8 on financing climate-safe infrastructure, developing infrastructure in the future should be more systems- and outcome-oriented to both reveal and take account of the multi-faceted challenges and multi-sectoral benefits that can be generated (Figure 7.8). This is not just a nice idea, but a critical necessity given the high degree of infrastructure interconnectedness and interdependence[165]. The current institutional set-up and common ways of working, however, are not conducive to this approach.

In deliberating these institutional barriers, the CSIWG recognizes that there is little taste and few resources for major government reorganizations. A "softer" approach to improving cross-sector coordination and integration that help operationalize the transition to climate-safe infrastructure might involve:

- Minimizing obstacles to collaboration;
- Experimenting with new forms of coordination (e.g., coordinated integrative budgeting for projects);
- Fostering standing cross-agency working groups for infrastructure;
- Ensuring wider and more effective stakeholder participation; and
- Fostering regular communication across silos.

A long and more specific list of suggestions for improving cross-sector coordination and collaboration was provided in Moser and Finzi Hart[165].

In some instances, where infrastructure projects cross-jurisdictional lines, more formal institutional entities might need to be created. There is precedent for this, too, in the form of special districts. As we will discuss in Chapter 8, such special districts (made up of local jurisdictions, but involving State funding) are often essential for complex infrastructure projects to go forward.

Figure 7.8: Integrated infrastructure development can create many synergies and co-benefits. This multi-family housing unit, known as Colorado Court, in Santa Monica was the first LEED "Gold" certified multi-family building in the U.S. It combines many sustainability features and provides affordable housing to lower-income residents. (Photo: Calder Oliver, Wikimedia Commons, licensed under Creative Commons license 2.0)

8 *Funding Infrastructure:*

Trends, Needs, Challenges and Tools

Introduction

In Chapter 2, we described the status of state infrastructure and in many cases were able to capture in fiscal terms the size of the backlog that currently exists, even without consideration of climate change or the needs for new infrastructure given demographic trends, technological changes and the desire to maintain California as an attractive and vibrant economy. The multi-billion-dollar need across infrastructure sectors for deferred maintenance, ongoing operation and maintenance (O&M) and new investment is not a unique California story, however, but one that is a shared challenge across the nation[2,257-264].

Figure 8.1: Over the past two decades, progress on infrastructure planning and investment has been made, but there is widespread consensus that spending has been insufficient. (Photo: State Capitol workers; John Chacon, DWR, used with permission)

For decades, California lawmakers and infrastructure experts have recognized the importance of state infrastructure for its economy and the health and well-being of its residents (Appendix 12). As recently as June 2018, in recognition of the nationwide Infrastructure Week, California Senate Concurrent Resolution 136[1] noted, among other things, that:

- "Decades of underfunding and deferred maintenance have pushed infrastructure across the state to the brink of crisis, with preventable failures occurring in some communities that impose financial costs to the public and government;
- ...California risks compromising its competitive advantage by failing to adequately invest in its infrastructure;
- ...California's failure to invest in infrastructure systems is more than a drag on the economy, it can be harmful to health and safety, even though most tragedies resulting from infrastructure failures are preventable with adequate investment;
- ...Every dollar invested in infrastructure generates in excess of $2 in economic output and jobs; and
- ... now, therefore, be it resolved, that despite fiscal challenges, it is important for the Legislature to dedicate sufficient resources to transportation, infrastructure and green investments in our community" (Figure 8.1).

This call to action to make the necessary investments in the future comes amidst and despite the fact that over the course of every legislative session, tens of bills are introduced into the Legislature, and over the past two decades, incremental progress on infrastructure planning and financing has indeed been made. And yet, there is widespread consensus – from the ASCE to members of

[1] The full text of SCR136: http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SCR136.

the Climate-Safe Infrastructure Working Group (CSIWG), from not-for-profits advocating for greater infrastructure investment to lawmakers across both houses of the California Legislature, and across party lines – that investment in infrastructure, and thus in the future of the state is insufficient.

Recent Trends in Infrastructure Spending in the US and in California

Federal Infrastructure Spending Trends

To frame California infrastructure spending trends, it is helpful to place them into the larger context of federal trends, which were analyzed within the last few years as the national debate over infrastructure spending heated up. These national trends are also important given the significant influx of federal dollars, particularly for transportation infrastructure.

Federal non-defense infrastructure investment rose sharply after World War II, particularly during and following the Eisenhower Administration, and has been increasing overall in gross terms. But when depreciation of the capital is taken into account, infrastructure investment has actually followed a declining trend (in constant/inflation-adjusted dollars) through 2015, the infusion of federal investment in the late 2000's notwithstanding[258,259]. This decline is particularly evident when tracing the federal investment as a share of Gross Domestic Product (GDP) or as a share of federal spending overall[258]. Most of federal infrastructure spending is in the transportation sector (particularly highways), followed by aviation, mass transit and rail and water resources[258,261].

At the same time, State and local expenditures on infrastructure has always been significantly larger than the federal share and gross investment has grown faster than federal spending: over the past two decades, State and local governments have spent 7-9 times more on infrastructure than the federal government[261]. State and local investment took a sizable hit, however, during the Great Recession of the late 2000's and is recovering since, although trends for any particular type of infrastructure did not all follow the same pattern.[2]

Over the same period (1956-2015), private sector investment in infrastructure (particularly in the electricity sector, and to a lesser extent in water, transportation and communication) has increased, with the strongest increase seen since the mid-2000's, particularly in the power sector[258].

California's Infrastructure Spending Trends

In 2011, the California Legislative Analyst's Office (LAO) produced an analysis of infrastructure investment trends over the preceding ten years[262]. No comparable update has been produced since. However, the Five-Year Infrastructure Plans – by law to be prepared annually as part of the Governor's budget[3] – as well as independent analyses, provide some insights on recent trends in infrastructure spending across the state.

California's gross infrastructure investment trends – to the extent they have been studied longitudinally – appear to be quite similar to the national trends summarized above (data for 1957-2002[263,265]; data for 1998-2010[262]). After an early peak in infrastructure investment during the P. Brown Administration, and a steep decline in the 1970's and 1980's, infrastructure spending recovered to 1960's levels in the last decade of the 20th century and continued to increase into the early 2000's[263]. The proportion of spending on different infrastructure sector changed profoundly over these decades, with, for example, a much greater proportion spent on transportation early on, and a much bigger proportion spent on schools in more recent decades[263].

Over the past two decades, State and local governments have spent 7-9 times more on infrastructure than the federal government.

Drivers of infrastructure spending included the need to maintain existing infrastructure, build new infrastructure to accommodate growth, comply with State and/or federal mandates and fulfill new priorities and voter initiatives[262]. During the decade from 2000 to 2010, California spent $102 billion on infrastructure[262]. From 2011-18, new general bond issuance was limited to $24.1 billion. An additional $36 billion of general obligation and lease revenue bonds that voters had authorized have not yet been issued to avoid increasing the debt burden, as California works to pay down pre-existing bond obligations[266].

Bond funding cannot be used for regular maintenance. Thus, the growing share of bond-financed infrastructure investment obscures the fact that departments must draw on the General Fund to fund O&M. With every new investment that demand is increasing. At the same time, there is a persistent amount of deferred maintenance. Figure 8.2 illustrates – with an example from the

[2] For more detail on particular infrastructure sectors, see: see: http://www.governing.com/gov-data/state-local-government-construction-spending.html.

[3] While the law requires these plans to be prepared annually, this has not always been the case.

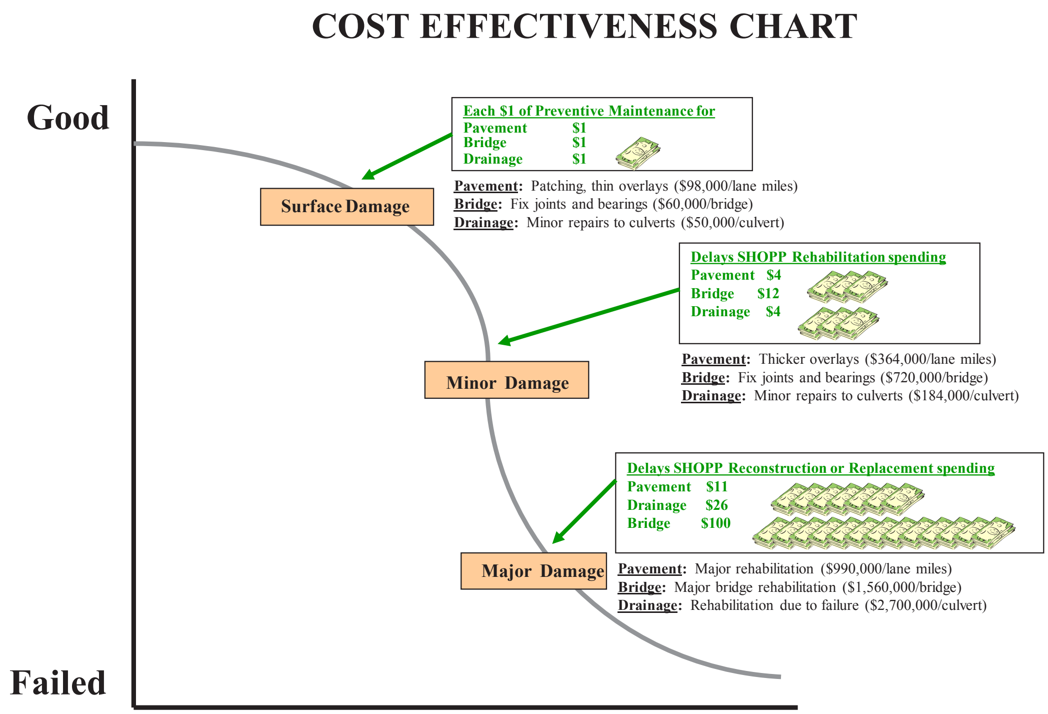


Figure 8.2 The cost-effectiveness of timely maintenance: Earlier maintenance keeps infrastructure in better condition and costs less than deferring maintenance to a later date. (Source: Caltrans 2015[267], p.8; used with permission)

transportation sector – what the fiscal implications of deferred maintenance are: the longer infrastructure is not maintained, in a state of good repair, the more expensive the repair ultimately gets.

As recently as 2018, California's LAO stated, "The State does not have a comprehensive inventory of the condition of its existing infrastructure. However, according to the administration's 2016-17 estimate, the state has $77 billion in deferred maintenance, most of which is in the transportation area"[6]. "In 2015-16 and 2016-17, the State provided almost $1 billion for deferred maintenance, mostly from the General Fund (non-Proposition 98)"[6].[4] The 2018 Five-Year Infrastructure Plan identified statewide deferred maintenance needs amounting to a slightly improved backlog of currently $67.3 billion[6], p.132 and $383 million was actually allocated in the 2018-19 budget, an increase over previous years.

Estimates of future infrastructure funding needs vary widely by source, by year and for different time periods and infrastructure categories and it is unclear whether they include or exclude deferred maintenance. There is also no indication in any of these estimates that infrastructure spending needs account for climate change (Box 8.1).

Box 8.1: Selected Estimates of Infrastructure Funding Needs

- 2007 First California Strategic Growth Plan[268]:
  $500 billion over 20 years
- 2015 California Forward[269]:
  $853 billion over 10 years for transportation, water and K-12 school construction
- 2016 Five-Year Infrastructure Plan[270]:
  $55 billion over 5 years
- 2017 ASCE infrastructure investment need estimates for California[7]:
  $78.75 billion ($44.5 billion for drinking water; $26.2 billion for wastewater; $3.2 billion for schools; and $4.85 billion for State parks)[5];
- 2018 Five-Year Infrastructure Plan[266]:
  $61.3 billion over 5 years (93% for transportation)

[5] No estimates for other types of infrastructure and no timeframe given.

[4] On Proposition 98, see: http://lao.ca.gov/2005/prop_98_primer/prop_98_primer_020805.htm.

With the generally improved fiscal situation of the State as seen, for example, in its strong revenues and establishment of a State rainy-day fund, and recently approved bills and propositions providing additional funding for infrastructure (see Chapter 1), the State is in a better situation at this time than probably at any time over the past 20 years with regard to infrastructure funding. Between the widely recognized need for infrastructure investment and the (greater) ability to do so, California is in a strong position to have meaningful conversations about how to invest in its future and ensure that this investment seriously considers climate change.

The State is in a strong position to have meaningful conversations about how to invest in its climate-safe future.

Structural Challenges to State Infrastructure Financing: The Pre-Existing Condition

To fully appreciate the added financial challenges posed by climate change, it helps to take a look at the ways in which California funds infrastructure at present. In general, "spending on infrastructure can be categorized as either capital spending or operation and maintenance spending. Capital spending consists of purchasing and modernizing new structures – [such as] roads and sewer systems - and equipment. Operation and maintenance include the cost of maintenance and upkeep as well as administration of public infrastructure – such as air traffic controllers. Associated education and research and development devoted to infrastructure is also included in this category of expenditure"[258], pp. 10-11. Taylor[262], p.6 counts local assistance by the State as an additional budget item related to infrastructure spending, and notes that infrastructure planning and design is included by some State agencies in their O&M budgets, but not by others.

The sources of money for these categories of infrastructure spending come – generally speaking – from two key sources: (1) so-called pay-as-you-go funding, which draws on the General Fund and fees collected in Special Funds; and (2) borrowed funding, which uses financial vehicles such as General Obligation (GO) bonds, Lease-Revenue or Traditional Revenue bonds (Figure 8.3). During the first decade of the 21st century, 35% of infrastructure spending came from pay-as you go funding and 65% came from bonds[262].

Hanak and Reed[265], in their 2009 report on needed financial reforms in the ways California funds its infrastructure, note the following key structural challenges (reiterated by other analysts, including the J. Brown administration itself):

- An overreliance on GO bonds, which require only a simple majority to pass but which increase the debt burden and debt service expenditures (the capital and interest of GO bonds are paid back over several decades from the General Fund);
- A relatively high debt service burden can lead to downgrading of credit ratings and thus increase the cost of debt and/or demand cuts to other budget items paid for from the General Fund – the situation witnessed in the early 2000's.[6]
- Since the passage of Proposition 13 in 1978, local governments require a 2/3 (super) majority to increase taxes, i.e., to increase the revenue sources required to pay for local infrastructure investment. This has dramatically altered the funding situation of local governments. State bonds, by contrast, require only a simple majority to pass and thus are increasingly called upon to pay for infrastructure investment. (Since 2000 and the passage of Proposition 39, local school bonds require only a 55% voter approval rate and are thus easier to get passed);
- Traditionally, the State has made insufficient use of generating revenue for infrastructure through user fees, which do not require voter approval. This is an option to improve funding streams in the water and transportation sectors in particular, and to increase efficiencies through demand management such as water pricing, gas tax increases, local development impact fees etc.; and
- Public-private partnerships (P3) with private equity sharing is still limited, obscuring opportunities for private sector investment in public infrastructure.

Figure 8.3: Bonds are often used for upfront capital outlays, but bond money cannot be used for operation and maintenance. (Photo: American Canyon High School; Wikimedia Commons, licensed under the Creative Commons license 3.0)

[6] See also: http://www.dof.ca.gov/Reports/Budget/documents/CompleteDebtsandLiabilitiesat2018-18GB(Website).pdf

Nearly a decade later, the 2018 Five-Year Infrastructure Plan still mirrors these observations, although some aspects have been improved in the intervening years, while others remain challenging for California to this day[266]. It adds to the understanding of the current infrastructure finance situation by illuminating some of the infrastructure financing tools traditionally used in and by the State and pointing to the fiscal implications:

> "Budget challenges in the early 2000's resulted in a greater reliance on debt financing, rather than pay-as-you-go spending. From 1974 to 1999, California voters authorized $38.4 billion of general obligation bonds. From 2000 to 2010, voters expanded the types of programs funded by bonds and authorized approximately $111.9 billion of general obligation bonds."(p.129)

> "The [J. Brown] Administration has greatly tempered the use of debt, supporting $24.1 billion of new general obligation bonds from 2011 to 2018 - including $8 billion on the ballot for Natural Resources and Housing in 2018 - and strengthening oversight of bond spending for educational facility bonds enacted through initiative. Of all previously approved infrastructure bonds, debt obligations of $73.4 billion in general obligation bonds and $9.3 billion in lease revenue bonds remain outstanding. Additionally, there are $36 billion of general obligation and lease revenue bonds ($31.3 billion and $4.7 billion, respectively) that are authorized but not yet issued, which represents a significant decrease from the 2011 reported total of $48 billion. The bonds will be issued when projects are approved and ready for construction."(p. 129)

> "When the State borrows to pay for infrastructure, roughly one out of every two dollars spent on infrastructure investments pays interest costs, rather than construction costs. The amount of funds required to service the debt had increased steadily over past years, but that growth has slowed during this Administration. Annual expenditures on debt service grew from $2.9 billion in 2000-01 to $6.4 billion in 2010-11 - an average annual growth of 9.2%. Since that time, debt service grew more slowly to $7.3 billion in 2017-18 - an average annual growth rate of only 1.7%."(pp. 129-130)

As a result of recent efforts by the J. Brown Administration and the Legislature to work toward a balanced State budget, California's debt situation (measured, for example, as a ratio to personal income or as debt/capita) has significantly improved compared to the height of its debt crisis in 2011 but is still higher than the national average[266].

When the State borrows to pay for infrastructure, roughly one out of every two dollars spent on infrastructure investments pays interest costs, rather than construction costs.

Figure 8.4 When the State borrows to pay for infrastructure, roughly one out of every two dollars spent on infrastructure investments pays interest costs, rather than construction costs. (Photo: three bridges; Justin Dolske, flickr, licensed under Creative Commons license 2.0)

Recent Developments

In addition to efforts in reducing debt and ensuring the more efficient use of government funds, as well as a generally stronger economy, several other steps have been taken to ease some of the challenges noted in the Public Policy Institute of California's report calling for financial reform[265]. Maybe most notably, SB 628 (Beale), passed in 2014, and effective as of January 1, 2015, enables local governments to form Enhanced Infrastructure Finance Districts (EIFDs) – a special governance district empowered to collect tax increments (i.e., the additional taxes generated from the new development within the bounds of the EIFD) to finance infrastructure development. Voter approval is not required to form an EIFD, but a 55% majority is required to pass bonds[271-273]. While oriented toward local governments, this new financing tool is likely to ease local financing capabilities, indirectly reducing pressure on State funds to support local infrastructure projects.

Even more recently, Assembly Resolution ACA-21 (Mayes, Obernolte, an active bill, remaining in progress[7]) proposes to amend the State constitution by establishing a California Infrastructure Investment Fund. It would create a permanent fund in the State Treasury and require the Controller, beginning in the 2019–20 fiscal year, to transfer from the General Fund to the California Infrastructure Investment Fund in each fiscal year an amount equal to up to 2.5% of the estimated General Fund revenues for that fiscal year. The measure would require, for the 2019–20 fiscal year and each fiscal year thereafter, the amounts in the fund to be allocated, upon appropriation by the Legislature, for specified infrastructure investments, including the funding of deferred maintenance projects.[8]

Lack of Vision, Prioritization and Coordinated Strategy

While the fate of ACA-21 is yet to be determined, long-standing observers of state infrastructure investment argue that more than additional funds are needed to move California toward modern, climate-safe and sustainable infrastructure. For example, the Little Hoover Commission, in its 2010 Building California report[2], warned – as the state was barely emerging out of years of fiscal deficits and the late 2000's Great Recession – that the state needed to profoundly reconsider its infrastructure investment thinking and approaches.

It bemoaned that the State seemed to lack a compelling vision and coordinated strategy to guide its infrastructure investment decisions. Since 1999, the legislature had mandated that an annual Five-Year Infrastructure Plan be submitted alongside the Governor's budget, summarizing state infrastructure needs compiled by department staff in collaboration with the Department of Finance (DOF). It was mandated to be considered by the legislature during its deliberations and budget decisions.[11]

> "If California is to emerge from the recession more economically competitive, State leaders must develop an infrastructure strategic plan that prioritizes the state's most pressing needs and identifies new ways to pay for the billions of dollars of infrastructure the state will need. This plan must integrate the state's existing strategy for reducing greenhouse gas emissions and improving sustainable development. A smart infrastructure strategy can help the State meet its environmental goals as well as foster a healthy economy. Likewise, the transformation envisioned by AB 32[9] and SB 375[10] only can be achieved with a growing economy, one supported by strategic infrastructure investments." (para. 2, Letter to Governor and Legislature)

Twenty years after passage of the Infrastructure Planning Act, however, the Little Hoover Commission remarked,

> "What governmentwide planning exists – collated in the administration's annual Five-Year Infrastructure Plan – is segmented by department without a view to overarching goals or a ranking of projects by relative need or the value they would deliver economically or environmentally. Though the plan is delivered to the Legislature, lawmakers have yet to engage the administration in a discussion about which projects are most important or how California can use existing state assets more efficiently." (para. 4, Letter to Governor and Legislature)

Discussions during the CSIWG meetings made clear that this situation has barely improved since. Little significance was given to the Five-Year Infrastructure Plan, as it lacks coordination across agencies and an integrated vision that would allow for prioritization. Moreover, while the

[7] See: http://leginfo.legislature.ca.gov/faces/billStatusClient.xhtml?bill_id=201720180ACA21.

[8] The CSIWG provides information on this pending legislation to provide the full context of activity at the State level. It states no opinion on whether or not this legislation should be approved.

[9] All past Five-Year Infrastructure Plans and other reports related to infrastructure financing are available from the California Department of Finance at: http://www.dof.ca.gov/Programs/Capital_Outlay/.

[10] See: http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf.

[11] See: http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200720080SB375.

Natural Hazard Mitigation Saves

Natural Hazard Mitigation Provides the Nation $6 in Benefit for Every $1 Invested

National Benefit-Cost Ratio (BCR) Per Peril *BCR numbers in this study have been rounded	Beyond Code Requirements	Federally Funded
Overall Hazard Benefit-Cost Ratio	$4:1	$6:1
Riverine Flood	$5:1	$7:1
Hurricane Surge	$7:1	Too few grants
Wind	$5:1	$5:1
Earthquake	$4:1	$3:1
Wildland-Urban Interface Fire	$4:1	$3:1

This Interim Study quantified a number of benefits from mitigation, including reductions in:

- Future deaths, nonfatal injuries, and PTSD
- Repair costs for damaged buildings and contents
- Sheltering costs for displaced households
- Loss of revenue and other business interruption costs to businesses whose properties are damaged
- Loss of economic activity in the broader community
- Loss of service to the community when fire stations, hospitals, or other public buildings are damaged
- Insurance costs other than insurance claims
- Costs for urban search and rescue

Figure 8.5 A recently updated comprehensive study undertaken by the National Institute for Building Safety (NIBS) in collaboration with the Federal Emergency Management Agency (FEMA) and other partners illustrates that pre-disaster investment in hazard mitigation pays manifold. For every dollar invested, the nation saves $6 (avoided damages and other benefits) (Source: FEMA, based on NIBS 2017[275])

J. Brown Administration set forth funding priorities, and mentioned that Executive Order B-15 – which demands that State agencies account for climate change in long-term investment decisions – is being implemented, the statement about implementation is vague and the priorities list does not reflect any overt consideration of climate change.

And while California's credit rating has improved steadily in recent years as a result of the improvements in its fiscal situation[12], making State borrowing more affordable, the debt burden of the State – as shown above – is still significant. Given tax rules in the state, voters would need to be convinced that higher taxation is needed to increase revenues for infrastructure rather than borrow more money (which they have tended to approve at a greater rate than bonds have been issued) (Figure 8.5). Previous studies suggest the public has only limited understanding of how bonds affect State finances[263,265], but the comparatively high success rate of fiscal measures in the June 2018 election suggests it is not impossible to make a convincing case for why Californians should invest in their own communities, economy, education, quality of life and their future[274].

The State lacks a compelling vision and coordinated strategy to guide its infrastructure investment decisions.

[12] See: https://www.treasurer.ca.gov/ratings/current.asp.

Recommendation 7

Because improving resilience is not a zero-sum activity, adding resilience in one area cannot be balanced by relaxing resilience requirements somewhere else. Adding requirements for resilience will come at a cost, so unfunded mandates are not feasible. The true costs over the full life-cycle of infrastructure projects should be assessed broadly, and the State should make efforts to help policy-makers and the public better understand the necessity of bearing these costs. Educational, promotional and other outreach should be conducted to generate support for the expenditures.

A concrete way forward with implementing this recommendation is for the Strategic Growth Council and other State agencies to launch serious engagement (persistent and creative education and outreach) efforts to help Californians more fully understand why investment in climate-safe infrastructure is necessary, why the Climate-Safe Path for All is the safest and – in light of observed climate trends and already-experienced catastrophic impacts – likely a highly cost-effective way forward (Figure 8.6). This will help make the case for continued financial reforms that remove some of the structural obstacles to a more reliable and affordable approach to infrastructure financing (see Stakeholder Engagement discussion in Chapter 9).

Figure 8.6 The State must engage elected officials at all levels and the public to help them better understand the necessity for paying for resilience and generate the necessary support. (Photo: In the streets of Oakland; Thomas Hawk, flickr, licensed under the Creative Commons License 2.0)

The Added Challenges of Infrastructure Financing in the Face of Climate Change

Greater Damages and New Costs to Infrastructure Due to Unmitigated Climate Change

First, it is important to understand how climate change can cause greater damages and higher costs to infrastructure if the impacts of climate change and related extreme events are not prevented or mitigated. Possible cost increases from unmitigated climate change fall into several categories:

Increased damages to existing infrastructure and related increases in the costs for operation, maintenance and repair.

- Gradually increasing stresses may depreciate infrastructure more rapidly than previously estimated, requiring more frequent maintenance, repair or earlier-than-expected replacement (such as higher temperatures affecting the need for road resurfacing);
- Gradually increasing stresses may also increase operating costs (such as extreme heat requiring more air conditioning in state buildings);
- Due to more frequent and/or more intense climate-related extreme events, wear-and tear will increase, resulting in shorter expected lifespans of infrastructure or require more frequent repairs (such as the need to replace culverts more frequently);
- More intense or concurrent extreme events may lead to premature failure of infrastructure (such as the scour from concurrent coastal and inland flooding, as occurred in Hurricane Katrina[276]);
- As climate change increases the occurrence of extreme events – in California and beyond – there is empirical evidence that the cost of materials and of labor increases due to the higher demand for both in post-disaster times. If infrastructure were built back to pre-disaster conditions, and thus insufficiently prepared for the next (and possibly worse) extreme event, replacement needs/costs would incur more frequently;

Increased costs of new infrastructure and retrofits.

- Higher material and labor costs also affect new infrastructure. Labor shortages during such times may add to potential cost overruns. The CSIWG deliberations revealed how the disasters in 2017 and 2018 resulted in such cost increases to current projects in California (particularly in the Building sector). Thus, estimates made today of the cost of new infrastructure without considering the spill-over effects of increasingly frequent climate-driven disasters may well be too low;
- To the extent new construction takes climate change into account, upfront costs for infrastructure may be higher than construction without doing so (e.g., by laying the foundation now for adaptive design), but over multiple decades may be significantly more cost-effective than overestimating or underestimating what kind of infrastructure is ultimately needed over the course of its lifetime;[13]

Increased indirect losses from failing infrastructure.

- Whenever infrastructure fails, there are significant indirect damages to life and safety of communities and to the economy, as the lack of functional infrastructure can severely disrupt and delay the return to full economic activity[277,278];
- Given that infrastructure funding comes from all levels of government and the private sector, lack of funding from local and federal levels or failure of the private sector to take climate change into account can increase the economic vulnerability of the state, for example by more frequent demands on disaster recovery funds, supply-chain disruptions or slowed local recovery and hence diminished economic returns to the State treasury;

Increased R&D costs but also opportunities for significant return on investment (ROI)

- Earlier sections pointed to significant needs for investment in the relevant science, tools and platforms to make actionable climate science available to engineers and architects. This type of investment requires sustained support;
- Because adaptive design is still in its early stages of development, there is a need for increased investment in applied engineering science; and
- Investment in Research and Development (R&D), however, is likely to pay off as the need for such knowledge is global and rapidly growing, providing a significant opportunity to generate a return on investment over time. Put differently, failing to invest in this area may be a significant lost opportunity.

[13] There is no example – anywhere in California or in the United States – of ever having structurally "over-protected" against a natural disaster such as floods, wildfires, storms, earthquakes and so on. There are examples of having taken sufficient precautionary measures and, sadly, many examples of having not protected ourselves enough, either because we did not believe certain extremes would be possible to occur or because we believed ourselves safe, ignored best hazard management practices or stopped short of making adequate investments in our safety (the disasters of the 21st century alone suffice to underscore this point).

A selective literature review conducted as part of a study for the Fourth Assessment revealed that the state has no comprehensive or reliable estimates of what climate change impacts and adaptation would cost at the state or local level[279](Figure 8.7). A range of factors make such estimates difficult, but significant opportunities for filling knowledge gaps and improving on existing partial assessments are possible. This is why we suggested earlier – as a concrete step forward to realizing the Climate-Safe Path for All – to invest more heavily in research that assesses the economics of climate change impacts and of different infrastructure adaptation options, as well as seriously evaluates different financing vehicles to support building adaptive infrastructure.

Figure 8.7: A study conducted for the California's Fourth Climate Assessment revealed that the state has no comprehensive or reliable estimates of what climate change impacts and adaptation would cost at the state and local level, yet that is where most of the costs will be borne. (Photo: Stakeholder workshop on adaptation finance challenges in Los Angeles; Robert Kay, used with permission)

There are as yet no comprehensive or reliable estimates of what climate change impacts and adaptation would cost at the state or local level

Distribution of Damages and Costs

At present, the (mostly) increased damages and costs listed above are not adequately known, nor accounted for in the finance systems at any level of the public or private sectors. One reason for it is that it is not easy to determine how, when, where and to whom these costs and damages accrue. Geography, changing climate patterns and past patterns of infrastructure investment (or, as the case may be, dis- and underinvestment), however, guarantee that they will accrue unevenly. Moreover, it is not easy to determine what a fair distribution of the added economic burden should be. Questions of responsibility, liability and capability are a long-standing feature of greenhouse gas mitigation policy debates and are now also emerging in public debate around adaptation. We expect them to become more pronounced in the future.

Credit rating agencies, such as Standards & Poor's and Moody's, recently announced that they will take climate change into account in assessing the credit worthiness of local government entities[280,281]. As rating agencies move to assessing climate risks, and these risks show up in the interest rates and insurance costs paid by localities, the benefits from climate-safe infrastructure can be monetized upfront. Over time, all financing becomes climate financing. However, this places a strong onus on local governments to get serious about addressing the growing risk from climate change. Given the significant constraints local governments face, however, in funding adaptation[279], not to speak of major infrastructure upgrades, given the tax-limited nature of California local governments and the growing burden on local budgets from pension obligations, it is not to be taken for granted that local governments can face this challenge without significant help from higher levels of government. It is particularly unlikely that low-income communities will have the necessary fiscal capacity to do so. Thus, in addition to the increased outlay to make state infrastructure climate-safe, the demands on State budgets may grow as local governments require additional help.

At the same time, federal willingness to invest in infrastructure is unclear at present. While the Trump Administration has promised greater infrastructure investment and streamlining of the infrastructure permitting process[282], the source of funding is far from clear[283]. A greater involvement of the private sector is expected, but there is no clarity or any standardized procedure for how to draw in private financing. Further, because the federal Administration has reversed most positions, guidance and priorities related to climate change, it is not clear to what extent expenditure of federal infrastructure funding coming into the state can explicitly account for climate change. State-federal consistency requirements, however, may allow the State to put those dollars to good use, i.e., toward climate-safe infrastructure investment, if it raises the bar through design guidance and sets strong regulatory requirements.

Against the backdrop of historical patterns and complexities in infrastructure funding, taking climate change into account from a fiscal perspective is thus everything but straightforward. In a fiscally constrained and uneven environment, with little clarity on the relative roles of private and public sectors, many questions arise. These include:

- How will climate-safe infrastructure projects be funded (i.e., what is the source of revenue) and/or financed (i.e., how can additional money be borrowed) and what is the proper deal structure?
- How will costs be distributed across different infrastructure owners and different levels of government?
- What role can or should the private sector play?
- What improvements are needed to allow for effective P3s?
- What can or should finance seekers do to attract investment funds?
- What do investors need to come to view infrastructure as a viable place to invest?
- How should the cost-benefit analysis be calculated?
- How will social equity in the access to and distribution of funds be ensured?

A follow-on activity to the work of the CSIWG should explore them in detail.

Accounting for Climate Change in Infrastructure Financing

Many analysts and practitioners call for the development of new financial tools (see review in Moser et al. 2018[279]) to generate new funds for adaptation, including for forward-looking, climate-safe infrastructure investment. Some, however, recognize that the financial tools alone will not suffice[225,279,284]. Instead, an integrated financing system needs to be built instead, and this report follows this advice, with Chapters 5-9 constituting the elements of such a system.

There is important precedent for developing complex financing systems in many areas of public responsibility. In climate adaptation there are now many financing experiments and development of innovative financing instruments underway, but they do not yet constitute a "system."

A more fully developed "system" would have standardized complex transactions so they can be predictably executed on a routine basis (Figure 8.8). It would entail (1) strong data and analytics to support economic assessments and financial transactions, including an assessment of the performance of climate-safe infrastructure (see Chapter 5); (2) a pipeline of well-developed projects ready for investment (see Chapter 6); (3) clear governance processes and structures that allow moneys from various sources to be received, integrated and applied toward properly designed climate-safe infrastructure (see Chapter 7); (4) a range of readily available and proven financing tools (this chapter); and (5) a variety of efforts that enable appropriate implementation (see Chapter 9). Figure 4.8 in Chapter 4 illustrated these five components as well as the need to integrate them across scales of governance.

Below, we highlight more specific needs to realize the finance-related needs. The CSIWG considers progress on each essential to actually get climate-safe infrastructure built on the ground.

Data and Analytics in Support of Climate-Safe Infrastructure Finance

Chapter 4 provided an overview of what data is already available and what more is needed to assist engineers and architects in the planning and design of climate-safe infrastructure. In addition, however, there are several non-climate science information needs that are essential to make the economic case for adaptation investment.

Figure 8.8 An integrated system of skills, capacities and mechanisms is needed to analyze, design, plan, govern, finance and implement infrastructure projects. (Photo: San Francisco Main Public Library; Thomas Hawk, flickr, licensed under Creative Commons license 2.0)

An assessment of the economic feasibility of a project is commonly the first step in the infrastructure development cycle but assessing costs and benefits in the face of both climate and societal uncertainties is not trivial. What is commonly lacking are:

- **Appropriate benefit cost analysis tools** deployed in robust decision-making in the face of deep uncertainty, risk management and adaptation pathways contexts, applied over the entire life-cycle of a project, along with the necessary capacity of many analysts to use these tools appropriately (see also Chapter 6);
- **Adequate data on costs** of non-traditional designs as well as well-established methodologies for assessing costs over the entire life-cycle of an infrastructure project, not only its upfront costs;
- **Adequate data on benefits** to the project owner and to society, including trusted methodologies for assessing difficult-to-monetize benefits such as ecological or cultural values; from an investor's perspective, this also requires performance data on the environmental, social and governance (ESG) factors that would satisfy green and/or climate bond requirements; and, last but not least,
- **Defensible metrics of "success" of adaptive infrastructure projects**, which would give infrastructure owners and investors/lenders the confidence that the chosen adaptation pathway is viable and well-considered, and progress toward climate safety is being made.

At the moment, none of these approaches are standardized, and for some types of projects, such as nature-based infrastructure, they are only in development. This lack of established approaches and metrics of success makes it difficult for investors to assess with confidence whether a project is a good investment or not.

The lack of established approaches and metrics of success makes it difficult for investors to assess with confidence whether a project is a good investment or not.

[14] This might be a possible opportunity for collaboration with the Sustained National Climate Assessment (see Box 5.3).

A number of practical steps forward can help implement the overarching recommendation on developing the funding and public support for investment in a climate-safe future:

1. The State should include economic analyses of the costs and benefits of climate-safe infrastructure as an explicit focus in the next update of the Climate Change Strategic Research Plan to develop better estimates of the fiscal challenges and opportunities;
2. With available and improved methodologies in hand, State agencies should carefully evaluate expected costs and benefits of current and proposed policy approaches to infrastructure planning and design, including via interdependencies with other agencies and policies. They should also publicly and transparently disclose those costs, benefits, interdependencies and related climate-risks. This evaluation should include consideration of factors such as:
   - Timing (life-cycle);
   - Equity (who bears the costs and who enjoys the benefits);
   - Appropriate cost-benefit tests (such as participant costs, total resource costs, and full accounting of externalities); and
   - Second-order effects (such as the impacts of adopting one policy on the success of another).
3. The State should find ways to compile and critically assess economic valuation methodologies, particularly of difficult-to-assess costs and benefits, that are available in the literature[14] and update outdated State economic valuation practices, so that the environmental and social benefits can be more effectively integrated into feasibility studies; and
4. The Technical Advisory Council of the State's Integrated Climate Adaptation and Resiliency Program's (ICARP) has begun investigating indicators and metrics of adaptation success. This is also subject to ongoing research in the research community[285]. The TAC or a subset of the TAC, in cooperation with relevant State agency staff, external researchers, stakeholders representing social equity interests and financial experts should develop a suite of metrics that are meaningful to all parties – funding seekers and funding providers.

Pipeline of Investment-Ready Projects

As discussed above and in Chapter 6, California does not currently have an integrated vision and clearly prioritized strategy of how to modernize its infrastructure. Each agency puts forward its own set of projects and budget priorities get made in a non-transparent fashion. The legislature has its own priorities and does not appear to follow the Five-Year Infrastructure Plans. Voter initiatives reflect popular demand (or at least popular support) but again, do not constitute an integrated strategy.

Private-sector investment is sometimes seen as an additional option to supplement State or federal funds. With private-sector funding, however, traditional models to deliver enough return-on-investment to motivate investors could be undermined by climate change variability, resulting in potentially increased costs or shifts in how project liability is shared between the State and the private investor.

P3 authorizing legislation does not exist for every infrastructure sector in California (it is available for highways, the high-speed rail and courthouses)[1] and is thus still relatively rare compared to the use of such approaches in other countries. In the few instances in which California State agencies have engaged in P3s to date, the public-private partnership was hampered by lack of project selection criteria, lack of clarity whether the P3 was actually the best procurement approach, limited oversight from the State's Public Infrastructure Advisory Commission (PIAC), and uneven expertise in procurement[286].[15] Many consider P3s to be complex arrangements that require considerable expertise to carry out appropriately[223,287]. As we will discuss in Chapter 9, workforce development for procurement staff on how to re-orient toward climate-safe infrastructure investment is a critical aspect of realizing climate-safe infrastructure.

These complexities notwithstanding, P3s are commonly invoked as potential vehicles to attract more funding to infrastructure, particularly in light of the need for growing investment due to climate change. This potential should only be realized, however, if rules and accountability mechanisms have been clarified, and if there is a series of projects lined up (see Chapter 6), ready for investment and in final costs to the taxpayer are sufficiently prudent as compared to traditional government financing.

[15] The California legislative authority (Section 143 of the Streets and Highways Code) for P3 projects expired on January 1, 2017. See additional information on P3s used by DOT at: http://www.dot.ca.gov/hq/innovfinance/public-private-partnerships/PPP_main.html.

Dedicated Climate Funds vs. Climate Accountability in All Infrastructure Finance

Proposition 68[16] (a ballot measure deciding the fate of SB 5, De Léon[17]) was approved in the June 2018 election. It approved the issuance of general obligation bonds for parks, natural resources protection, ocean and coastal protection, water quality and supply, including groundwater management, flood protection, climate preparedness/adaptation and resiliency projects[266]. While Prop. 68 is one of several bond measures and $4 billion dollars is indeed significant, it has many intended purposes, climate adaptation being one, and it only begins to make a down-payment on the estimated funding needs for infrastructure cited above. How much of the $4 billion will actually be spent on adaptation – and on state infrastructure specifically – remains to be seen.

Another bill is currently making its way through the Assembly (AB 733, Berman)[18], which would explicitly allow EIFDs to be used for local climate change adaptation projects. While it is awaiting action from a concurrent Senate bill in the next legislative session and it focuses on local rather than state infrastructure funding mechanisms, Prop. 68 and AB 733 are examples of how voters and the legislature try to improve the availability of funding for climate-safe infrastructure through dedicated funding sources.[19]

The alternative – or rather, additional – approach particularly promoted in this report is to ensure that all new or retrofitted infrastructure accounts for climate change, which requires changes in standards, codes, guidelines and planning processes (see Chapter 7). If such changes are made, all available funding mechanisms – not just a limited dedicated source – provide a pool of resources to make the state's infrastructure climate safe.

The two complementary approaches point to the different demands of effective governance systems required to put climate-safe infrastructure financing in place. In the case of dedicated funds, infrastructure project owners may claim adaptation benefits but accountability mechanisms would need to be established. EIFDs might constitute critically important governance structures for projects that cross jurisdictional lines (as is often the case with infrastructure projects). Moreover the 55% voter approval

[16] See: https://ballotpedia.org/California_Proposition_68,_Parks,_Environment,_and_Water_Bond_(June_2018).
[17] See: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB5.
[18] See: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180AB733.
[19] Here again, the CSIWG only provides information on pending legislation to provide the full context of activity at the state level. It does not state an opinion on whether or not this legislation should be approved.

of bonds issued through EIFDs makes it easier to obtain financing compared to taxation requiring a super majority. Yet, as with dedicated funds, what is being built with those funds does not have to follow strict codes or standards unless they are established by the State.

Innovative Climate-Safe Financing Tools

Another set of governance issues relates to the design of financing instruments that reduce the barrier of upfront costs versus O&M costs over the course of the project's entire life cycle. An example from the building sector illustrates the point: arguably, climate adaptation strategies can be more easily incorporated into new construction as the building is being planned and designed. Existing facilities pose a greater challenge on many fronts. Major retrofits to an existing facility are a significant investment in time and resources that will need to provide clear value to the building owner.

Upfront capital, in particular, is limited, in the public sector. To avoid the need for upfront funding in energy retrofits, building owners often enter into arrangements with energy service companies (ESCOs), whereby the ESCO provides an energy savings guarantee and the building owner secures a loan from a lender based on the guaranteed savings provided. From the owner's perspective, the savings from the retrofits will offset the loan payments. From a lender's perspective, the savings guarantee provided by the ESCO gives the lender confidence that the project will generate a positive cash flow.

Climate adaptation strategies could conceivably be integrated in existing buildings, in a similar fashion. Either as part of an energy retrofit or as a stand-alone effort, financing options to offset the initial costs would relieve a key barrier to implementation. However, unlike energy retrofits, climate adaptation strategies may not result in immediate short-term financial benefits such as utility bill reductions. Therefore, financing products may need to be structured to recognize the longer-term benefits such as reducing risks from extreme climate events like wildfires, flooding, high heat and so on.

Similar ideas have led to the creation of "resilience bonds"[224]. Resilience bonds combine the benefits of catastrophe insurance (also called "cat bonds" – namely, to have insurance coverage for the unlikely case of a catastrophic event)- with the benefits of investing in resilience which aims at reducing losses - namely, to reduce catastrophe insurance premiums and the risk to the principal (i.e., the cat bond holder). Resilience bonds put a price on the risk reduction that would be achieved from a resilience project, turn it into a rebate on the catastrophe insurance policy, and return that rebate as financing to the resilience project.

Resilience bonds were created as one way to ensure that the financial value created by public investments in resilience is returned to the public sector. While still in the pilot phase, interest in resilience bonds is rapidly growing in part due to the growing climate risks and expected losses, partly due to the requirement for many infrastructure projects to carry insurance and partly due to the pressure to find financing for upgrades/retrofits or new infrastructure projects. Resilience bonds can fill project funding gaps for upfront costs, funding future project phases, cover O&M costs or buy additional insurance; they can help meet insurance obligations; and they enhance project design integrity.

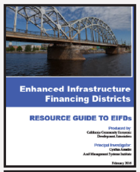
A number of other innovative finance instruments have been developed or are being proposed (e.g., project cost overrun insurance[288, 289]; green bonds[290,291]; climate bonds; environmental performance bonds[292,293]; and social impact investment[294,295]). For many, however, these novel instruments are still too risky because they are unproven, certification and/or accountability is lacking, or existing governance structures present obstacles. Thus, to realize the full potential of these innovative finance instruments, these governance structures and components need to be reworked, revised or invented and users must become familiar and skilled in using them. For example, finances are often handled within departmental budgets but benefits of multi-faceted infrastructure projects may accrue to other sectors. Thus, to enable those benefits to be counted against the costs incurred, financial accounting must be able to "bust" governance silos (see the discussion at the end of Chapter 7).

Over the course of the Climate-Safe Infrastructure webinar series, three webinars were dedicated to infrastructure finance. Those webinars were some of the best attended. Similarly, the Third California Adaptation Forum has a stronger-than-ever focus on funding and financing. These observations suggest the growing interest and need for infrastructure designers, planners, consultants and not-for-profits to learn more about adaptation finance, particularly for large infrastructure projects (Box 8.2).

To advance innovative financing for state climate-safe infrastructure projects, additional concrete follow-up steps would include:

1. Building greater in-house technical know-how on innovative financing mechanisms; and
2. Working closely with financial advisers from the private and public sectors, including philanthropy, to explore and implement innovative funding mechanisms.

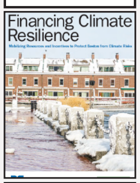
Box 2.2 Selected Resources on Funding and Finance Relevant to Climate Adaptation and Infrastructure



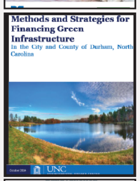
Amador, C. 2016. *Enhanced Infrastructure Financing Districts: Resource Guide to EIFDs.* Los Angeles: California Community Economic Development Association.

Keenan, J.M (2018). *Climate Adaptation Finance and Investment in California*. London, UK.: Routledge.

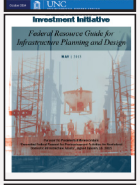
Sims et al. 2016. *Taking the High Road to More and Better Infrastructure in the United States*. Washington, DC: Natural Resources Defense Council.



Levy et al. 2018. *Financing Climate Resilience: Mobilizing Resources and Incentives to Protect Boston from Climate Risks.* Boston, MA: Sustainable Solutions Lab, UMass Boston.

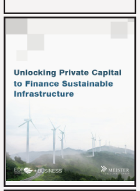


Hughes. 2014. *Methods and Strategies for Financing Green Infrastructure In the City and County of Durham, North Carolina.* Chapel Hill, NC: Environmental Finance Center at the University of North Carolina.

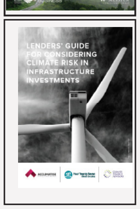


Build America Investment Initiative. 2015. *Federal Resource Guide for Infrastructure Planning and Design.* Washington, DC: Build America Investment Initiative

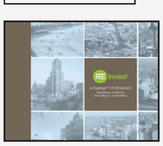
Fairchild and Rose. 2018. *Inclusive Procurement and Contracting: Building a Field of Policy and Practice.* Oakland, CA: PolicyLink & Emerald Cities Collaborative.



Andersen et al. 2017. *Unlocking Private Capital to Finance Sustainable Infrastructure.* EDF Business and Meister Consultants Group

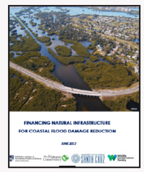


Firth, Swann and Kim. 2018. *Lenders' Guide for Considering Climate Risk in Infrastructure Investments.* Acclimatise, Climate Finance Advisors and Four Twenty Seven.

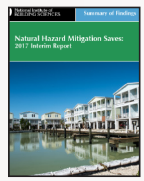


Re:focus. 2015. *A Roadmap for Resilience: Investing in Resilience, Reinvesting in Communities.* RE:invest collaborative.

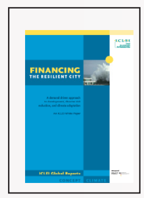
Hacke, Wood and Urquilla. 2015. *Community Investment: Focusing on the System.* Troy, MI and Initiative for Responsible Investment, Harvard. and Cambridge, MA: The Kresge Foundation



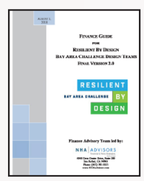
Colgan, Beck and S. Narayan. 2017. *Financing Natural Infrastructure for Coastal Flood Damage Reduction.* London: Lloyd's Tercentenary Research Foundation.



National Institute of Building Sciences (NIBS). 2017. *Natural Hazard Mitigation Saves: 2017 Interim Report.* Washington, DC: NIBS.

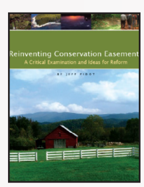


Brugmann. 2011. *Financing the Resilient City: A Demand Driven Approach to Development, Disaster Risk Reduction, and Climate Adaptation.* Bonn, Germany: ICLEI Local Governments for Sustainability.

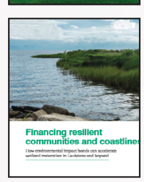


Northcross et al. 2017. *Finance Guide for Resilient By Design Bay Area Challenge Design Teams: Final Version 2.0.* San Rafael, CA: NHA Advisors.

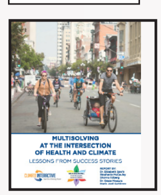
Ernst & Young Global Limited and 100 Resilient Cities. 2017. *Getting Real About Resilience: How Cities Can Build Resilience Thinking into Infrastructure Projects.* New York, NY: EYGL and The Rockefeller Foundation.



Pidot. 2005. *Reinventing Conservation Easements: A Critical Examination and Ideas to Reform.* Policy Focus Report PF013. Cambridge, MA: Lincoln Institute of Land Policy.



Environmental Defense Fund (EDF) and Quantified Ventures. 2018. *Financing Resilient Communities and Coastlines: How Environmental Impact Bonds Can Accelerate Wetland Restoration in Louisiana and Beyond.* EDF New York, NY.



Sawin et al. 2017. *Multisolving at the Intersection of Health and Climate: Lessons from Success Stories.* Washington, DC: Climate Interactive.

Conclusions

In this chapter, we have reviewed infrastructure funding trends, challenges and the needs and opportunities to put in place finance systems that can make further progress on improving infrastructure finance in the state, and address the growing cost of infrastructure in the face of climate change. This review illustrates that California has long grappled with infrastructure funding, has made incremental progress, and, in fact, is probably in a better position today than at any time in the past 20 years to make more strategic moves and investments in a climate-safe future. Our report makes clear that integration of forward-looking climate science is not only a necessary ingredient in the planning and design stage of infrastructure but is also needed as an integral part of a comprehensive system required to finance climate-safe infrastructure. Climate data, demographic, land use and economic data, a variety of metrics of the environmental, social and governance performance of traditional and innovative funding mechanisms and additional metrics to measure adequate progress and success of adaptive infrastructure projects are required to secure the necessary funding (Figure 8.9).

Metrics to measure adequate progress and success of adaptive infrastructure projects are required to secure the necessary funding.

In Chapter 10, we will turn to additional conditions that will help or hinder the implementation of the Climate-Safe Path for All.

Figure 8.9 Metrics of the environmental, social and governance performance of infrastructure and related funding mechanisms are needed to attract funding and to evaluate progress and effectiveness over time. (Photo: Full moon over wetlands; Alice Cahill, flickr, licensed under Creative Commons license 2.0)

9 Implementation:
Steps Toward Realizing the Climate-Safe Path

At the End of the Day…

The final component of the framework to action introduced in Chapter 4 – which aims to chart the way to implementing the Climate-Safe Path for All proposed in this report – is to focus on a number of implementation challenges after all other pieces – data, projects, governance and finance – are in place. While an overall vision – and policy to give it prominence – were seen as critical, one phrase was used maybe more times than any other over the course of the Climate-Safe Infrastructure Working Group's (CSIWG) process – by members, expert panels and invited webinar speakers: and that is, “at the end of the day.” This phrase reflected the urgency and impatience felt by many to get on with making climate-safe infrastructure a reality yet pointed to common “last mile” challenges of getting such infrastructure actually built on the ground. Such challenges include:

- Having sufficient well-trained staff who know how to do it;
- Having mechanisms for coordination to move the Climate-Safe Path vision forward across administrations, across government silos and beyond government; and
- Having incentives, means and know-how on how to turn State-level policy into meaningful action at local and project levels.

In this chapter then, we address key implementation challenges that were raised over the course of the CSIWG’s work and recommend ways to address them.

Training, Capacity Building and Other Workforce Issues

Over the course of the CSIWG’s work, a reoccurring theme was the need to have the skilled workforce to actually get climate-safe infrastructure appropriately designed, built, operated and maintained. This is far from a new theme in infrastructure discussions, neither in the state[187,296,297], nor across the nation[188,189, 192,193,223]. But with regard to the central concern of this report, namely how to account for climate change in infrastructure engineering, the workforce issues take on a unique flavor.

Figure 9.1 California needs a skilled workforce to actually get climate-safe infrastructure appropriately designed, built, operated and maintained. (Photo: Solar installer lays a photovoltaic module; Department of Energy)

The CSIWG encountered the following 11 specific training and skills gaps and needs during its deliberations:

- **Climate skepticism:** CSIWG members reported regularly encountering and/or working with colleagues who do not know about the degree of scientific consensus on climate change or who overtly share the skepticism about predominantly human-caused climate change that can still be found in some parts of the American public[298] (Chapter 5).
- **Lack of understanding of climate science:** Among some in the workforce, this skepticism of climate change is rooted in a lack of deep familiarity or comfort with climate science – something that is still not regularly included in engineers' and architects' education[299]. Similar discomfort and lack of climate science understanding can be found among procurement staff, investors and financing experts, elected officials and planners who are now asked to prepare for climate change or account for it in their area of expertise. Some, even if they generally accept the scientific fact of climate change, do not feel solidly enough anchored in the science to defend it with skeptical audiences. Doing so would make them vulnerable to looking professionally incompetent (Chapter 5).
- **Lack of familiarity with sophisticated risk and uncertainty assessment tools and approaches to decision-making under deep uncertainty**: There is a similar situation arising from the lack of training in risk and uncertainty assessment methodologies, and how to make decisions in the face of uncertainty, all of which go beyond the traditional compendium in their professional trainings (Chapter 6).
- **Lack of familiarity with sophisticated economic analysis methodologies:** Traditional benefit-cost assessment methodologies, narrowly focused on easily quantifiable project costs and outcomes are well established, but they are inadequate for the systemic, silo-busting, integrative approach promoted throughout this report (Chapter 8).
- **Lack of knowledge of and disconnect from the adaptation literature and field:** Most engineers and architects are professionally anchored within their fields, disciplines and professional societies, which still have very small overlap with multiple decades of adaptation science and an emerging, but still small field of adaptation professionals[300]. Concepts like adaptive management, adaptation pathways, building adaptive capacity and so on are only slowly being integrated into the thinking of those who build our infrastructure.
- **Lack of familiarity with many available tools and platforms:** The webinar series and literature review unearthed a number of tools and platforms. While some had heard of some of these tools and platforms, most were unfamiliar – even among the experts on the CSIWG. Meanwhile, there is an overwhelming number of tools with little guidance as to which of them are most useful for what purposes. Platforms and processes for scientists to engage regularly and on an ongoing basis with engineers and architects are rare, and none were found that focus on exchange around climate change *per se* (Chapter 5).

Figure 9.2: Workforce development must reach into all segments of California society, and particularly open doors to minority, women and otherwise previously disadvantaged workers. (Photo: Workers erecting a telephone pole; Russ Allison Loar, flickr, licensed under Creative Commons license 2.0)

- **Lack of comfort with performance standards:** Engineers and architects are most familiar and comfortable with targeted structural design standards and technical specifications. As the tried and true standards of their respective fields, they give clear instructions on how to build and come with the trust of having been approved by standard-setting bodies through a consensus-based process. Performance standards, by contrast, entail far more flexibility and creativity, but also professional uncertainty, as to how to achieve desired outcomes (Chapter 7).
- **Lack of familiarity with adaptive design approaches and techniques:** Adaptive design is only an emerging paradigm and only few examples exist yet on how to build in ways that allow infrastructure to be built in stages and in modular ways over time. Practices are not yet well established and guidance is limited, leaving practicing engineers and architects with little know-how to go on (Chapter 7).

- **Resistance to integrative and systems thinking that crosses silos:** Broadening out from individual assets or structures to infrastructure systems embedded in social, ecological and economic environments, where there is a demand to account for costs and benefits across sectors and where disciplines, interest groups and jurisdictions need to come together to agree on a shared vision, engineers and architects are asked to step out of the comfort zone of traditional ways of doing things. Some welcome this opportunity, while other feel ill-prepared to do so effectively. Numerous institutional and educational barriers hinder effective collaboration.
- **Lack of skill in effective stakeholder engagement and communication:** From the start of this project, CSIWG members emphasized the need to effectively communicate climate change and to engage stakeholder communities. They asked for resources to improve these practices, as these skills, too, are not yet widely taught in their professional training. This is as true for climate scientists as it is for architects and engineers (see also webinars series) (Chapter 6).
- **Lack of cultural competency in working with diverse stakeholders to address long-standing legacies of social exclusion and inequity:** Finally, where infrastructure planners and designers need to address historical legacies of underinvestment in low-income communities and communities of color, there is inadequate skill and experience in practices of inclusive and transparent forms of visioning, deliberation and decision-making. Limited appreciation for the legacies of systemic racism, the need to (re)build trust and address immediate concerns such as health, economic opportunity and safety alongside infrastructure rehabilitation or expansion, all too often lead to contentious or unsatisfying interactions.

Many of these gaps in knowledge, skill and professional training were a stumbling block during the development of the State's *Sustainability Roadmap*, where The Governor's Office of Planning and Research (OPR) staff requested, for the first time, that climate risks be taken into account (L. Bedsworth presentation to the CSIWG 2018). Against the backdrop of the already well-recognized workforce challenges facing California (and the nation), it is essential that workforce development include a concerted effort to ensure that the existing and future workforce is prepared to deal with rapidly changing technologies, industry changes and climate change. "People readiness" thus must include "climate readiness." Importantly, as California engineers and architects become comfortable and proficient in the issue areas listed above, the state's infrastructure will benefit irrespective of the emissions pathway on which humanity finds itself.

"People readiness" must include "climate readiness."

Recommendation 8

The Strategic Growth Council should coordinate with the Government Operations Agency, the Labor and Workforce Development Agency, and other relevant agencies to develop a work plan on how to address the training and professional development gaps of its infrastructure-related workforce as identified in this report, and begin to implement that work plan as soon as feasible. Because the Strategic Growth Council does not currently have the staff capacity and funding to implement this task, it would require adequate funding to do so.

Workforce development of the magnitude and scope required is not a short-term program, and it cannot be accomplished through State agencies' efforts alone. Workforce development, as is already widely understood, requires partnerships with professional societies, universities, philanthropy, labor unions and the private sector[299,301]. It should not be narrowly disciplinary[302] and embrace the challenges over the entire course of the infrastructure lifespan. Workforce development efforts that are climate-cognizant must recognize that with an increasing number of disasters, the labor shortage can become acute quickly. Workforce development should clearly have a dedicated focus on benefiting youth, women, minorities and low-income populations already in need of well-paying jobs[303]. It does not begin only after high school but must reach back into K-12 for adequate STEM education and developing a pipeline of engaged and interested young women and men who have the breadth of skills needed to build the California of the future. Education, maybe like no other investment, is a form of "paying it forward" – as this report suggests.

According to a National Academy of Engineering 3-year project on engineering education on climate change[299], two challenges however persist in the education of engineers (and architects):

- Climate change remains largely absent in engineering curricula (except renewables engineering); and
- Few, if any materials, fully engage the integration of climate, society and engineering.

Through collaboration with professional societies and universities, professional training and education curricula and related materials must be developed as well as mechanisms through which practicing engineers and architects can obtain the necessary skills and competencies (Box 9.1).

A focus on engineers and architects, however, will not suffice to effectively and efficiently address the workforce issues. Societal decisions about climate change will involve a wide range of experts, decision-makers in various sectors and different publics. Climate scientists are not usually trained in effective engagement, human concerns, ecology and governance issues, hindering their ability to communicate fluently with practitioners. Likewise, social scientists are not usually trained in engagement with publics or with physical/natural/engineering scientists. None (engineers, architects, scientists and practitioners) are sufficiently trained in matters of finance and law that have emerged as crucial over the course of the CSIWG's exploration.

Box 9.1: Hard Engineering Skills and Professional Skills Required to Implement the Climate-Safe Path for All

"Hard" engineering skills:

- The ability to **apply knowledge of mathematics, science, and engineering, including a solid footing in climate science and climate impacts science**;
- The ability to **design and conduct experiments**, as well as to **analyze and interpret data**;
- The **ability to design a system, component, or process** to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability;
- The **ability to identify, formulate, and solve engineering problem**s; and
- The **ability to use the techniques, skills, and modern engineering tools** necessary for engineering practice.

"Professional" skills:

- The ability to **communicate** and connect across boundaries effectively;
- The ability to **function on multi- and transdisciplinary teams**;
- An understanding of **professional and ethical responsibility**;
- **Cultural competency** in working with diverse stakeholders;
- The propensity and skill in **systemic, integrative thinking**;
- The broad education necessary to understand the **impact of engineering solutions in a global, economic, environmental, and societal context**;
- A recognition of the need for, and an ability to engage in life-long learning; and
- A **knowledge of contemporary issues**.

Source: Adapted from[304-306]

The CSIWG clearly recognizes the magnitude of the infrastructure workforce challenge in California. It also recognizes that the State has taken the first step already by recognizing what is at stake due to climate change. As concrete next steps in operationalizing the recommendation to foster a "climate-ready workforce," the Strategic Growth Council and other State agencies should:

- Engage with professional societies, state-based engineering schools and universities, the American Society of Adaptation Professionals, private sector engineering and architecture firms and others deemed relevant in the development of the recommended workplan. As we suggest in the next section, a coordinating body at the state level could lead this effort;
- Incentivize – through the State's existing research programs – a rapid and substantial expansion of end-to-end, multidisciplinary climate change research, education and application programs;
- Set expectations through professional standards, qualification and continuing education requirements etc. of state engineers and architects as well as those receiving State funding; and
- Expand and institutionalize the State's internal decision support capabilities, including a professional development pipeline of well-trained professionals by requiring staff to engage in ongoing professional development in the areas found to be most in need of advancement.

Statewide Coordination at the Highest Level

In Chapters 6, 7 and 8, we repeatedly highlighted the need to coordinate across government silos in order to design better integrated projects, align policies and goals, appropriately assess multi-sector costs and benefits and develop adequate finance mechanisms. These are complex, often novel and thus unfamiliar tasks that are no one's explicit task. Mission agencies, while often responsible for a broad portfolio of issues, have agency-specific, not cross-agency coordinating missions. In 2010, the Little Hoover Commission, as pointed out earlier, criticized the lack of an integrated statewide infrastructure strategy and little has changed since. While the State now has the Integrated Climate Adaptation and Resilience Program (ICARP) to support integration of adaptation across State agencies and coordinate better with local government entities (and a Technical Advisory Council to support that effort), ICARP is not solely focused on climate-safe infrastructure, and simply tasking it with adding that on, may overwhelm existing capacity or sideline coordination around the Climate-Safe Path for All and climate-safe infrastructure issues to being one of many equal priorities.

Meanwhile, this report makes a number of recommendations and suggests many concrete follow-up steps to operationalize them with no single entity providing coordination or oversight, or even just a mechanism to deepen the work begun over the short period in which the CSIWG completed its tasks. Without some entity singularly focused on the implementation of the recommendations offered in this report, there is legitimate concern that the Climate-Safe Path for All will go nowhere.

Without some entity focused on the implementation of the recommendations in this report, the Climate-Safe Path for All will go nowhere.

Recommendation 9

The State should establish a Standing CSIWG to devise and implement a process for coordinating and prioritizing Climate-Safe Path-related resilience policies and actions at the highest level. This panel would provide a needed forum for agencies to coordinate their policies, take advantage of synergies, address potential conflicts and learn from one another. As AB 2800 is slated to sunset in 2020, the work of a standing CSIWG would require an extension of AB 2800 and adequate financial support to conduct its business.

The Foundations Are Already in Place

Over the last decade and a half, the State of California has led the nation in climate change mitigation, with key strategies initiated in 2006 with Governor Arnold Schwarzenegger signing EO S-3-05[1], which, in part, eventually was codified as AB 32[2] – the *Global Warming Solutions Act*. Recognizing the need to put as much attention on adapting to climate change, the State has since also strengthened its focus on preparedness. From these initial actions, the State has recognized the importance of ensuring climate-safe infrastructure – though it did not bear that name until AB 2800.

In 2009, the State released its first Climate Adaptation Strategy (CAS)[307]. This was intended to be a companion to the bold mitigation efforts of AB 32 several years before. The CAS laid the foundation for much of the work the State has done since, including two updates (in 2014 and 2018). The plan was renamed the *Safeguarding California Plan*. Annual implementation reports to the Legislature on the status of actions identified in *Safeguarding California* are required by statute (AB 1482)[3].

These strategies and related efforts were precursors to AB 2800 and the discussions of the CSIWG. The initial CAS recommendations in 2009 mandated that State agencies begin planning for climate change and initiated thinking about infrastructure adaptation. The most relevant subset of these recommendations stated:

- **Recommendation 4:** All State agencies responsible for the management and regulation of public health, infrastructure or habitat subject to significant climate change should prepare as appropriate agency-specific adaptation plans, guidance or criteria by September 2010;
- **Recommendation 6:** The California Emergency Management Agency (CalEMA) will collaborate with CNRA, the [Climate Action Team] CAT, the Energy Commission, and the [Clean Air Action Plan] CAAP to assess California's vulnerability to climate change, identify impacts to State assets and promote climate adaptation/mitigation awareness through the Hazard Mitigation Web Portal and My Hazards Website as well as other appropriate sites; and
- **Recommendation 10:** State fire-fighting agencies should begin immediately to include climate change impact information into fire program planning to inform future planning efforts.

The State has also developed an *Adaptation Planning Guide* (APG), first published in 2012[308], and is currently slated to be updated. The APG presents the basis for climate change adaptation planning and introduces a step-by-step process for local and regional climate vulnerability assessment and adaptation strategy development. It is intended as a resource primarily for local governments and provides specific guidance on infrastructure:

- Incorporate consideration of climate change impacts as part of infrastructure planning and operations;
- Assess climate change impacts on community infrastructure;
- Facilitate access to local, decentralized renewable energy; and
- Use low-impact development (LID) stormwater practices in areas where storm sewers may be impaired by high water due to sea-level rise or flood waters.

Finally, Governor Brown's 2015 EO B-30-15[4] mandated for how the State should plan infrastructure under a changing climate. The EO is specific in places, preceding some of the suggestions reiterated in this report:

- State agencies shall take climate change into account in their planning and investment decisions and employ full life-cycle cost accounting to evaluate and compare infrastructure investments and alternatives;
- State agencies' planning and investment shall be guided by the following principles:
  - Priority should be given to actions that both build climate preparedness and reduce greenhouse gas emissions;
  - Where possible, flexible and adaptive approaches should be taken to prepare for uncertain climate impacts;
  - Actions should protect the state's most vulnerable populations; and
  - Natural infrastructure solutions should be prioritized.
- The State's Five-Year Infrastructure Plan will take current and future climate change impacts into account in all infrastructure projects; and
- [State agencies shall] update the APG, to identify how climate change will affect California infrastructure and industry and what actions the State can take to reduce the risks posed by climate change.

[1] For more information, see: https://cetesb.sp.gov.br/proclima/wp-content/uploads/sites/36/2014/08/governor_state_california.pdf.
[2] For more information see: https://www.arb.ca.gov/cc/ab32/ab32.htm.
[3] For more information, see: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482.
[4] For more information, see: https://www.gov.ca.gov/2015/04/29/news18938/.

Pursuant that EO, a Technical Advisory Group – comprised of 50 members – met from March 2016 to January 2017 to develop a guidebook for State agencies, entitled *Planning and Investing for a Resilient California*[230]. The *Guidebook* provides five resilient decision-making principles, which align well with the CSIWG's recommendations and implementation suggestions:

1. Prioritize actions that promote integrated climate action;
2. Prioritize actions that promote equity and foster community resilience;
3. Coordinate with local and regional agencies;
4. Prioritize actions that utilize natural and green infrastructure solutions and enhance and protect natural resources; and
5. Base all planning and investment decisions on the best-available science.

This report and its specific recommendations on more detailed science, easily accessible tools and platforms for interaction, training and workforce development, engagement, financing and so on are intended to build directly on this State guidance and inform and enable its implementation in concrete ways. As experience both in California and elsewhere shows, without ongoing interaction with those who are expected to use information and tools or implement guidance, action can be stymied.

In addition, several State agencies – largely in response to the original CAS – are providing internal guidance for their own (agency-specific) operations and decisions and external guidance to the entities and communities that manage resources the State agencies oversee.[5] Since 2011, the California Coastal Commission (CCC), the Coastal Conservancy, the Department of Water Resources (DWR) and the Ocean Protection Council (OPC) have worked jointly to help identify the most up-to-date sea-level rise (SLR) projections and develop guidance to communities on how to use forward-looking climate information in their coastal planning and decision-making, notably through the updating of local coastal programs. The first *OPC Sea-Level Rise Policy Guidance* was developed in 2011, updated in 2014, and again recently updated in 2018[49]. The CCC has a longstanding concern about sea-level rise (since 1989), issued previous guidance on how to account for SLR in Local Coastal Programs and released an update in 2015[309]. The CCC is currently updating its guidance based on the 2018 *OPC SLR Policy Guidance* update.[6]

[5] As an example, DWR developed such agency-specific guidance documents: *The Climate Change Handbook for Regional Water Planning* (2011) and how to use climate change information in the Water Storage Investment Program (2016a and 2016b, see also Appendix 13).

[6] For more information, see: https://www.coastal.ca.gov/climate/climatechange.html.

This brief review of past and ongoing State efforts on adaptation make clear that the deliberations of the CSIWG are not new conversations. Many of the state engineers and architects, as well as the social and physical climate scientists on the Working Group, have incrementally advanced their respective agency's missions for many years. The Climate-Safe Path for All is intended to ambitiously push efforts even further and to provide an integrative vision and frame that unites the state's mitigation and adaptation efforts.

The Role of a Standing CSIWG

The Climate-Safe Path for All is thus not a new or extra process that communities or State agencies must understand and subsequently align with other State policies. It is not another series of meetings that are to be added to already overcommitted schedules. It should certainly not be another unfunded mandate. Rather, the Climate-Safe Path for All is intended to serve as the vision for connecting all of the State's disparate, but ultimately interconnected, climate adaptation and mitigation actions on infrastructure and related systems. It also prominently integrates the importance of social equity across these efforts and gives it a central and coherent place.

Figure 9.3: The role of a future Standing Climate-Safe Infrastructure Working Group would be to coordinate infrastructure-related efforts across State agencies, provide a central point of contact and forum for learning and exchange, and provide leadership in implementing the recommendations of this report (Photo: Joseph Wraithwall, used with permission)

As a concrete next step, the current CSIWG recommends the formation of a standing CSWIG panel to ensure that this vision is carried forward, that integration happens, and that the many challenges unearthed during this CSIWG's efforts are being addressed. The standing CSIWG would have the following roles:

- **Coordination:** The standing CSIWG would provide a central coordinating mechanism. The group would be comprised of State agency representatives who would devise and implement a process for coordinating and prioritizing potential resilience policies at the highest level. This panel would have no authority other than to require agencies to address conflicts and coordinate their policies.
- **Central point of contact for infrastructure:** In addition, the standing CSIWG should be considered a central point of contact whereby other existing planning and coordinating efforts (such as ICARP and its Technical Advisory Council, the Strategic Growth Council's Infrastructure Workgroup, the Climate Change Strategic Research Plan, future California Adaptation Forums (CAF) and so on) have a go-to place for infrastructure issues.
- **Forum to advance climate-safe infrastructure questions:** The panel should also function as a forum for exchange to foster internal learning and to solicit input – as needed – from outside subject matter experts and stakeholders, particularly in areas where State agencies' in-house capacity is more limited (social equity, financial tools etc.). It could coordinate engagement efforts to ensure fair and equitable social inclusion. As such, it could be responsible for ensuring – as we emphasized in earlier chapters – that climate-safe infrastructure is being planned *with* communities, not *for* communities.
- **Leadership in incorporating forward-looking information in engineering standards:** With this initial work and the proposed development of a California Manual of Practice (CA-MOP), there is an important opportunity for the future CSIWG to encourage and drive the integration of climate resiliency measures into the code-setting processes in California. Their deliberations and products can also serve as a national and international model as other communities, states and nations struggle with the same challenges.

Recommendation 10

The State Budget should provide full funding to State agencies to make deliberate efforts in reducing or eliminating the barriers that hinder or slow down adoption of State-level climate-safe infrastructure policy into practice. Key focus areas include the translation of Climate-Safe Path policy into practice manuals and contracting language, providing incentives to account for climate change in infrastructure projects, identifying metrics of success for monitoring and evaluation and developing a best-practices compendium.

Linking State Policy and Guidance to Project-Level Action

Ultimately, the best policy statements and guidance documents need a path to implementation if they are to make it off the shelves of agency bookcases. The CSIWG sought to make its recommendations actionable by providing concrete next steps to operationalize them. "At the end of the day", however, CSIWG members thought it was critical to ensure that high-level policies would become integrated into project-level action. This included discussions on the best way to incentivize climate-safe infrastructure development, translate policies to individual contractors and develop success metrics.

It is critical to ensure that high-level policies become integrated into project-level action.

Translation from State Policy to Local Decision-Makers to Individual Contractors

In general, infrastructure design at the scale at which AB 2800 is concerned, is driven by international standard-setting organizations, large federal entities such as the Army Corps of Engineers, the Bureau of Reclamation and the Federal Highway Administration (FHWA), and professional organizations such as the American Society of Civil Engineers (ASCE). But states always have the option of going above and beyond international and national standards and practices. By doing so, states often become the initiators and drivers of higher standards everywhere.

As California and other governments stand at the threshold of a new era, in which climate change is taken into account in infrastructure design, the State inevitably must hold the tension between leading and following. So, while some State agencies await clarity from standard-setting organizations, others move beyond existing guidance and develop their own manuals of practice, codes and/or guidelines to drive climate-cognizant design for their respective agencies. Caltrans, while also adhering to standards from the American Association of State Highways and Transportation Officials (AASHTO) and FHWA, also develops Design Manuals that run the gamut from design to construction to maintenance. As another example, the California Building Standards Commission oversees and updates Title 24 to guide building codes every three years. However, for the many reasons described throughout this report, standards, codes and guidelines used in California are not yet where they should be in incorporating forward-looking climate information. On the policy precedent recalled above, the State now has the opportunity to make the Climate-Safe Path for All statewide policy which must be translated to on-the-ground contractors.

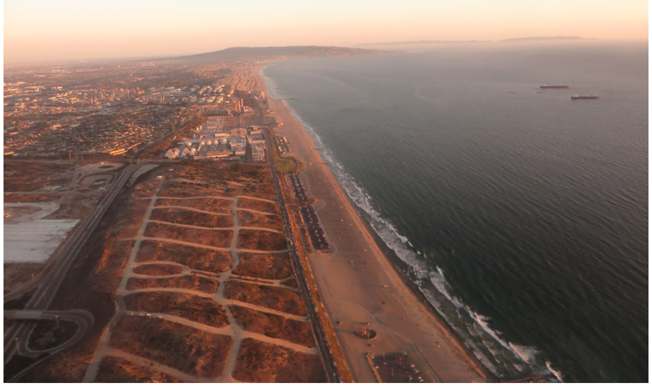


Figure 9.4: A California-specific MMOP should address all infrastructure types and the unique hazards they face across the state. (Photo: Different types of development along the El Segundo shoreline; Ken Lund, Wikimedia Commons, licensed under Creative Commons license 2.0)

There are two steps the State can take to move forward.

Developing a California Manual of Practice. The first is the previously recommended development of a California-focused infrastructure design Manual of Practice (Cal-MOP) for each infrastructure type and for all relevant climatic hazards. Advanced tools and methods introduced in Chapter 6 should be integrated into this step-by-step guide. With input, coordination and assistance from the recommended standing CSIWG, state architects and engineers, along with relevant external subject matter experts, and inclusive and effective stakeholder engagement (per Recommendations 4 and 5), this technical working group should develop infrastructure-specific guidance that incorporates the best available climate-information and the many innovative strategies outlined in Chapter 6 (e.g., systems thinking, climate screening, risk management, adaptive design for a range of plausible futures). This type of focused but coordinated attention to each infrastructure type will allow for a unified approach across the State and provide necessary impetus for moving forward.

Advancing Procurement Approaches. With a state engineer and architect-developed Cal-MOP for each infrastructure category, the second step then becomes more straightforward, i.e., the translation of State-level policy and guidance to on-the-ground contractors. The two most common procurement methods (in addition to the increasingly considered public-private partnerships (P3s) discussed in Chapter 8) that are used to get to project delivery are: Design-Bid-Build or Design-Build[310] (Figure 9,4). Design-Bid-Build is the more common of these approaches for project development and implementation. According to the Legislative Analysts Office[310], "The main difference between these approaches is which project phases – such as design, construction, maintenance, and funding – are performed under a single contract and which ones are performed separately. For example, under the design-bid-build approach, the State typically contracts with one firm to design an infrastructure project and a separate firm to build it. In contrast, under the design-build approach, the State typically contracts with one firm to design and build the infrastructure project." The latter shifts the responsibility of project delivery to the contractor. As described, "design-build, with its single point responsibility carries the clearest contractual remedies for the clients [in case of faults leading to liability claims] because the design-build contractor will be responsible for all of the work on the project, regardless of the nature of the fault"[311].

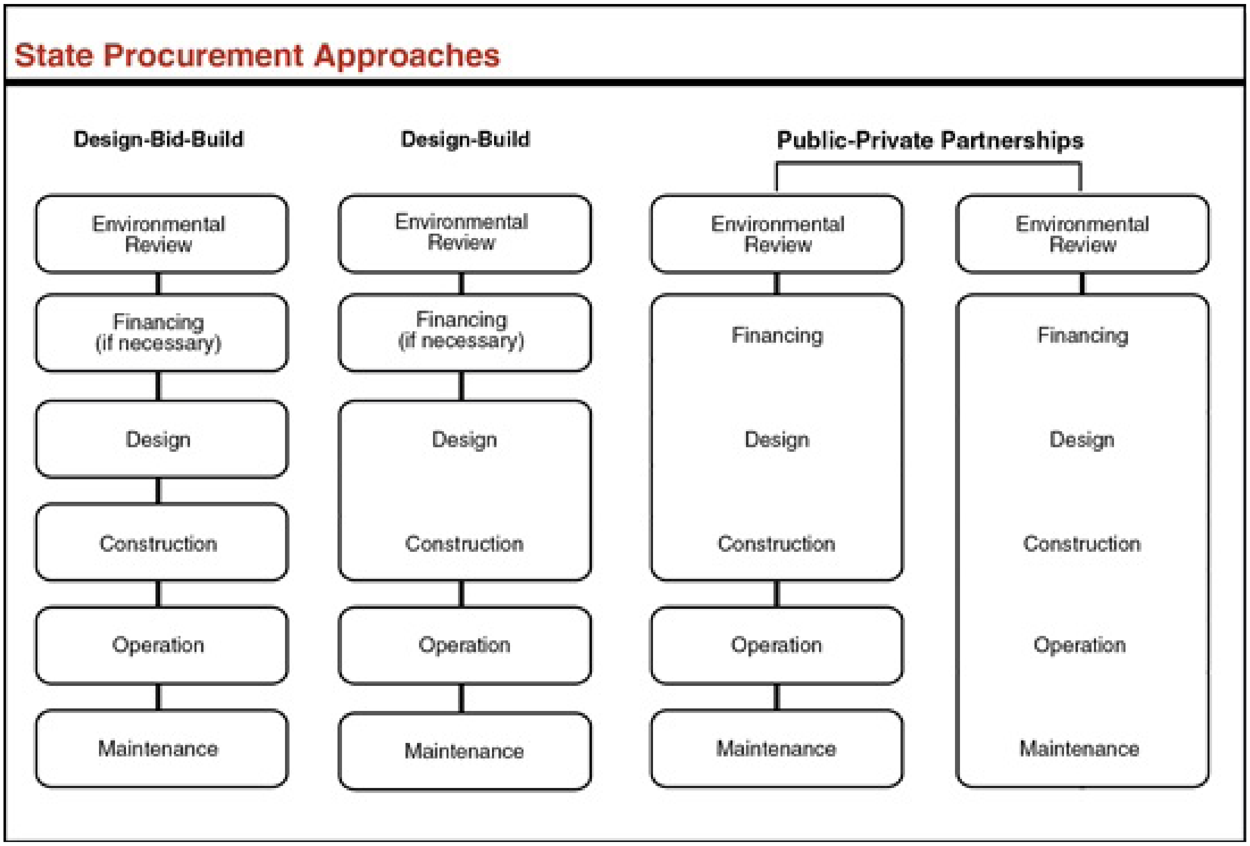


Figure 9.4 California's basic procurement approaches differ in how many contractors are involved from project initiation to construction and operation and maintenance. (Source: Legislative Analyst's Office 2018[310], used with permission)

There are various pros and cons to either of the three procurement approaches, although it was beyond the scope of the CSIWG to examine in detail the advantages and disadvantages of each vis-à-vis planning, designing and building climate-safe infrastructure. This should be undertaken by a future working group made up of relevant experts and interest groups. There are likely to be benefits and drawbacks to using one or the other for certain types of projects.

Infrastructure owners need help turning overall policy guidance into contractual language and clear statements of work.

Regardless of the procurement method chosen, infrastructure owners need help turning overall policy guidance into contractual language and clear statements of work. The Cal-MOP will help, but the CSIWG recommends several important follow-on steps from its work:

- Once procurement approaches have been thoroughly assessed by a future working group for their advantages and disadvantages for differing types of climate-safe infrastructure projects, guidance should be developed for infrastructure owners for writing different types of bids;
- Effectively assessing and managing bids, design proposals and contracts requires adequate training of staff in infrastructure agencies. Thus, the workforce development plan proposed above should explicitly include modules for evaluating design proposals; and
- The standing CSIWG or a designated working group should engage with legal and financial experts as well as engineering and climate change experts to develop model contract language and other support to assist with linking policy to project-level contracts.

To align the procurement and contracting process with the overall intent of the Climate-Safe Path for All, however, it is not enough to work only on integrating climate concerns. The social equity component needs to be carried down to the procurement and project level as well. A recent report on inclusive procurement[197], p.5 noted,

> "State and local governments are the most important venues for advancing inclusive procurement and contracting policies in the infrastructure sector. Federal infrastructure investments are blended with local public funds, and a great deal of infrastructure investment is exclusively derived from State and local revenue."

The State of California generally follows a "race-neutral" procurement approach, which has helped women and minorities but has not overtly supported them[197]. Deliberate efforts are needed to ensure minority-owned, women-owned and disadvantaged business entities (MWDBEs) have access to and are able to bid on climate-safe infrastructure projects. This would be in line with the centrality given to social equity in this report.

According to Fairchild and Rose, "There is [however] no "one-size-fits-all" inclusion policy. The policy levers, revenue streams, business motives, historical precedents, and strategies to strengthen inclusive procurement differ for transportation, water, energy, public housing, health, educational institutions, and other sectors"[197],p.5. They note the following challenges:

- Disconnect between inclusive procurement policies and their realization in practice, including lack of enforcement;
- Lack of readiness on the supply side and lack of awareness and competency on the demand side of procurement;
- Public-sector practitioners operate in silos with a wide range of disparate approaches and policies, creating inefficiencies, duplication, burdensome procurement processes and suboptimal outcomes;
- Lack of tools and processes for proactively monitoring the compliance and enforcement of inclusion policies, and lack of resources and capacity to find them;
- Large-scale infrastructure projects are using sophisticated project delivery methods to address risk and capital needs, increasing the size and time horizon of projects; and, thus, diminishing opportunities for MWDBEs to effectively participate in bids;
- Lack of technical assistance for MWDBEs to help them effectively participate in larger projects;
- The movement in the construction industry toward "green", modular approaches is shifting work toward a supply chain involving pre-fabrication; historically, however, there are few MDWBEs in the prefabrication supply chain, further excluding them from contracts;
- An aging MDWBE workforce and lack of succession planning among MDWBEs (see above); and
- The legacy of discrimination.

The CSIWG thus recommend a number of best practices and steps (Box 9.2). The CSIWG recommends as a practical follow-up step to its work, that the standing CSIWG or a designated working group systematically examine the hurdles and opportunities for improved inclusive procurement practices as it transitions to building more climate-safe infrastructure and develop the inclusive procurement practices toolbox (Recommendation 3) called for in Fairchild and Rose[197] (Box 9.2).

Box 9.2: Best Practices for Inclusive Procurement

- Strengthen the community constituency for and advocacy efforts around MWDBEs;
- Increase the capacity of local and state elected officials and agency staff to implement legal (race-averse and race-conscious) and effective inclusive procurement policies;
- Develop inclusive procurement policy toolkits by sector;
- Proactively engage the private sector;
- Use triggers in tax credits and Community Reinvestment Act requirements to build regional capital pools that can provide lines of credit and bonding capacity to help grow participating MWDBEs; and
- Strengthen accountability mechanisms to ensure policy goals are met, including assigning 1% of project costs to support capacity building of MWDBEs.

Source: Fairchild and Rose[197]

Incentives

If the development of a Cal-MOP provides the technical guidance required to design and implement a climate-safe infrastructure project, and improved procurement approaches help with the legal and financial translation of such projects, incentives – financial or otherwise – provide the inducements to break from traditional and well-trodden paths and try the innovative approaches. Eventually, such incentives will help spread the new practices and foster the paradigm shift necessary to move infrastructure design into this new climate-changed era. As the State works to update its own codes and standards to incorporate forward-looking climate science, incentives can encourage design above minimum standards, providing a bridge between the infrastructure work that needs to happen today to deal with decades of deferred maintenance, with the engineering standard and code updates that will take some time to develop.

Financial incentives. Financial incentives are the most likely to gain immediate attention, and while State agencies do not have "extra" funds, there is considerable funding available already for infrastructure projects in the immediate and near future through bonds. Embedding climate change language in Request for Proposals (RFP) and establishing transparent proposal selection criteria that favor projects that are consistent with the Climate-Safe Path for All proposed here are ways to make use of available funds toward climate-safe infrastructure. State regulation and oversight of different infrastructure sectors and activities is already used to incentivize preferred actions by the entities overseen (e.g., incentives for energy efficiency measures, incentives for consideration of climate change in disaster preparedness plans). Similar mechanisms could be used to foster climate-safe

Non-financial incentives. There are non-financial incentives that should also be considered and may be more feasible more quickly. They would not require added expenditures from agency budgets and they all have to do with speed and time (which, in fact, translates into money).

- **Expedited permitting.** The most promising incentive identified by the CSIWG is the concept of expedited permitting for infrastructure projects that meet climate-safe infrastructure goals and are resilient. This can be achieved at the local and state level. It can also help to address permitting bottlenecks between State and federal agencies. For instance, if a State-funded project encroaches into federal jurisdiction, federal rules and regulations can impede project progress. Moreover, combining an expedited permitting process with the use of a rating system (e.g., LEED or Envision, see Chapter 7) can further incentivize and encourage climate-safe-designs and practices. There are, of course, limitations to rating systems. Notably, they are generally not mandatory and cannot be enforced and meeting rating systems require financial outlays, leading to further potential exacerbation of inequities. These challenges notwithstanding, rating systems and voluntary standards have been demonstrated to continuously raise the floor of mandatory building standards (see Chapter 7; see also Sullen 2018 webinar and Georgiakoulis 2018 webinar).
- **Pre-disaster planning and code changes.** The unprecedented natural disasters in 2017-18 created the need to rebuild damaged and impacted infrastructure throughout California – from removing mudflow debris from freeways, to rebuilding public structures burned down during the wildfires that ravaged the state. Fires in 2018 appear to continue this trend. Generally speaking, however, recovery

Figure 9.6 In a crisis, expedited permitting is crucial, but rebuilding with climate change in mind must become part and parcel of permitting and waiver guidance. (Photo: Bonds Flat Road near the Don Pedro Dam spillway, February 23, 2017; Dale Kolke, DWR, used with permission)

funding for public assets require building back to exact pre-disaster specifications unless prevailing codes allow for "building back better."[7] Thus, washed out culverts would need to be built to the old-size requirements; burnt buildings would be rebuilt without sprinkler systems; a wood utility pole gone up in flames would be replaced with another wood utility pole, rather than a steel pole that may be more resistant to future fire, unless codes had been established well before the disaster to require otherwise. Inquiries with State agency staff yielded no known examples, except possibly L.A.'s cool-roof ordinance. Systematic tracking of state and local adaptation actions such as climate-cognizant code changes would help the State know whether adaptation plans are being translated into binding code and thus whether infrastructure will be built back better after a disaster. This would have the added benefit of providing case studies and examples throughout the state for peer-to-peer exchange.[8] The significant resources available post-disaster cannot be used toward adaptation to climate change nor the transition toward climate-safe infrastructure without pre-disaster code changes and may in fact be squandered on projects that – based on the best available scientific understanding and even best available engineering knowledge – must be considered maladaptive.

The significant resources available post-disaster cannot be used toward adaptation to climate change nor the transition toward climate-safe infrastructure without pre-disaster code changes.

[7] With respect to public infrastructure specifically, FEMA's Public Assistance (PA) funding program provides federal assistance to government organizations (and certain private nonprofit (PNPs) organizations) following a Presidential disaster declaration. PA funds can be used for repair, replacement or restoration of disaster-damaged publicly-owned facilities including roads and bridges, water control facilities, buildings and equipment, utilities, parks, recreational and other infrastructure. FEMA covers no less than 75% of the costs and CalOES covers 75% of the remaining 25% non-federal share. FEMA provides PA funding to restore facilities on the basis of pre-disaster design and function and conformity with current applicable codes, specifications and standards.

[8] AB 2516 (Gordon, Sea-level rise planning database) established one way to track sea-level rise related adaptation measures. This approach might constitute a model for ongoing monitoring, but any statewide, cross-sector monitoring system should build on lessons learned from this pioneering effort. (For more information, see: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB2516 and the link to the database through the adaptation clearinghouse).

- **Clarification of policies on waivers.** In crisis situations such as after disasters or for projects under time pressure, infrastructure builders often seek waivers to allow for more rapid (re)building and recovery. This is understandable, as it is in everyone's interest to help communities get back on their feet quickly after major events. These waivers, however, may have negative consequences. These can range from impacts to the environment such as insufficient accounting of toxins inadvertently released in an attempt to quickly clean up debris, to impacts to people such as disregarding environmental justice concerns in an effort to get critical services back online. However, if managed and incentivized properly, waivers could be used to advance climate-safe principles. For instance, following an event:
    - infrastructure managers could receive waivers that expedite permitting if they meet the most climate-safe voluntary standards or rating systems;
    - they would not receive waivers if they do not use climate-safe infrastructure principles.

  Because waivers set precedent, granting them should be considered systematically prior to the urgent time when they are sought. For example, clarifying liability issues (see Chapter 7), developing waiver guidance to regulators (e.g., if x is replaced, replace it with a climate-safe asset, i.e., attach an infrastructure requirement to getting exemptions), developing statewide maps which rank the future likelihood of climate extremes under different emissions scenarios, particularly the high-emissions scenario, and not granting waivers in regions expected to experience such extremes frequently or making waivers contingent on good pre-disaster infrastructure management are just some of the ways in which granting waivers can be done in a
- **Improving the permitting process.** The State should examine common patterns as to where or when waivers and exemptions are sought. Many waiver requests are about speed. Such a systematic exploration may reveal patterns and identify priorities for where the permitting process can be streamlined, so that they are not needed or less frequently.
- **Pre-certification of contractors.** Pre-disaster, infrastructure managers should develop lists of pre-certified contractors (with an eye to inclusive practices) and put permitting structures in place to allow for the opportunity to "build back better." These certified contractors can also be used to update hazard mitigation plans. These pre-disaster plans (at the state and local level) should be developed in concert with CalOES to ensure that they would comply with State and federal funding requirement mandates.

Develop and Monitor Metrics for Success/ Performance

A repeated theme throughout the work of the CSIWG was the question of measuring success. What is the level of performance the State should aim for? What are meaningful metrics to investors that would attract them to invest in climate-safe infrastructure projects? How can State agencies show progress along the Climate-Safe Path for All, both for internal planning, budgeting, prioritization and design purposes, and for external communication to Californians, who are asked to pay for and bear the impact of infrastructure renewal.

As noted by one of the AB 2800 webinar series presenters: “Measurement is a fraction of the cost of restoration or mitigation and saves money over time by defining best practices for a changing world.” Metrics for success, and the monitoring protocols necessary for measuring these metrics, are critical at every stage of the infrastructure life cycle – from design, to planning, to construction, to maintenance and to decommissioning. Evaluation at every stage should be considered. While the issue of monitoring and evaluation (M&E) is widely discussed in the adaptation literature and is increasingly recognized in California (e.g., in discussions of the Technical Advisory Group of the ICARP), more attention – through applied research and changed practices – is required to advance the conversation.

The CSIWG thus believes that developing metrics for success and performance will play an important role in achieving many of the objectives and recommendations within this report and are thus a critical next step for the State to take. There are at least five fundamental reasons (based on[194]) why a concerted effort in establishing effective M&E mechanisms would aid the State in implementing the Climate-Safe Path for All. They include:

- **Enabling deliberate planning and decision-making.** Setting clear goals (e.g., performance standards or desirable outcomes related to the Climate-Safe Path for All) and aligning planning, design approaches and needs to those outcomes enables internal consistency. It also provides external consistency by providing transparency of goals, allowing other infrastructure or resource managers to better understand how their infrastructure fits in the larger system and ensures that State policy goals are not at odds.
- **Providing a mechanism for accountability and evidence of good governance.** When the CSIWG discussed what they found important in developing or participating in any State process that leads to climate-safe infrastructure, accountability and linkage to definable goals was identified as the most important. Recommendation 9 calls for the establishment of a standing CSIWG to provide coordination among the various components of State government that will need to work in concert to achieve climate-safe infrastructure. This group could play a central role in coordinating an agency-cross-cutting effort in developing metrics. While accountability would need to be anchored in rules, professional standards of care and liability policies, achievement of these metrics offer important opportunities for communication with the public and could serve as a clear mechanism for the State legislature to track progress toward State goals.

Developing metrics for success and performance will play an important role in achieving many of the objectives and recommendations within this report and are thus a critical next step for the State to take.

- **Supporting adaptive design, management and performance-based standards**. As described in the ASCE MOP[253] – and expected in a California-specific MOP – adaptive design requires identifying the triggers or thresholds at which the next set of adaptive measures gets implemented (see Chapter 4 and Figure 4.2). Both climate patterns and the infrastructure itself must therefore be monitored to determine when/if those triggers or thresholds are expected to being crossed to ensure readiness for the next phases of adaptive design implementation. Moreover, determining whether or not an asset meets the metrics pre-identified will support learning and adaptive management. Adaptive management assumes that learning is critical. With critical infrastructure there is little room for catastrophic mistakes, but combining multiple strategies (Chapter 4, Box 4.2) and implementing equitable safe-to-fail design options (Chapter 6) can help ensure that there is room for flexibility and deliberate learning, and that those lessons are taken seriously as adaptation progresses.

- **Justifying adaptation expenditures.** Whether true or not in the final accounting, there is a perception that climate-safe infrastructure will cost more – at least at the outset if adaptive design principles are implemented. Full life-cycle analysis as recommended in this report will help make the case, however, that building climate-safe infrastructure is not only economically smart but has many other benefits. This must be shown – with measurable metrics – to State policy-makers, to investors and to the public. Providing clear accounting of the different expenditures and how they are achieving the pre-defined metrics for success will be critical for effective demonstration of the success of innovative strategies that perhaps run counter to more traditional methods and cost-benefit accounting.
- **Supporting communication, public engagement and, ultimately, public support.** Public infrastructure is in place to serve the public good; moreover, it is publicly funded. Climate-safe infrastructure is there first and foremost to protect the people of California and support their well-being and lives. Accountability to this ultimate goal must be paramount. In a socially-inclusive process, in which infrastructure is developed with a common vision shared by diverse stakeholders, illustrating progress and success is critical to demonstrate that state infrastructure is both meeting the needs of constituents as well as a wise use of financial resources. Public support is arguably the most important tool in engineers and architects' toolbox. It is only with public support and demand that climate-safe infrastructure will be prioritized and will be able to receive the ongoing financial commitment required to safeguard climate-safe infrastructure into the future.

Develop Compendium of Best Practices

Finally, measuring progress and success will provide the evidence basis on which we can argue that certain practices are better or "best practices." We conclude this chapter with a call for developing such a compendium because of what is at stake for practicing engineers and architects.

Engineers and architects enjoy an immense level of public trust. We drive over the bridges they build, not even thinking about whether they will hold. We live and work in buildings trusting they will withstand the vagaries of nature. This trust can't be squandered as we move into a more volatile future.

Engineers and architects enjoy an immense level of public trust. This trust can't be squandered as we move into a more volatile future.

Like all individuals, engineers and architects rely on each other to do high-quality work, and in this rapidly changing climate, there is simply no way to replace the trust that comes from sharing experiences and learning from peers. As the field moves together to build more climate-safe infrastructure, having a compendium of best practices, vetted by practicing engineers, will provide an invaluable resource that practitioners can turn to for support, inspiration and on-the-ground guidance. The California Adaptation Clearinghouse (www.CAresilience.org) could be one important point of access to such a compendium as it already contains case studies and resources for other aspects of adaptation planning. This has the dual benefit of pulling engineers and architects into the budding adaptation community and for the thinking embedded in the best practices compendium to reach a broader audience. It also links directly to the Cal-Adapt platform available for sharing climate science. Rather than creating an entirely new compendium or clearinghouse that runs in parallel to these already existing State efforts, resources should be directed to incorporating climate-safe engineering practices for California at these central sites.

Recognizing that engineers may not yet be familiar with these sites, however, a multi-pronged outreach approach should be used to bring engineers to the compendium and the compendium to engineers. In other words, it is critical to link to wherever they already go for the information and best practices they need. State agencies should partner with professional societies, existing platforms (see Table 5.3 in Chapter 5) in promoting the available resources. They should also reference them as key resources to contractors and partner entities in RFPs and statements of work. Such compendiums should be – in the spirit of adaptive design – be living documents that are regularly updated. Projects employing them could become case studies from which others can learn and be included in the Adaptation Clearinghouse.

In this way, peer-to-peer learning from trusted sources, combined with a continually updated scientific data basis, performance-based standards, and evidence-based evaluation of what is working, will – in time – change the way we think, and what we do.

10 Summary: Barriers and Recommendations

To close this report, we return to the mandate of AB 2800, which asked to identify the informational, institutional and other barriers that stand in the way of integrating forward-looking climate science into all aspects of infrastructure planning and decision-making. We have discussed them throughout the preceding chapters and compiled them systematically in [Appendix 11](). We use the synthesis of this work below to set up a high-level summary of our recommendations, which address the challenges the CSIWG identified and answer the call of the enabling legislation.

Barriers: Informational, Institutional and Other Hurdles to Building Climate-Safe Infrastructure

AB 2800 stipulated, in Section 2 (c), that “[t]he Working Group shall consider and investigate, at a minimum, the following issues: (1) The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design.” The topic of barriers was considered throughout the Climate-Safe Infrastructure Working Group’s (CSIWG) deliberations and was also an integral part of the webinar series that supported the CSIWG’s work.

Here we summarize and discuss the barriers we have identified throughout this project. Appendix 11 lists the full list of barriers that were discovered, organized by the stages in the adaptation process[312] (which are similar to the stages in an infrastructure lifecycle) and by type of barrier (for example, informational, institutional, financial and so on).

We discuss these barriers at a higher level of synthesis by type, but caution against seeing barriers in an isolated manner. For example, informational barriers such as not having a particular type of data can be reinforced by financial barriers such as lack of investment in relevant research; similarly, institutional barriers such as being tied to or lacking a particular standard or process can be reinforced by lack of capacity/skill or by particular attitudes around thinking about the future or inclusionary, meaningful stakeholder engagement. In other words, barriers are interrelated to create persistent obstacles that stymie progress on integrating forward-looking science into infrastructure planning and design.

Barriers of all types are observed across the entire life cycle of infrastructure design and operation and across every stage of the adaptation process.

Importantly, barriers of all types are observed across the entire life cycle of infrastructure design and operation and across every stage of the adaptation process. While they are fairly evenly distributed across types, overall most barriers are encountered in the Planning and in the (prior) Understanding phases of the adaptation process, with fewer currently noted in the Implementation phase. This is not so much a reflection of the severity of these barriers, but of the greater familiarity with barriers in those early stages of adaptation as most climate preparedness efforts across the state and elsewhere in the U.S. are still in the early stages[279,313]. As earlier barriers are successfully overcome, other (not-yet-recognized) barriers may emerge as adaptation progresses to implementation.

Synthesis of Barriers

We describe each type of barrier, including subcategories, prevalence and their overall significance. Appendix 11 and the discussion on sector-specific issues throughout this report provide additional detail (Figure 10.1).

Informational and knowledge barriers. Informational and knowledge barriers are significant, particularly as they are tied to the institutional ones, namely to design standards. Traditionally, engineers and architects have relied on design standards that are based on decades of empirical data of environmental conditions which were statistically constant, both regionally and seasonally. Using those standards (and data), engineers and architects designed civil infrastructure with confidence, believing that the public is protected. Because of climate change, environmental conditions now deviate significantly from the previous statistical norms and those conditions continue to change in ways that are not predictable for specific places with high confidence. As a result, the standards still used are no longer reliable. Shifting toward performance standards and the use of risk management approaches and decision-making frameworks for deep uncertainty still requires the best available science, however. The CSIWG identified a large number of specific information needs, which fell into six categories. The specific information needs and knowledge barriers (detailed in Appendix 5) vary by sector and require different interventions to overcome them.

- Lack of knowledge and understanding in certain areas, requiring more research (e.g., in methods, adaptive design, trade-offs, value/benefits of resilient design) or cross-disciplinary education on existing knowledge;
- Lack of investment in certain types of research, monitoring and evaluation (M&E) (e.g., no benchmarks, no M&E, hence no understanding of performance; lack of metrics);
- Existing knowledge and approaches are contested, i.e., experts do not agree on what is most credible or reliable; as a result, practitioners avoid new/contested approaches or rely on outdated information and methods (e.g., traditional cost-benefit analysis);
- Lack of information in usable/actionable/standardized formats (including incomplete or missing information, inconsistent information (e.g., flood risk information from FEMA vs. other sources) or information is not available at the right temporal/spatial scale (e.g., precipitation data);
- Lack of (easy) access to information either because the data is proprietary, developed by individual researchers or not in a centralized repository; and
- Lack of guidance on, and familiarity with, how to use data/information/tools/methods appropriately (e.g., lack of guidance on decision-making under uncertainty).

Figure 10.1: A wide variety of barriers make the use of forward-looking climate and other science challenging in infrastructure design. (Photo: Dismantling of a drought barrier along the West False River which served to block salt water from pushing into the central Sacramento-San Joaquin Delta from San Francisco Bay; Florence Low, DWR, used with permission).

Capacity/skill barriers. Capacity barriers can be understood in the sense of adequate numbers of staff and adequately trained and skilled employees to do the necessary work of planning for, building and operating climate-safe infrastructure. This category was among those with the greatest number of individual barriers mentioned. Together, the barriers in this category paint a consistent picture of inadequate training and skill-building to date to enable both the scientific and engineering workforce to take on the challenge of building climate-safe infrastructure for all.

- Inadequate/narrow/siloed disciplinary or sectoral perspectives on what are, in fact, systemic, interconnected challenges;
- Widespread lack of engagement of scientists, engineers and architects on climate change issues;
- Lack of sufficient knowledge about climate change, climate models and lack of expertise in or guidance on how to appropriately use climate data;
- Lack of training in and guidance on assessing and interpreting uncertainty and making decisions under uncertainty;
- Lack of awareness of or education about resilient, adaptive and sustainable designs (including green/nature-based infrastructure options);
- Lack of skills and staff capacity in tracking performance, assessing non-monetary benefits;
- Insufficient capability of translating policy and guidance into standards and codes;
- Lack of training in and guidance on effective stakeholder engagement and other professional skills;
- Lack of awareness, familiarity and skill in considering social equity issues in infrastructure planning and decision-making from the start (Figure 10.1).

The barriers paint a consistent picture of inadequate training and skill-building to enable both the scientific and engineering workforce to take on the challenge of building climate-safe infrastructure for all.

Attitudinal barriers. Attitudinal barriers were among the most frequently mentioned barriers overall, but they are difficult to synthesize (e.g., whose attitudes? attitudes about what?). Some pointed to attitudinal challenges among engineers and architects, such as:

- Abiding skepticism of global climate models and sometimes even the reality of climate change;
- Lack of acceptance of citizen science as valuable input to monitoring performance;
- Neglect of social equity as a central concern, integrated from the start of infrastructure planning;
- Perceived incompatibility of green/nature-based infrastructure with prevailing professional norms (Figure 10.2);
- Strict adherence to established professional norms resulting in resistance to innovation and experimentation; and
- Premature narrowing of the range of options considered due to assumptions about their public acceptance.

But engineers' and architects' attitudes were not the only barriers identified in this category. Decision-makers' and stakeholders' attitudes were also discussed:

- Lack of leadership, a pervasive lack of urgency about climate change and lack of commitment to invest in infrastructure;
- Culturally prevalent attitudes that do not favor long-term thinking;
- Lack of willingness to pay for resilience (resulting from the above-mentioned attitudes);
- Lack of trust among stakeholders partly due to divergent values and priorities, partly due to past experience; and
- Varying levels of risk aversion/risk tolerance.

Finally, scientists often are less interested in applied problem solving and there are disciplinary prejudices that can prevent active and frequent multi- and transdisciplinary interaction and collaboration.

Political barriers. While fewer in numbers, political barriers were often seen as being of ultimate importance for progress to be made toward climate-safe infrastructure. Some of those barriers do not originate from within California but reflected the current lack of leadership at the federal level. Others referred to politics with a "small p" – the politics in the room or at the local/state level.

- Lack of federal political leadership on climate change in general, resulting in de-prioritization at best and unhelpful controversy at worst, as well as inadequate progress on federal infrastructure investment;
- Against a background of politicized debate and near-term priorities absorbing limited funds, lack of political will to prioritize climate change and commit to climate preparedness and adaptation;
- Lack of support for novel infrastructure designs (e.g., green/nature-based infrastructure);
- Lack of political will to address past legacies of institutional racism, neglect of certain communities and to redress those infrastructure inequities now;
- Inability to generate public support for infrastructure investment, including lack of skill and willingness to effectively communicate costs and benefits; and
- Lack of commitment to aspects of infrastructure operation and maintenance (e.g., monitoring) if they don't generate political benefits.

Figure 10.2: Attitudinal barriers – such as the perceived incompatibility of green or nature-based infrastructure with prevailing professional norms in engineering – can pose significant hurdles to moving toward climate-safe infrastructure designs. (Photo: Tree-planting in urban area; USDA)

Financial barriers. Another category of barriers that weighed heavily not by the number of unique barriers identified but by the overriding importance to actually getting infrastructure built. Many of the types of funding challenges are not unique to infrastructure[279] but are often magnified due to the large price tag on infrastructure. Financial barriers are the substance of a nationwide debate over the past several years, and the need for infrastructure investment was a leading priority in California's June 2018 primary election cycle. But, again, the more specific categories of barriers identified point to different foci and intervention points.

- Lack of funding for every stage in the infrastructure lifecycle, including inadequate resources for infrastructure-related research, lack of funding for strategic planning; lack of funding for infrastructure in general and for green/nature-based infrastructure in particular; difficulty of keeping infrastructure in state of good repair (high maintenance costs); and lack of funding for monitoring systems and for long-term, ongoing data collection;
- Higher upfront cost, particularly of climate-resilient infrastructure;
- Long-term funding uncertainty;
- Limited funding options available or considered;
- Lack of coordination among funding agencies; inability to coordinate or combine funding sources and types due to disconnected timing or other factors; and lack of funding for coordination;
- Unfunded mandates;
- Lack of monetary incentives to plan for climate change;
- Restrictions on use of funds (e.g., disaster recovery funding) or constraining eligibility criteria;
- High discount rates that devalue the future; and
- Difficulties related to valuing risks and benefits and thus with making the economic case for infrastructure investment.

Financial barriers weigh heavily due to their over-riding importance to actually getting climate-safe infrastructure built.

Legal/regulatory barriers. We distinguish legal and regulatory barriers from other institutional barriers (discussed next) due to the weight that regulatory issues have in how and where infrastructure is built. As with the political barriers, legal and regulatory issues did not only arise from within State jurisdictions, but sometimes were related to different regulatory requirements at different levels of governance. In general, however, the large number of barriers in this group arose predominantly from the lack of relevant and needed or useful regulation and – in a smaller number of cases - from the existence of a law or regulation that constrained consideration of climate change and alternative designs.

- Lack of policy guidance on what to plan for and difficulty of translating existing (high-level) guidance into action;
- Lack of rules and regulations that would foster/require consideration of climate change (e.g., no requirement to assess exposure to climate change; no requirement to use certain data, no requirement to do a full life cycle assessment);
- Lack of design criteria, standards, performance goals/targets and guidelines for inclusion of climate change in infrastructure design, implementation, monitoring and evaluation;
- Lack of clarity on liability (via a standard of care) with regard to considering climate change in infrastructure design;
- Lack of professional standards related to climate change;
- Lack of regulatory incentives (e.g., accelerated permitting);
- Rating systems are not adopted as code leaving them without regulatory power;
- Lack of code enforcement, including exemptions after disaster or in other special circumstances, and lack of accountability for inadequate designs or maintenance;
- Existing laws, regulations and standards/codes that could be or have already been experienced as limiting the consideration of climate change, even if infrastructure owners have been willing to do so (e.g., Americans with Disabilities Act (ADA) access requirements; regulations pertaining to the preservation of historical buildings and cultural resources; codes that prevent rebuilding after disaster taking climate change into account);
- Unclear jurisdiction where infrastructure crosses jurisdictional lines (including the possibility that different jurisdictions have different priorities, capacities and needs); and
- Different or even contradictory standards and risk assessment approaches (e.g., FEMA's recognition of certified levees only; the National Flood Insurance Program's (NFIP) exemption of historical buildings from flood protection requirements even in high-hazard zones).

Figure 10.3: Institutional barriers, such as differences in planning horizons, lack of long-term planning and lengthy permitting processes can delay the transition to climate-safe infrastructure being built. (Photo: Port of Oakland waterfront; 1FlatWorld, flickr, licensed under Creative Commons license 2.0)

Institutional barriers. Institutional barriers identified by the CSIWG frequently affected or interacted with other barriers, but most commonly these types of barriers related to siloed governance of infrastructure, even though there are many cross-sectoral, cross-lifeline, cross-jurisdictional interdependencies (Figure 10.3). These barriers result in delays, miscommunication, lack of coordination, inefficiencies, missed opportunities and disjointed planning. Common subcategories included the following:

- Differences in planning time horizons across levels of government or types of infrastructure;
- General lack of longer-term planning;
- Lengthy time from initiation to complete implementation of infrastructure projects (up to 20 years), (e.g., due to lengthy reviews and permitting);
- Lack of cross-sectoral and cross-jurisdictional communication, coordination and partnerships (e.g., due to siloed management, zoning inflexibility, lack of awareness of other sectors' concerns and resources; lack of a State "infrastructure czar" overseeing integration of systems; loss of coordination through and power of Community Redevelopment Authorities);
- Lack of processes for comprehensive valuation, evaluation, assessing the quality of risk assessment, risk management or evaluation approaches;
- Competing rating systems (mandatory, voluntary) and competing standards (backward-looking/static standards, forward-looking standards); and
- Externalization of certain consequences from systemic assessment;

Other barriers. The final (smaller) category of barriers contains a variety of barriers that did not fit the other seven categories but were mentioned as having played or as potentially playing a significant role. For example:

- Repeated extreme events and disasters across California in recent years, particularly in 2017 and 2018 (extended drought, multiple record-breaking wildfires, landslides and flooding) are now garnering significant media, public and political attention. Prior to these events, California lacked the catastrophic weather-related events of the magnitude of Hurricanes Katrina (2005), Sandy (2012) or Maria (2017). Without swift yet thoughtful policy initiatives that use such windows of public and policy-makers' attention, the State will miss the opportunity to advance policies to move toward greater climate-safety;
- Physical limitations related to existing infrastructure, i.e., the greater difficulty of integrating climate change considerations in retrofits than in new infrastructure;
- Industry lag time in adopting new practices in design and construction; and
- A general lack of demonstration projects, including monitoring of their effectiveness.

Summary of Recommendations

From Vision to Implementation

In this report, we have charted a path – the Climate-Safe Path for All – that starts out from the challenges and pre-existing conditions to a vision of climate-safe infrastructure via a framework to action. We have described our current infrastructure and the challenges faced from climate change today and in the future We have discussed the best-available climate science, highlighting where our existing science can be bolstered to best suit the needs of state architects and engineers. We have outlined the current paradigm for planning, designing and building infrastructure and have demonstrated how that old path is not robust enough for a future under changing climate conditions. Through the development of the Climate-Safe Path for All, we have provided a vision for how state engineers and architects can take the knowledge that exists today and use it to build the climate-safe infrastructure of tomorrow – infrastructure that is accessible and available to everyone. We have identified the institutional and information gaps and barriers, and we have developed a suite of recommendations to address each (Table 10.1).

Below, we pull together the 10 major recommendations, which, when taken in concert, provide a clear pathway from vision to implementation. They answer the mandate of AB 2800 and more, and we view them as essential to realizing the vision. We also highlight the initial first steps the State can take to start its journey along the Climate-Safe Path for All.

Recommendation 1

The State Legislature should establish as official State policy "The Climate-Safe Path for All", which is a flexible adaptation pathway realized through a variety of strategies, in multiple stages over the course of decades. The Climate-Safe Path for All accounts for the full life-cycle costs of infrastructure and uses a multi-sectoral, systems approach. It prioritizes infrastructure investments based upon the greatest risks and investment gaps, as well as where investment can most reduce inequality and increase opportunity. For highly vulnerable, long-lived infrastructure, State agencies should consider climate change im-pacts associated with a high-emissions scenario while continuing to implement all applicable State laws related to stringent greenhouse gas emissions reductions.

Adopt the Vision

As with the State's bold greenhouse gas emissions reductions goals, the Climate-Safe Path sets out an equally bold path to plan, design and build new and retrofit existing infrastructure to be safe for all. With the Climate-Safe Path, the State recognizes that to do this, future infrastructure projects must assume a high-emissions scenario future (currently RCP8.5), where infrastructure will be exposed to severe levels of climate impacts. Initial first steps include:

- All state infrastructure agencies should establish as a matter of agency-wide policy an adaptation and resilience requirement, namely that all investments in new and existing State-owned, -funded and -regulated infrastructure employ the five sets of strategies of robustness, resiliency, redundancy, adaptability and avoidance/retreat/removal to work toward increasing climate-safety.
- State agencies should furthermore establish formal and readily implementable guidelines at the agency/programmatic level and at the project level as to what it means to "incorporate climate change" into infrastructure planning, design, construction, operation and maintenance.
- Development of guidance will often require workload and expertise beyond what is available in current budgets. To achieve this recommendation, agencies should have adequate funding and efficient ways to leverage similar activities from other agencies and solicit outside scientific and technical expertise.
- State legislation, propositions and State agency policy directives related to infrastructure should direct infrastructure investment where it is needed most as determined by a rating of climate risks, the infrastructure investment gap and the potential to reduce social inequities.

Take a Systems Approach

Following the "It Takes a System" approach, the remaining recommendations discuss how best to advance the state's collection of existing and needed data and analytics (Recommendations 2 and 3), their imminent projects and project pipeline (Recommendation 4 and 5), existing and needed governance structures and mechanisms (Recommendation 6), financing tools (Recommendation 7) and implementation aides (Recommendations 8, 9 and 10) necessary for building climate-safe infrastructure for all.

Recommendation 2

In the past, the State's financial support for its various climate science efforts and decision-support tools has been uneven and insufficient. At a minimum, the State Legislature should provide a permanent source of funding for the State's mandated Climate Change Assessment process, the State's ongoing Climate Change Research Program, and decision-support tools and other assistance that disseminate their findings, so as to meet the needs for improved understanding and forward-looking science information.

Through the pioneering work of several State agencies such as the California Energy Commission (CEC) and the Department of Water Resources (DWR), the State already has an impressive compendium of publicly-funded, state-of-the-art climate science that can be used to support state engineering and architectural projects. The CSIWG identified these valuable resources and identified critical gaps in the available information. Once a sustained source of funding is developed, an important next step is to convene a follow-up panel or process to prioritize information gaps identified by the CSIWG into high, medium and low priority. Some of the highlighted research and science needs identified by the current CSIWG include:

- Produce statewide IDF curves with associated uncertainty for future climate conditions;
- Continue to invest in high-resolution climate modeling to better define spatial and temporal structure of extreme events;
- Prioritize funding for inclusion of traditional knowledges and paleoclimatology;
- Building on the State's previous investment in USGS's CoSMoS model[1] for sea-level rise and storm surge, determine where exactly in the state even more fine-scaled hydrodynamic modeling is needed and focus additional resources there;
- Invest in research that merges case studies, ensemble modeling and forecast experiments to investigate the likelihood, mechanisms, joint probabilities and predictability of climatic extremes that pose significant threats to California's infrastructure;
- Develop fine-spatial scale historical demographic information as well as information on infrastructure use and foster a detailed understanding of the factors that drive those use patterns so as to inform projections of future changes in these trends; and
- Produce projections of changes in technology and infrastructure use.

A monitoring program is an essential companion to future research in support of climate-safe infrastructure.

With the help of the Strategic Growth Council (SGC), the California Natural Resources Agency (CNRA) and the CEC, future renditions of the Strategic Climate Change Research Plan should incorporate the identified research priorities, including the most appropriate agencies and outside partners capable of addressing them. Moreover, DWR, working with other State agencies as well as a diverse group of stakeholders, has recommended formally establishing and funding a California Climate Science and Monitoring Program. Monitoring of how both the climate and existing infrastructure is responding to the climate is critical for ensuring adaptive approaches to maintaining safe infrastructure; a monitoring program is thus an essential companion to any future research. Finally, the State should provide modest and stable additional funding to expand the State Climatologist Office to enable the State Climatologist to engage the climate science community and in turn advise State government on climate change issues.

[1] For more information, see: https://walrus.wr.usgs.gov/coastal_processes/cosmos/

Recommendation 3

Because of the diversity of State agencies, types of infrastructure and their vulnerabilities, and the specific needs for climate science, there cannot be a one-size-fits-all recipe for State agencies to engage with the climate change science community. That said, the State budget should provide full funding to State infrastructure agencies so they can dedicate time and support to their engineers and architects to substantively and collaboratively interact with climate scientists and other relevant experts in the creation of useful advice, guidance and tools on a regular and ongoing basis, in a way and at a level appropriate to their needs.

Whether it is through a national scale connection to the Sustained Climate Assessment, or through augmentation of the state's Adaptation Clearinghouse (Figure 10.4), including its Technical Advisory Group, or the better use of gatherings such as the California Adaptation Forum (CAF), formalized processes should be developed in which state engineers and architects have deliberate and sustained interaction with physical and social climate change scientists from diverse research institutions, as well as professional organizations and other experts and stakeholders. Some of the immediate first steps discussed earlier include:

- Expand timely options for state engineers and architects to travel outside of California to participate in professional conferences in order to continue learning about and gaining comfort with climate science, as well as continuing to build their network of peers and colleagues;
- Through a user-needs driven and broadly inclusive process, Cal-Adapt should be bolstered and updated to incorporate California-specific, engineering-scale information to have an authoritative site of publicly available information. Concurrently, a concerted outreach effort is needed to raise awareness of this information among state engineers and architects; and
- Equally important to the quality of the data provided via Cal-Adapt, once the tool is established, tool developers (within academia, consultancies, or State agencies) should provide training to end users to help them become familiar with and supportive of innovation and best practices related to sustainability and resilience, including support for collaborative processes.

Formal processes should be developed in which state engineers and architects have deliberate and sustained interaction with physical and social climate change scientists, professional societies and stakeholders.

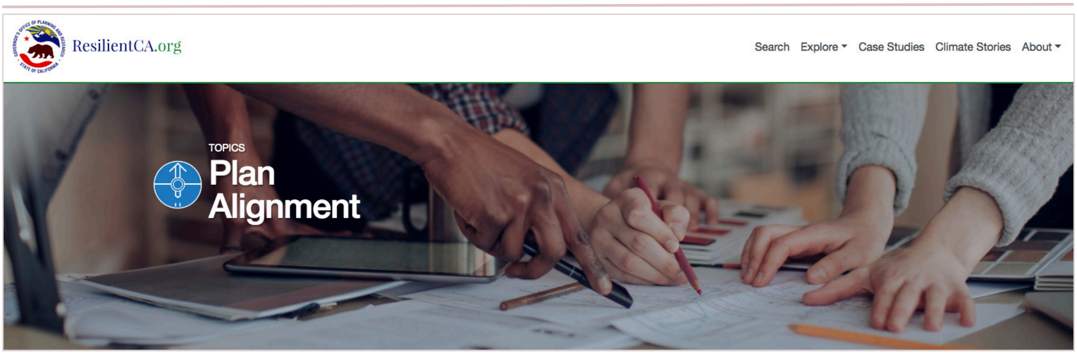


Figure 10.4: The state's recently launched Adaptation Clearinghouse could become an important resource for centralized delivery of scientific information needed by engineers and architects, but concerted outreach to practicing engineers is needed to raise awareness of this treasure trove of resources. (Photo: Screenshot of CA.resilience.org)

Recommendation 4

During the all-important pre-development phase, projects are conceptualized, planned and designed. The State budget should improve this process by building staff capacity and greatly increasing project funding to better account for a changing and uncertain climate, by addressing social inequity, and by assessing and accounting for the true costs and benefits of integrated projects across their full life-cycle.

During pre-development, infrastructure projects go from being just an idea to being plans and designs ready to be built. Pre-development determines the goals of the project, assesses their economic and technical feasibility, explores and decides among different design options, and involves all necessary components of project planning to make projects investor-ready. The most effective pre-development is more than a technical planning and design exercise (Figure 10.5). In keeping with the CSIWG's definition of climate-safe infrastructure, it should consider the broader concepts of statewide, sectoral or cross-sectoral and systems-oriented infrastructure investment. Examples of this type of work is being piloted in the San Francisco Bay Area Resilient by Design competition.

The most effective pre-development considers systems-oriented infrastructure investment

Figure 10.5: Training of engineers, architects and infrastructure planners is needed in the principles and approaches of effective pre-development of climate-safe infrastructure. (Photo: Training of scientists and practitioners; Susanne Moser, used with permission)

There are critical elements of successful pre-development planning and a range of tools to assist it. These include:

- Effective and inclusive stakeholder engagement from the start (see also Recommendation 5 below);
- Developing a climate-screening process to help identify the level of analysis needed and - together with stakeholders - to prioritize which projects to include in the "project pipeline";
- Comprehensively calculating the cost effectiveness of climate-safe infrastructure;
- As appropriate and where information is available, employing a probabilistic risk management approach, using techniques such as robust decision making, scenario planning, adaptation (or adaptive) pathways and flexible engineering design analysis;
- Effective communication to link the small initial steps and successes with the goals of the larger adaptation pathway; and
- Training on the above principles and approaches to ensure that practitioners are employing these strategies appropriately.

Recommendation 5

Difficult decisions will have to be made and the impacts of potential policies or decisions on different stakeholder groups are complex and challenging to assess. It is critical therefore to engage all affected stakeholders in a meaningful way, from early on and throughout any decision-making process, using the seven principles of equitable planning and decision-making.1 The Strategic Growth Council is well positioned to take a range of steps to encourage, improve and provide guidance on effective stakeholder engagement in the context of infrastructure development.

Stakeholder engagement is essential at every step of the process of crafting climate-safe infrastructure, from initial stages of discussion, to implementation, to maintenance and decommissioning. An important check against decision-making at any stage should always consider whether decisions are being made *with* communities, rather than *for* communities. Intentional stakeholder engagement is instrumental for developing a just, fair and socially inclusive process that gives voice to all members of society (Figure 10.6). To operationalize this recommendation, State agencies, policy-makers and project owners should:

- Create opportunities for timely and meaningful engagement by a wide range of stakeholders to help develop and evaluate potential policies and programs;
- Develop guidelines (or even requirements) for effective stakeholder engagement in infrastructure projects;
- Encourage agency staff to attend relevant conferences and meetings to make their constituents aware of proposed guidelines and to solicit comments;
- Hold trainings for stakeholder engagement facilitators; and
- Track progress on social equity.

Intentional stakeholder engagement is instrumental for developing a just, fair and socially inclusive process that gives voice to all members of society.

Figure 10.6: Many infrastructure decisions involve difficult trade-offs and engineers and architects need to have the skills to effectively convene, facilitate and navigate stakeholder conversations. (Photo: Carlsbad, California, desalination plant; vanderhe1, flickr, licensed under Creative Commons license 2.0)

Recommendation 6

Consistent with Executive Order B-30-15 and AB 1482, State agencies should update all relevant (i.e., climate-sensitive) infrastructure standards and guidelines that they can directly affect. Alternatively, or in addition, they should develop new state-specific guidelines where there are gaps to address climate resiliency by incorporating forward-looking climate information in those standards and codes. Where State agencies rely on standards developed by standard-setting organizations, state engineers and architects should work through the relevant professional organizations to advance development of climate-cognizant standards. Until new standards and codes are in place, State agencies should develop guidelines that go above and beyond minimum standards and codes to meet the goals of the Climate-Safe Path for All. Where agencies don't have resources to fulfill this workload, they should be fully funded in the State budget.

In the course of its deliberations, the CSIWG identified many institutional barriers to integrating forward-looking climate science into existing standards, codes and guidelines. State agencies differ in their technical capacity to make needed updates to existing standards and codes (and/or developing new ones where needed) vs. those who must await standard-setting organizations to provide those updated standards, which the State would then adopt. While policy guidance should be unambiguous, the way to implement it at the level of standards and codes will need to be flexible to reflect this range of in-house capacities.

Thus, Recommendation 6 encourages State agencies, when possible, to update their respective standards and codes to address climate resilience; when not possible, they should provide subject matter expertise to standard-setting bodies to ensure that climate resiliency is addressed in updates or new codes. Moreover, as new codes are being developed, or old ones are being updated, State agencies should use voluntary standards that are relevant to their respective infrastructure and that go above and beyond minimum standards and ensure climate resilience.

Among the most important barriers are questions around liability, which constitute a large and complicated enough challenge that a separate panel should be convened to address all the nuances and complexities and to provide guidance and recommendations to infrastructure agencies.

New types of standards and procedural mechanisms provide opportunities for increased climate resiliency. These include:

- Performance-based standards;
- Standards for professional practice;
- Standards of care;
- Different procurement approaches for various types of climate-safe infrastructure projects; and
- ASCE's Manual of Practice (MOP) that recommends an adaptive design approach.

Building on the ASCE's forthcoming MOP, the CSIWG proposes the development of a California-specific MOP that: addresses all critical infrastructure in the state; references the climate science information that is most relevant to California and produced in and for the state; and adequately supports the work of this Working Group with in-house staff and external experts and commensurate funding.

Finally, State agencies require supporting information, tools and innovative design approaches to implement climate-safe infrastructure (Figure 10.7). The CSIWG sees an important opportunity for the State to improve the benefit-cost assessment (BCA) approaches it uses. Instead of conventional BCA, the State should use more sophisticated methods that account for:

- The full infrastructure life-cycle, not just initial capital outlays;
- The cost of inaction;
- The deep uncertainty in both climatic and non-climatic aspects of the future;
- Adaptation pathways and the adaptive implementation of design choices;
- Benefits and costs to systems, not just projects; and
- The social costs and benefits to ensure that equity is explicitly accounted for.

In addition, the State should support applied research and testing of adaptive design for different types of critical infrastructure as well as developing rigorous economic methodologies for determining the true cost and benefits of implementing adaptive design; and design policies that allow and encourage infrastructure which is either sufficiently "modular" or built with sufficient "safety buffer" to accommodate changing climate change risks over time.

Figure 10.7: Different agencies require different types of information to support climate-safe infrastructure during planning, operation and maintenance. Close interaction between scientists, engineers and architects helps to identify those context-specific information needs. (Photo: Folsom hydropower dam; DWR, used with permission)

Recommendation 7

Because improving resilience is not a zero-sum activity, adding resilience in one area cannot be balanced by relaxing resilience requirements somewhere else. Adding requirements for resilience will come at a cost, so unfunded mandates are not feasible. The true costs over the full life-cycle of infrastructure projects should be assessed broadly, and the State should make efforts to help policy-makers and the public better understand the necessity of bearing these costs. Educational, promotional and other outreach should be conducted to generate support for the expenditures.

A follow-on activity to the work of the Working Group should explore the complex questions that arise about how to take climate change into account from a fiscal perspective. Moreover, the State has no comprehensive or reliable estimates of what climate change impacts and adaptation would cost at the State or local level. A range of factors make such estimates difficult to determine, but significant opportunities for filling knowledge gaps and improving on existing partial assessments is possible. The CSIWG identified a number of practical steps forward to implement the overarching recommendation on developing the funding and public support for investment in a climate-safe future:

- The State should include economic analyses of the costs and benefits of climate-safe infrastructure as an explicit focus in the next update of the Strategic Climate Change Research Plan to develop better estimates of the fiscal challenges and opportunities;
- With available and improved methodologies in hand, State agencies should carefully evaluate expected costs and benefits of current and proposed policy approaches to infrastructure planning and design, including via interdependencies with other agencies and policies, and to publicly disclose those costs, benefits and interdependencies;
- The State should find ways to compile and critically assess economic valuation methodologies, particularly of difficult-to-assess costs and benefits, that are available in the literature and update outdated State economic valuation practices, so that the environmental and social benefits can be more effectively integrated into feasibility studies;
- Agencies should build greater in-house technical know-how on innovative financing mechanisms;
- Working closely with financial advisers from the private and public sectors, including philanthropy, the State should explore and implement innovative funding mechanisms; and
- The Technical Advisory Council (TAC) of the State's Integrated Climate Adaptation and Resiliency Program's (ICARP) has begun investigating indicators and metrics of adaptation success. The TAC or a subset of the TAC, in cooperation with relevant State agency staff, external researchers, stakeholders representing social equity interests and financial experts should develop a suite of metrics that are meaningful to all parties – funding seekers and funding providers.

Equally important is for the Strategic Growth Council and other State agencies to launch serious outreach efforts to help Californians more fully understand why investment in climate-safe infrastructure is necessary.

Equally important to the above is for the Strategic Growth Council and other State agencies to launch serious outreach efforts to help Californians more fully understand why investment in climate-safe infrastructure is necessary, why the Climate-Safe Path for All is the safest and – in light of observed climate trends and already-experienced catastrophic impacts – likely a highly cost-effective way forward, and to make the case for continued financial reforms that remove some of the structural obstacles to a more reliable and affordable approach to infrastructure financing.

Recommendation 8

The Strategic Growth Council should coordinate with the Government Operations Agency, the Labor and Workforce Development Agency, and other relevant agencies to develop a work plan on how to address the training and professional development gaps of its infrastructure-related workforce as identified in this report, and begin to implement that work plan as soon as feasible. Because the Strategic Growth Council does not currently have the staff capacity and funding to implement this task, it would require adequate funding to do so.

Over the course of the CSIWG's work, a recurring theme was the need to have the skilled workforce to get climate-safe infrastructure appropriately designed, built, operated and maintained (Figure 10.8). The CSIWG identified a subset of actions that can be taken immediately to help advance this recommendation:

- Engage with professional societies, state-based engineering schools and universities, the American Society of Adaptation Professionals, private sector engineering and architecture firms and others deemed relevant in the development of the recommended workplan;
- Incentivize a rapid and substantial expansion of end-to-end, multidisciplinary climate change research, education and application programs;
- Set expectations through professional standards, qualification and continuing education requirements of state engineers and architects and those receiving State funding; and
- Expand and institutionalize the State's internal decision support capabilities, including a professional development pipeline of well-trained professionals by requiring staff to engage in ongoing professional development in the areas found to be most in need of advancement.

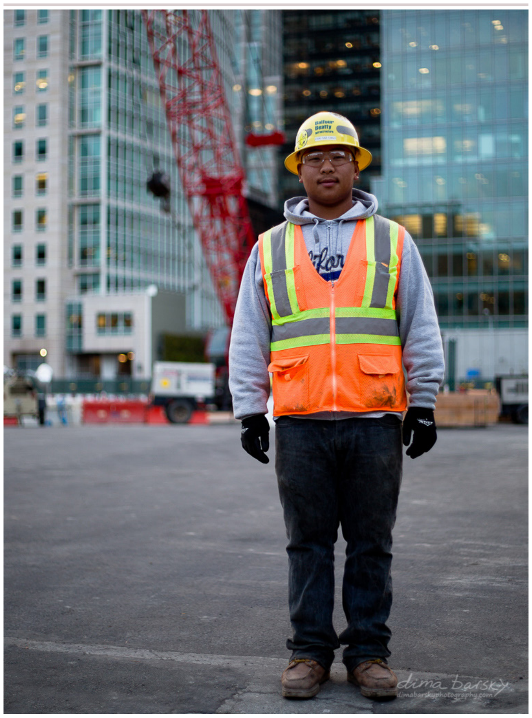


Figure 10.8: A recurring theme during the deliberations of the Climate-Safe Infrastructure Working Group was the need for a skilled workforce to appropriately use, interpret and act on scientific information. (Photo: Construction worker; Dima Barsky, flickr, licensed under Creative Commons License 2.0)

California is not alone with this struggle, thus the recommendations in this report for how to implement sustained and effective training and professional development can have implications beyond just the State of California.

The State should set expectations of a quality workforce through professional standards, qualifications and continuing education requirements of state engineers and architects and those receiving State funding.

Recommendation 9

The State should establish a Standing CSIWG to devise and implement a process for coordinating and prioritizing Climate-Safe Path related resilience policies and actions at the highest level. This panel would provide a needed forum for agencies to coordinate their policies, take advantage of synergies, address potential conflicts and learn from one another. As AB 2800 is slated to sunset in 2020, the work of a standing CSIWG would require an extension of AB 2800 and adequate financial support to conduct its business.

The CSIWG proposes the development of a standing CSIWG, which would have the following roles:

- Coordination;
- Central point of contact for infrastructure across the state;
- Forum to advance climate-safe infrastructure questions; and
- Leadership in incorporating forward-looking information in engineering standards.

The standing CSIWG panel would improve cross-sector coordination and integration by:

- Identifying ways to minimize obstacles to collaboration;
- Experimenting with new forms of coordination (e.g., coordinated integrative budgeting for projects);
- Fostering standing cross-agency working groups for infrastructure (such as for the development of the California-specific Manual of Practice (MOP), to explore legal issues around liability, or to prioritize infrastructure-related research needs;
- Ensuring wider and more effective stakeholder participation; and
- Fostering regular communication across silos.

Figure 10.9: A standing Climate-Safe Infrastructure Working Group would coordinate the State's infrastructure-related activities, serve as a central point of contact and as a forum to advance climate-safe infrastructure questions, and provide critical leadership to ensure forward-looking science is incorporated into infrastructure planning, design and construction. (Photo: Bridge work at night; Caltrans, flickr, licensed under Creative Commons license 2.0)

Recommendation 10

The State budget should provide full funding to State agencies to make deliberate efforts in reducing or eliminating the barriers that hinder or slow down adoption of State-level climate-safe infrastructure policy into practice. Key focus areas include the translation of Climate-Safe Path policy into practice manuals and contracting language, providing incentives to account for climate change in infrastructure projects, identifying metrics of success for monitoring and evaluation and developing a best-practices compendium.

Ultimately, for all of these recommendations to be used by on-the-ground contractors – those who implement the plans developed by state architects and engineers – they must be translated and made accessible to all working on infrastructure. The California-specific MOP provides one mechanism for this by providing step-by-step guidance for how to incorporate some of the more novel and non-traditional approaches to engineering described in Chapter 6.

The CSIWG recommends several important additional steps to help with the translation of State-level policy into climate-safe infrastructure project implementation on the ground:

- Once procurement approaches have been thoroughly assessed by a future working group for their advantages and disadvantages, guidance should be developed for infrastructure owners for writing different types of bids;
- Effectively assessing and managing bids, design proposals and construction requires adequate training of staff in infrastructure agencies, which is not always a given at this time;
- The standing CSIWG or a designated working group should engage with legal and financial experts as well as engineering and climate change experts to develop model contract language and other support to assist with linking policy to project-level contracts; and
- The standing CSIWG should also systematically examine the hurdles and opportunities for improved inclusive procurement practices as it transitions to building more climate-safe infrastructure and develop an inclusive procurement practices toolbox.

Furthermore, incentives – financial and otherwise – provide the inducements to break from traditional and well-trodden paths and try the innovative approaches and paradigm shifts necessary to move infrastructure design into the new Climate-Safe Path paradigm. Metrics of success and performance also provide tools that achieve multiple goals such as: enabling deliberate planning and decision-making; providing a mechanism for accountability and governance; providing justification of adaptation expenditures; providing the information needed for adaptive design; and supporting communication, public engagement and public support. And, finally, peer-to-peer learning supported by the development of a best practices compendium provides references, tools, ideas and inspiration for engineers and architects as they work towards a safer future for all.

Figure 10.10: For State policy to be translated into projects on the ground, planners need help in developing appropriate contract language. A California-specific Manual of Practice, model contracts, incentives and a set of performance metrics are all ways to support implementation. (Photo: Trinidad Head, Humboldt County; R. Bertolf, Wikimedia Commons, licensed under Creative Commons license 2.0)

In Closing

Through all of its climate-focused activities, the State of California has been laying the foundation for the work of the CSIWG. AB 2800 allowed the Working Group to tackle the tensions and challenges with changing ways of thinking and doing and creating new paths for infrastructure planning in the state. In using the systemic approach to move from vision to implementation, and in following the recommendations that provide the bricks for the Climate-Safe Path, California has the opportunity to Pay it Forward. It must make these investments today to ensure the safety, well-being and prosperity of all Californians tomorrow.

California has the opportunity to Pay it Forward. It must make these investments today to ensure the safety, well-being and prosperity of all Californians tomorrow.

Figure 10.11: Investing in California's climate-safe infrastructure today is "paying it forward" – for the sake of the safety, well-being and prosperity of all. (Photo: Ian D. Keating, flickr, licensed under Creative Commons license 2.0)

References

Note: Whenever possible, references are provided with a link to an online and free source so as to make the resources that informed this report accessible to all interested readers. These links are current and active as of August 18, 2018. California Fourth Climate Change Assessment Reports are available from the California Climate Change Portal once released; see: http://resources.ca.gov/climate/safeguarding/research/ and http://www.ClimateAssessment.ca.gov.

1. Douglass, B.S. and J.A. Sykes. 2013. Public-Private Partnerships in California *California Public Law Journal* (Available at: http://documents.jdsupra.com/f7690ccc-bb17-4fda-9ba3-b98ef22cfd78.pdf).
2. Little Hoover Commission. 2010. *Building California: Infrastructure Choices and Strategy.* Little Hoover Commission: Sacramento, CA (Available at: http://www.lhc.ca.gov/sites/lhc.ca.gov/files/Reports/199/Report199.pdf).
3. Rogers-Gibson, J. 2017. *Built to Last Challenges and Opportunities for Climate-Smart Infrastructure in California.* Union of Concerned Scientists: Oakland, CA (Available at: https://www.ucsusa.org/sites/default/files/attach/2017/11/gw-whitepaper-smart-infrastructure.pdf).
4. ASCE Committee on America's Infrastructure. 2017. *2017 Infrastructure Report Card: A Comprehensive Assessment of America's Infrastructure.* ASCE: Reston, Virginia. (Available at: https://www.infrastructurereportcard.org/).
5. Meyer-Morse, N. and E. Levin. 2018. *Disaster Funding to Support the Development of Climate Safe Infrastructure: Presentation to the Climate-Safe Infrastructure Working Group*, Meeting #4, Davis, CA.
6. Legislative Analyst's Office (LAO). 2018. *Infrastructure Maintenance*. Sacramento, CA: LAO (Available at: http://www.lao.ca.gov/Infrastructure/Maintenance).
7. ASCE Committee on America's Infrastructure. 2017. *Infrastructure in California*. ASCE: Reston, Virginia (Available at: https://www.infrastructurereportcard.org/state-item/california/).
8. U.S. Global Change Research Program (USGCRP). 2017. *Climate Science Special Report: Fourth National Climate Assessment.* Fourth National Climate Assessment, ed. D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock. Vol. 1. Washington, DC: USGCRP (Available at: https://science2017.globalchange.gov/)
9. Bedsworth, L., et al. 2018. Summary Report. California's Fourth Climate Change Assessment. *California's Fourth Climate Change Assessment. Publication number: SUM-CCCA4-2018-013*, Sacramento, CA.
10. Iacobellis, S.F., et al. 2016. *Climate, in Ecosystems of California,* H. Mooney and E. Zavaleta, Editors. University of California Press: Oakland, CA. pp. 9-25
11. Muir, J. 2011 (1911). *My First Summer in the Sierra: And Selected Essays.* Paperback Classics, ed. B. McKibben. New York, NY: Library of America.
12. Dettinger, M.D., et al. 2011. Atmospheric rivers, floods and the water resources of California. *Water*, 3: 445-478 (Available at: http://www.mdpi.com/2073-4441/3/2/445).
13. Stahle, D., et al. 2013. The ancient blue oak woodlands of California: Longevity and hydroclimatic history. *America Meteorological Society*, 17(12): 1-23 (Available at: https://doi.org/10.1175/2013EI000518.1).
14. Seager, R. and M. Hoerling. 2014. *Atmosphere and ocean origins of North American droughts.* Journal of Climate, 27(12): 4581-4606 (Available at: https://doi.org/10.1175/JCLI-D-13-00329.1).
15. Namias, J. 1979. *Premonitory signs of the 1978 break in the West Coast drought.* Monthly Weather Review, 107: 1675-1681 (Available at: https://doi.org/10.1175/1520-0493(1979)107<1675:PSOTBI>2.0.CO;2).
16. Ralph, F., P. Neiman, and G. Wick. 2004. Satellite and CALJET aircraft observations of atmospheric rivers over the eastern north pacific ocean during the winter of 1997/98. *Monthly Weather Review*, 132: 1721-1745 (Available at: https://doi.org/10.1175/1520-0493(2004)132<1721:SACAOO>2.0.CO;2).
17. Dettinger, M.D. 2013. Atmospheric rivers as drought busters on the U.S. West coast. *Hydrometeorology*, 14: 1721-1732 (Available at: http://tenaya.ucsd.edu/~dettinge/drought_busters.pdf).
18. Dettinger, M.D. 2016. Historical and future relations between large storms and droughts in California. *San Francisco Estuary and Watershed Science*, 14(2): 1-21 (Available at: http://cw3e.ucsd.edu/wp-content/uploads/2016/07/Dettinger2016.pdf).
19. Swain, D.L., et al. 2016. Trends in atmospheric patterns conducive to seasonal precipitation and temperature extremes in California. *Science Advances*, 2(4): e1501344 (Available at: http://advances.sciencemag.org/content/2/4/e1501344).

20. Georgakakos, A.P., et al. 2012. Value of adaptive water resources management in Northern California under climatic variability and change: Reservoir management. *Journal of Hydrology*, 412-413: 34-46 (Available at: https://www.researchgate.net/publication/237999094_Value_of_adaptive_water_resources_management_in_Northern_California_under_climatic_variability_and_change_Reservoir_management).
21. Draper, A.J., et al. 2003. Economic-engineering optimization for California water management. *Journal of Water and Resource Management-ASCE*, 129(2): 155-164 (Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.7.9629&rep=rep1&type=pdf).
22. Faunt, C.C., ed. 2009. Groundwater Availability of the Central Valley Aquifer. California: *U.S. Geological Survey Professional Paper 1766* (Available at: https://pubs.usgs.gov/pp/1766/).
23. Diffenbaugh, N.S., D.L. Swain, and D. Touma. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, 112(13): 3931-3936 (Available at: http://www.pnas.org/content/early/2015/02/23/1422385112.long).
24. Hanak, E., et al. 2010. Myths of California water: Implications and reality. *West-Northwest*, 16(1): 3-73 (Available at: https://repository.uchastings.edu/faculty_scholarship/1364/).
25. Lund, J. 2017. *Reflections on Cadillac Desert, CaliforniaWaterBlog.com* (Available at: https://californiawaterblog.com/2017/07/09/reflections-on-cadillac-desert/).
26. Barnett, T.P., et al. 2008. Human-induced changes in the hydrology of the Western United States. *Science*, 319(5866): 1080-1083 (Available at: http://science.sciencemag.org/content/319/5866/1080).
27. Intergovernmental Panel on Climate Change (IPCC). 2013. *Summary for Policymakers, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY (Available at: https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf).
28. USGCRP. 2017. *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, D.J. Wuebbles, et al., Editors. U.S. Global Change Research Program: Washington, DC. (Available at: https://science2017.globalchange.gov/).
29. Pierce, D.W., J.F. Kalansky, and D.R. Cayan. 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. *California's Fourth Climate Change Assessment. Publication number: CCCA4-CEC-2018-006*. California Energy Commission: Sacramento, CA.
30. Pierce, D.W., D.R. Cayan, and B.L. Thrasher. 2014. Statistical downscaling using localized constructed analogs (LOCA). *J. Hydrometeorology*, 15: 2558-2585 (For more information on LOCA, see loca.ucsd.edu).
31. Flint, L.E. and A.L. Flint. 2014. California Basin Characterization Model: A Dataset of Historical and Future Hydrologic Response to Climate Change, in *U.S. Geological Survey Data Release*. USGS, California Water Science Center: Sacramento, CA (Available at: https://ca.water.usgs.gov/projects/reg_hydro/basin-characterization-model.html).
32. Huang, H.-Y., et al. 2015. Downscaling near-surface wind over complex terrain using a physically-based statistical modeling approach. *Climate Dynamics*, 44(1-2): 529-542 (Available at: http://research.atmos.ucla.edu/csrl/publications/Huang_etal_2014.pdf).
33. Berg, N. and A. Hall. 2015. Increased interannual precipitation extremes over California under climate change. *Journal of Climate*, 28(16): 6324-6334 (Available at: http://research.atmos.ucla.edu/csrl/publications/Hall/Berg_CA_extremes_revised.pdf)
34. Romero-Lankao, P., et al. 2014. *North America, in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, C.B. Field, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY pp. 1439-1498 (Available at: http://www.ipcc.ch/report/ar5/wg2/).
35. Vose, R.S., et al. 2014. Improved historical temperature and precipitation time series for U.S. climate divisions. *Journal of Applied Meteorology and Climatology*, 53(5): 1232-1251 (Available at: https://www.ncdc.noaa.gov/monitoring-references/docs/vose-et-al-2014.pdf).
36. Diffenbaugh, N.S., et al. 2017. Quantifying the influence of global warming on unprecedented extreme climate events. *Proceedings of the National Academy of Sciences of the United States of America*, 114(19): 4881-4886 (Available at: http://www.pnas.org/content/114/19/4881).
37. Diffenbaugh, N.S., et al. 2008. Global warming presents new challenges for maize pest management. *Environmental Research Letters*, 3: 044007 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/3/4/044007/meta).
38. Gao, Y., et al. 2015. Persistent cold air outbreaks over North America in a warming climate *Environmental Research Letters*, 10(4): 044001 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/10/4/044001/pdf).
39. Pierce, D.W., et al. 2013. Probabilistic estimates of future changes in California temperature and precipitation using statistical and dynamical downscaling. *Climate Dynamics*, 40: 839-856 (Available at: http://tenaya.ucsd.edu/~cayan/New_Pubs/D30_Pierce_etal_2012_CD.pdf).
40. Kalansky, J., et al. 2018. San Diego Summary Report. *California's Fourth Climate Change Assessment. Publication number: SUM-CCCA4-2018-009*. Sacramento, CA.

41. Rauscher, S.A., et al. 2008. Future changes in snowmelt-driven runoff timing over the western US. *Geophys. Res. Lett.,* 35: L16703 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2008GL034424).
42. Ashfaq, M., et al. 2013. Near-term acceleration of hydroclimatic change in the western U.S. *Journal of Geophysical Research*: Atmospheres, 118: 10,676–10,693 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/jgrd.50816).
43. Pierce, D.W., D.R. Cayan, and B.L. Thrasher. 2014. Statistical downscaling using localized constructed analogs (LOCA). *Journal of Hydrometeorology*, 15: 2558 (Available at: http://loca.ucsd.edu/loca-bibliography/).
44. Dettinger, M., et al. 2018. Sierra Nevada Summary Report. *California's Fourth Climate Change Assessment. Publication number: SUM-CCCA4-2018-004*. Sacramento, CA.
45. Huang, X., A.D. Hall, and N. Berg. 2018. Anthropogenic warming impacts on today's Sierra Nevada snowpack and flood risk. *Geophysical Research Letters*, 45(12): 6215-6222 (Available at: https://doi.org/10.1029/2018GL077432).
46. Griggs, G., et al. 2017. *Rising Seas in California: An Update on Sea-Level Rise Science. A Report by the California Ocean Protection Council's Science Advisory Team Working Group.* Ocean Science Trust: Oakland, CA (Available at: http://www.opc.ca.gov/webmaster/ftp/pdf/docs/rising-seas-in-california-an-update-on-sea-level-rise-science.pdf).
47. DeConto, R.M. and D. Pollard. 2016. Contribution of Antarctica to past and future sea-level rise. *Nature*, 531(7596): 591-597 (Available at: http://www.documentcloud.org/documents/2823837-DeConto-Pollard-2016-Contribution-of-Antarctica.html).
48. Kopp, R.E., et al. 2017. Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future*, 5(12): 1217-1233 (Available at: https://doi.org/10.1002/2017EF000663).
49. California Ocean Protection Council (OPC). 2018. *State of California Sea-Level Rise Guidance: 2018 Update.* California Natural Resources Agency and OPC: Sacramento, CA (Available at: http://www.opc.ca.gov/updating-californias-sea-level-rise-guidance/).
50. DeConto, R. and H.A. Fricker. 2017. *Appendix 2: Role of Polar Ice Sheets in Future Sea-Level Rise: Implications for California, in Rising Seas in California: An Update on Sea-Level Rise Science*, G. Griggs, et al., Editors. California Ocean Science Trust: Oakland, CA. pp. 47-71 (Available at: http://www.documentcloud.org/documents/2823837-DeConto-Pollard-2016-Contribution-of-Antarctica.html).
51. Erikson, L.H., A.C. O'Neill, and P.L. Barnard. 2018. Estimating fluvial discharges coincident with 21st century coastal storms modeled with CoSMoS. *Proceedings from the International Coastal Symposium (ICS) 2018*. Busan, Republic of Korea: Journal of Coastal Research (Available at: http://www.bioone.org/doi/10.2112/SI85-159.1).
52. O'Neill, A.C., et al. 2018. Projected 21st century coastal flooding in the Southern California Bight. Part 1: Development of the third generation CoSMoS model. *Journal of Marine Science and Engineering*, 6(2): 59 (Available at: http://www.mdpi.com/2077-1312/6/2/59).
53. National Research Council (NRC). 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Committee on Sea Level Rise in California, Oregon, and Washington, Board on Earth Sciences and Resources and Ocean Studies Board, Division on Earth and Life Studies*. Washington, DC: National Academies Press (Available at: https://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington).
54. Graham, N., et al. 2013. Multi-model projections of twenty-first century North Pacific winter wave climate under the IPCC A2 scenario. *Climate Dynamics*, 40: 1335-1360 (Available at: https://pdfs.semanticscholar.org/7595/b089131f0796077a5385aca4f1dbcd828aad.pdf).
55. Bromirski, P.D., Flick R.E, and A.J. Miller. 2017. Storm surge along the Pacific coast of North America. *Journal of Geophysical Research-Oceans*, 122: 441-457 (Available at: http://horizon.ucsd.edu/miller/download/Storm_surge/Storm_surge.pdf).
56. Moftakhari, H.M., et al. 2017. Compounding Effects of Sea Level Rise and Fluvial Flooding. *Proceedings of the National Academy of Sciences of the United States of America*, 114(37): 9785-9790 (Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5603992/).
57. Cloern, J.E., et al. 2011. Projected Evolution of California's San Francisco Bay-Delta-River System in a Century of Climate Change. *PLOS ONE*, 6(9): e24465 (Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0024465).
58. Ragno, E., et al. 2018. Quantifying changes in future intensity-duration-frequency curves using multimodel ensemble simulations. *Water Resources Research*, 54(3): 1751-1764 (Available at: https://www.researchgate.net/publication/323363918_Quantifying_Changes_in_Future_Intensity-Duration-Frequency_Curves_Using_Multi-Model_Ensemble_Simulations).
59. Zscheischler, J., et al. 2018. Future climate risk from compound events. *Nature Climate Change*, 8(6): 469-477 (Available at: https://meetingorganizer.copernicus.org/EGU2018/EGU2018-5439.pdf).
60. Goebel, M., A. Pidlisecky, and R. Knight. 2017. Resistivity imaging reveals complex pattern of saltwater intrusion along Monterey coast. *Journal of Hydrology*, 551: 746-755 (Available at: https://www.sciencedirect.com/science/article/pii/S0022169417301154).
61. Metropolitan Water District of Southern California (MWDH2O). 2017. *Modernizing the System: California Waterfix Physical Infrastructure.* MWDH2O: Los Angeles, CA. 33 pp. (Available at: http://www.mwdh2o.com/DocSvcsPubs/WaterFix/assets/cawaterfix_infrastructure_whitepaper_factsheet.pdf).

62. Hoover, D.J., et al. 2016. Sea-level rise and coastal groundwater inundation and shoaling at select sites in California, USA. *Journal of Hydrology*, 11: 234-249 (Available at: https://www.sciencedirect.com/science/article/pii/S2214581815002050).
63. Befus, K.M., et al. 2017. The magnitude and origin of groundwater discharge to eastern U.S. and Gulf of Mexico coastal waters. *Geophysical Research Letters*, 44(20): 10,396–10,406 (Available at: https://www.researchgate.net/publication/320483615_The_Magnitude_and_Origin_of_Groundwater_Discharge_to_Eastern_US_and_Gulf_of_Mexico_Coastal_Waters_US_East_Coast_Groundwater_Discharge).
64. Vitousek, S., et al. 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. *Journal of Geophysical Research*: Earth Surface, 122(4): 782-806 (Available at: https://static1.squarespace.com/static/5732929107eaa0f51dce43a1/t/591ddeead482e9423da718b2/1495129838932/Vitousek_2017a_JGR_EarthSurface.pdf).
65. Limber, P.W. and P.L. Barnard. 2018. Coastal knickpoints and the competition between fluvial and wave-driven erosion on rocky coastlines. *Geomorphology*, 306: 1-12 (Available at: https://www.sciencedirect.com/science/article/pii/S0169555X17305433?via%3Dihub).
66. Knowles, N., D. MD, and C. DR. 2006. Trends in snowfall versus rainfall in the Western United States. *Journal of Climate*, 19: 4545-4559 (Available at: https://journals.ametsoc.org/doi/10.1175/JCLI3850.1).
67. Mote, P.W., et al. 2018. Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, 1(1): 2 (Available at: https://www.nature.com/articles/s41612-018-0012-1).
68. Ault, T.R., et al. 2016. Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest. *Science Advances*, 2(10): e1600873 (Available at: http://advances.sciencemag.org/content/2/10/e1600873).
69. Seager, R., M., et al. 2015. Causes of the 2011 to 2014 California drought. *American Meteorological Society*, 28: 6997-7024 (Available at: https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00860.1).
70. Griffin, D. and K.J. Anchukaitis. 2014. How unusual is the 2012–2014 California drought? *Geophysical Research Letters*, 41: 9017-9023 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2014GL062433).
71. Park, W.A., et al. 2015. Contribution of anthropogenic warming to California drought during 2012–2014. *Geophysical Research Letters*, 42(16): 6819-6828 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015GL064924).
72. Sewall, J.O. and L.C. Sloan. 2004. Disappearing Arctic sea ice reduces available water in the American west. *Geophysical Research Letters*, 31(6): L06209 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2003GL019133).
73. Sewall, J.O. 2005. Precipitation shifts over Western North America as a result of declining Arctic sea ice cover: The coupled system response. *Earth Interactions*, 9: [26] (23 pp.) (Available at: https://journals.ametsoc.org/doi/abs/10.1175/EI171.1).
74. Denniston, R.F., et al. 2007. Episodes of late Holocene aridity recorded by stalagmites from Devil's Icebox Cave, central Missouri, USA. *Quaternary Research*, 68: 45-52 (Available at: https://static1.squarespace.com/static/56fec047b654f939134dc814/t/572263b4ab48de744db2ddca/1461871541828/Denniston_etal_2007.pdf).
75. Wagner, J.D.M., et al. 2010. Moisture variability in the southwestern United States linked to abrupt glacial climate change. *Nature Geoscience*, 3: 110-113 (Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.471.8193&rep=rep1&type=pdf).
76. Asmerom, Y., V.J. Polyak, and S.J. Burns. 2010. Variable winter moisture in the southwestern United States linked to rapid glacial climate shifts. *Nature Geoscience*, 3: 114-117 (Available at: https://www.nature.com/articles/ngeo754).
77. Oster, J.L., et al. 2014. Millennial-scale variations in western Sierra Nevada precipitation during the last glacial cycle MIS 4/3 transition. *Quaternary Research*, 82: 236-248 (Available at: https://www.cambridge.org/core/journals/quaternary-research/article/millennialscale-variations-in-western-sierra-nevada-precipitation-during-the-last-glacial-cycle-mis-43-transition/20C6E420311700DC26352E5E1E4B9C0F).
78. Cvijanovic, I., et al. 2017. Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall. *Nature Communications*, 8(1): 1947 (Available at: https://www.nature.com/articles/s41467-017-01907-4).
79. Swain, D.L., et al. 2018. Increasing precipitation volatility in twenty-first-century California. Nature Climate Change, 8(5): 427-433 (Available at: https://www.nature.com/articles/s41558-018-0140-y).
80. Pierce, D.W., D.R. Cayan, and J.F. Kalansky. 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. *California's Fourth Climate Change Assessment, Publication number: CCCA4-CEC-2018-006*. California Energy Commission: Sacramento, CA.
81. Diffenbaugh, N.S. and F. Giorgi. 2012. Climate change hotspots in the CMIP5 global climate model ensemble. *Climatic Change*, 114(3): 813-822 (Available at: https://www.researchgate.net/publication/256469107_Climate_change_hotspots_in_the_CMIP5_global_climate_model_ensemble).
82. Lavers, D.A., et al. 2015. Climate change intensification of horizontal water vapor transport in CMIP5. *Geophysical Research Letters*, 42: 5617–5625 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015GL064672).

83. Polade, S.D., et al. 2017. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. *Scientific Reports*, 7(1): 10783 (Available at: https://www.researchgate.net/publication/319555340_Precipitation_in_a_warming_world_Assessing_projected_hydro-climate_changes_in_California_and_other_Mediterranean_climate_regions).
84. Bryant, B.P. and A.L. Westerling 2014. Scenarios for future wildfire risk in California: Links between changing demography, land use, climate and wildfire. *Environmetrics*, 25(6): 454-471 (Available at: https://onlinelibrary.wiley.com/doi/pdf/10.1002/env.2280).
85. Crockett, J.L. and A.L. Westerling. 2018. Greater temperature and precipitation extremes intensify Western US droughts, wildfire severity, and Sierra Nevada tree mortality. *Journal of Climate*, 3(1): 341-354 (Available at: https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-17-0254.1).
86. Williams, A.P., et al. 2018. Effect of reduced summer cloud shading on evaporative demand and wildfire in coastal Southern California. *Geophysical Research Letters*, 45(11): 5653-5662 (Available at: https://www.deepdyve.com/lp/wiley/effect-of-reduced-summer-cloud-shading-on-evaporative-demand-and-g8Z2yv9OFp).
87. Hamlet, A.F. and D.P. Lettenmaier. 2007. Effects of 20th century warming and climate variability on flood risk in the western U.S. . *Water Resources Research*, 43(6): 1-17 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2006WR005099).
88. Das, T., et al. 2013. Increases in flood magnitudes in California under warming climates. *Journal of Hydrology*, 501: 101-110 (Available at: https://pdfs.semanticscholar.org/2fc6/cd8efae58dec9e15850c12710107b800211c.pdf).
89. Gleick, P.H. 1987. Regional hydrologic consequences of increases in atmospheric carbon dioxide and other trace gases. *Climatic Change*, 10(2): 137-161 (Available at: https://link.springer.com/article/10.1007/BF00140252).
90. Georgakakos, K.P., et al. 2012. Value of adaptive water resources management in northern California under climatic variability and change: Dynamic hydroclimatology. *Journal of Hydrology*, 412-413: 47-65 (Available at: http://www.academia.edu/23379151/Value_of_adaptive_water_resources_management_in_Northern_California_under_climatic_variability_and_change_Reservoir_management).
91. Nassopoulos, H., P. Dumas, and S. Hallegatte. 2012. Adaptation to an uncertain climate change: cost benefit analysis and robust decision making for dam dimensioning. *Climatic Change*, 114(3-4): 497-508 (Available at: https://hal-enpc.archives-ouvertes.fr/hal-00719113/document).
92. Hartmann, D.L., et al. 2013. Observations: Atmosphere and surface, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY (Available at: http://www.ipcc.ch/report/ar5/wg1/).
93. Guzman-Morales, J., et al. 2016. Santa Ana Winds of Southern California: Their climatology, extremes, and behavior spanning six and a half decades. *Geophysical Research Letters*, 43(6): 2827-2834 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016GL067887).
94. Westerling, A.L., et al. 2004. Climate, Santa Ana Winds and Autumn Wildfires in Southern California. Eos, *Transactions American Geophysical Union*, 85(31): 289, 296 (Available at: http://meteora.ucsd.edu/cap/pdffiles/04EOS_Westerling.pdf).
95. Jin, Y., et al. 2014. Contrasting controls on wildland fires in Southern California during periods with and without Santa Ana winds. *Journal of Geophysical Research: Biogeosciences*, 119(3): 432-450 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2013JG002541).
96. Hughes, M., A. Hall, and J. Kim. 2011. Human-induced changes in wind, temperature and relative humidity during Santa Ana events. *Climatic Change*, 109(1): 119-132 (Available at: https://www.researchgate.net/publication/227583809_Human-induced_changes_in_wind_temperature_and_relative_humidity_during_Santa_Ana_events).
97. Westerling, A.L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 371(1696) (Available at: http://rstb.royalsocietypublishing.org/content/371/1696/20150178).
98. Mann, M.L., et al. 2016. Incorporating Anthropogenic Influences into Fire Probability Models: Effects of Human Activity and Climate Change on Fire Activity in California. *PLOS ONE*, 11(4): e0153589 (Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0153589).
99. Abatzoglou, J.T. and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences*, 113(42): 11770-11775 (Available at: http://www.pnas.org/content/113/42/11770).
100. Westerling, A.L., et al. 2011. Climate change and growth scenarios for California wildfire. *Climatic Change*, 109(1): 445-463 (Available at: https://www.researchgate.net/publication/227583836_Climate_change_and_growth_scenarios_for_California_wildfire).
101. Jin, Y., et al. 2015. Identification of two distinct fire regimes in Southern California: implications for economic impact and future change. *Environmental Research Letters*, 10(9): 094005 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/10/9/094005).

102. Clemesha, R.E.S., et al. 2016. The northward march of summer low cloudiness along the California coast. *Geophysical Research Letters*, 43(3): 1287-1295 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015GL067081).
103. Schwartz, R.E., et al. 2014. North American west coast summer low cloudiness: Broadscale variability associated with sea surface temperature. *Geophysical Research Letters*, 41: 3307-3314 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014GL059825).
104. Clemesha, R.E.S., et al. 2017. Daily variability of California coastal low cloudiness: A balancing act between stability and subsidence. *Geophysical Research Letters*, 44(7): 3330-3338 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL073075).
105. Johnstone, J.A. and E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. *Proceedings of the National Academy of Sciences of the United States of America*, 107(10): 4533-4538 (Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2822705/).
106. Williams, A.P., et al. 2015. Urbanization causes increased cloud base height and decreased fog in coastal Southern California. *Geophysical Research Letters*, 42(5): 1527-1536 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015GL063266).
107. Iacobellis, S.F. and D.R. Cayan. 2013. The variability of California summertime marine stratus: Impacts on surface air temperatures. *Journal of Geophysical Research: Atmospheres*, 118(16): 9105-9122 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/jgrd.50652).
108. Knutti, R. 2008. Should we believe model predictions of future climate change? *Philosophical Transactions of the Royal Society A*, 366: 4647-4664 (Available at: http://rsta.royalsocietypublishing.org/content/366/1885/4647).
109. Hawkins, E. and R.T. Sutton. 2011. The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, 37: 407-418 (Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.383.8139&rep=rep1&type=pdf).
110. United Nations (UN). 2015. The Paris Agreement. UN: New York, NY (Available at: http://unfccc.int/paris_agreement/items/9485.php).
111. Hsu, A., et al. 2016. *Taking stock of global climate action: As recorded on the Non-State Action Zone for Climate Action (NAZCA) Prepared by the Yale Data-Driven Environmental Solutions Group.* Yale University: New Haven, CT (Available at: http://datadriven.yale.edu/wp-content/uploads/2016/12/Data_Driven_Yale_Taking-Stock-of-Global-Climate-Action_Nov_2016_final.pdf).
112. Kuyper, J.W., B.-O. Linnér, and H. Schroeder. 2018. Non-state actors in hybrid global climate governance: justice, legitimacy, and effectiveness in a post-Paris era. Wiley Interdisciplinary Reviews: *Climate Change*, 9(1): e497 (Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/wcc.497).
113. Denton, F., et al. 2014. *Climate-resilient pathways: Adaptation, mitigation, and sustainable development, in Climate Change 2014: Impacts, Adaptation and Vulnerability. Contribution of Working Group 2 of the Intergovernmental Panel on Climate Change*, C.B. Field, et al., Editors. Cambridge University Press: Camrbidge, New York. Ch.20 (Available at: https://www.ipcc.ch/report/ar25/wg22/).
114. Tørstad, V. and H. Sælen. 2018. Fairness in the climate negotiations: what explains variation in parties' expressed conceptions? *Climate Policy*, 18(5): 642-654 (Available at: https://scholar.google.fr/citations?user=8nkn3q4AAAAJ&hl=en).
115. Ranger, N., et al. 2012. Is it possible to limit global warming to no more than 1.5°C? *Climatic Change*, 111(3): 973-981 (Available at: https://link.springer.com/article/10.1007/s10584-012-0414-8).
116. Schleussner, C.-F., et al. 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. *Earth System Dynamics*, 7: 327-351 (Available at: https://www.earth-syst-dynam.net/7/327/2016/esd-7-327-2016.pdf).
117. Haszeldine, R.S., et al. 2018. Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A*: Mathematical, Physical and Engineering Sciences, 376(2119): 20160447 (Available at: http://rsta.royalsocietypublishing.org/content/376/2119/20160447).
118. Kriegler, E., et al. 2018. Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119): 20160457 (Available at: http://rsta.royalsocietypublishing.org/content/376/2119/20160457.e-letters).
119. MacMartin, D.G., K.L. Ricke, and D.W. Keith. 2018. Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2119): 20160454 (Available at: http://rsta.royalsocietypublishing.org/content/376/2119/20160454).
120. Obersteiner, M., et al. 2018. How to spend a dwindling greenhouse gas budget. *Nature Climate Change*, 8(1): 7-10 (Available at: https://www.nature.com/articles/s41558-017-0045-1?WT.feed_name=subjects_climate-change-mitigation).
121. Burke, M., M. Davis, and N. Diffenbaugh. 2018. Large potential reduction in economic damages under UN mitigation targets. *Nature*, 557: 549–553 (Available at: https://www.nature.com/articles/s41586-018-0071-9).
122. Schleussner, C.-F., et al. 2016. Differential climate impacts for policy-relevant limits to global warming: The case of 1.5°C and 2°C. Earth System Dynamics, 7: 327-351 (Available at: https://www.earth-syst-dynam.net/7/327/2016/esd-7-327-2016.pdf).

123. Shindell, D., et al. 2018. Quantified, localized health benefits of accelerated carbon dioxide emissions reductions. *Nature Climate Change*, 8: 291-295 (Available at: https://www.nature.com/articles/s41558-018-0108-y).
124. Ciais, P., et al. 2013. Carbon and other biogeochemical cycles, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,* T.F. Stocker, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY. pp. 465-570 (Available at: http://www.ipcc.ch/report/ar5/wg1/).
125. Goldblatt, C. and A.J. Watson. 2012. The runaway greenhouse: implications for future climate change, geoengineering and planetary atmospheres. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 370(1974): 4197-4216 (Available at: http://rsta.royalsocietypublishing.org/content/370/1974/4197).
126. Flato, G., J. , et al. 2013. Evaluation of climate models, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker, et al., Editors. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA (Available at: http://www.ipcc.ch/report/ar5/wg1/).
127. Eyring, V., et al. 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization *Geoscientific Model Development*, 9: 1937-1958 (Available at: https://www.geosci-model-dev.net/9/1937/2016/).
128. Taylor, K.E., R.J. Stouffer, and G.A. Meehl. 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(April): 485-498 (Available at: https://journals.ametsoc.org/doi/10.1175/BAMS-D-11-00094.1).
129. Deser, C., et al. 2012. Communication of the role of natural variability in future North American climate. *Nature Climate Change*, 2: 775-779 (Available at: https://www.nature.com/articles/nclimate1562).
130. Mankin, J.S., et al. 2015. The potential for snow to supply human water demand in the present and future. *Environmental Research Letters*, 10(11): 114016 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/10/11/114016/pdf).
131. Swain, D.L., B. Lebassi-Habtezion, and N.S. Diffenbaugh. 2015. Evaluation of nonhydrostatic simulations of Northeast Pacific atmospheric rivers and comparison to in situ observations. *Monthly Weather Review*, 143(9): 3556-3569 (Available at: https://journals.ametsoc.org/doi/abs/10.1175/MWR-D-15-0079.1).
132. Giorgi, F., et al. 2008. The regional climate change hyper-matrix framework. *Eos, Transactions American Geophysical Union*, 89(45): 445-446 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008EO450001).
133. Dow, K., R.L. Murphy, and G.J. Carbone. 2009. Consideration of user needs and spatial accuracy in drought mapping. *Journal of the American Water Resources Association (JAWRA)*, 45(1): 187-197 (Available at: https://www.hydroreform.org/sites/default/files/drought%20mapping%20dow%20et%20al%202009.pdf).
134. Franco, G., et al. 2003. Climate Change Research, Development, and Demonstration Plan. *Public Interest Energy Research Program. Publication number: P500-01-025FS*. California Energy Commission: Sacramento, CA (Available at: http://www.energy.ca.gov/reports/2003-04-16_500-03-025FS.PDF)
135. Hidalgo, H.G., M.D. Dettinger, and D.R. Cayan. 2008. Downscaling with Constructed Analogues: Daily Precipitation and Temperature Fields over the United States. *CEC PIER Project Report. Publication Number CEC-500-2007-123.* Sacramento, CA: California Energy Commission (Available at: http://www.energy.ca.gov/2007publications/CEC-500-2007-123/CEC-500-2007-123.PDF).
136. Hansen, J., et al. 2013. Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLOS ONE*, 8(e81648) (Available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648).
137. Trump, D.J. 2017. *Statement by President Trump on the Paris Climate Accord*. June 1, 2017. Washington, DC: The White House (Available at: https://www.whitehouse.gov/briefings-statements/statement-president-trump-paris-climate-accord/).
138. Steffen, W., et al. 2018. Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences*, 115(33): 8252-8259 (Available at: http://www.pnas.org/cgi/doi/10.1073/pnas.1810141115).
139. California Department of Finance (CDF). 2018. *New demographic report shows California population nearing 40 million mark with growth of 309,000 in 2017*. CDF: Sacramento, CA (Available at: http://www.dof.ca.gov/Forecasting/Demographics/Estimates/e-1/documents/E-1_2018PressRelease.pdf).
140. Department of Water Resources (DWR). 2016. *California State Water Project at a Glance.* (Available at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/What-We-Do/Infrastructure/Files/Publications/Californias-State-Water-Project-at-Glance.pdf).
141. Department of Water Resources (DWR). 2018. *Infrastructure*. July 5, 2018 (Available at: https://water.ca.gov/What-We-Do/Infrastructure).
142. Mann, M.E. and P.H. Gleick. 2015. Climate change and California drought in the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, 112(13): 3858-3859 (Available at: http://www.meteo.psu.edu/holocene/public_html/Mann/articles/articles/MannGleickPNAS15.pdf).

143. Vahedifard, F., et al. 2017. Lessons from the Oroville Dam. *Science*, 355(6330): 1139-1140 (Available at: https://www.researchgate.net/publication/315113567_Lessons_from_the_Oroville_dam).
144. Brooks, B., et al. 2018. High Resolution Measurement of Levee Subsidence Related to Energy Infrastructure in the Sacramento-San Joaquin Delta. *California Fourth Climate Change Assessment Core Technical Reports. Publication number: CCCA4-CEC-2018-003*, California Energy Commission: Sacramento, CA.
145. Hummel, M.A., M.S. Berry, and M.T. Stacey. 2018. Sea level rise impacts on wastewater treatment systems along the U.S. coasts. *Earth's Future*, 6: 1-12 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017EF000805).
146. Schwarz, A., et al. 2018. Climate Change Risks Faced by the California Central Valley Water Resource System. *California's Fourth Climate Change Assessment. Publication number: CCCA4-EXT-2018-001*. Sacramento, CA.
147. Knowles, N., et al. 2018. Modeled Responses of Unimpaired Flows, Storage, and Managed Flows to Scenarios of Climate Change in the San Francisco Bay-Delta Watershed. *California's Fourth Climate Change Core Technical Reports.* U.S. Geological Survey (USGS): Sacramento, CA.
148. Wang, J., et al. 2018. Mean and Extreme Climate Change Impacts on the State Water Project. *California's Fourth Climate Change Assessment. Publication number: CCCA4-EXT-2018-004*. Sacramento, CA.
149. Green-Nylen, N., et al. 2018. Addressing Institutional Vulnerabilities in California's Drought Water Allocation, Part 2: Improving Water Rights Administration and Oversight for Future Droughts. *California Fourth Climate Change Assessment Core Technical Report. Publication number: CCCA4-CNRA-2018-010*. California Natural Resources Agency: Sacramento, CA.
150. Ekstrom, J.A., et al. 2018. Drought Management and Climate Adaptation among Small, Self-Sufficient Water Systems in California. *California's Fourth Climate Change Assessment. Publication number: CCCA4-CNRA-2018-004*. California Natural Resources Agency: Sacramento, CA.
151. Department of Water Resources (DWR). 2017. 2017 *Flood System Status Report.* DWR: Sacramento, CA (Available at: https://cawaterlibrary.net/document/2017-flood-system-status-report/).
152. Caltrans. 2018. *California Transportation Asset Management Plan: Fiscal Years 2017/18-2026/27*. CalTrans: Sacramento, CA (Available at: http://www.dot.ca.gov/assetmgmt/documents/TAMP_Final_03_30_18.pdf).
153. Union Pacific. 2009. *2009 Sustainability and Citizenship Report.* Union Pacific Corporation: Omaha, NE (Available at: https://www.up.com/cs/groups/public/documents/up_pdf_nativedocs/omhq10b29811006339.pdf).
154. Caltrans. 2018. *Caltrans Sustainability Roadmap 2018-2019* Caltrans: Sacramento, CA (Available at: http://test.gis.ca.gov/green/Documents/CALTRANS/CALTRANS_2018-2019_Roadmap_Complete_Document.pdf).
155. California Energy Commission (CEC). 2018. *California Energy Facility Status.* (Available at: http://www.energy.ca.gov/sitingcases/all_projects.html).
156. U.S. Nuclear Regulatory Commission (NRC). 2017. *California* (Available at: https://www.nrc.gov/info-finder/region-state/california.html).
157. California Energy Commission (CEC). 2018. *California Renewable Energy Programs*. (Available at: http://www.energy.ca.gov/renewables/renewable_links.html).
158. California Energy Commission (CEC). 2018. *California California Renewable Energy Statistics and Data*. (Available at: http://www.energy.ca.gov/almanac/renewables_data/).
159. California Energy Commission (CEC). 2018. *Age of Generating Units of California's Power Plants.* Sacramento, CA: CEC (Available at: http://www.energy.ca.gov/almanac/electricity_data/generating_units.html).
160. California Public Utilities Commission (CPUC). 2018. *Infrastructure*. (Available at: http://www.cpuc.ca.gov/infrastructure/).
161. California Energy Commission (CEC). 2016. *California Major Electric Transmission Lines Maps*. Sacramento, CA: CEC (Available at: http://www.energy.ca.gov/maps/infrastructure/transmission_lines.html).
162. Dale, L., et al. 2018. Assessing the Impact of Wildfires on the California Electricity Grid. *California's Fourth Climate Change Assessment Core Technical Reports. Publication number: CCCA4-CEC-2018-002*. California Energy Commission: Sacramento, CA.
163. Bruzgul, J., et al. 2018. Rising Seas and Electricity Infrastructure: Potential Impacts and Adaptation Actions for San Diego Gas & Electric. *California's Fourth Climate Change Assessment. Publication number: CCCA4-CEC-2018-004*. California Energy Commission: Sacramento, CA.
164. Burillo, D., et al. 2018. Climate Change in Los Angeles County: Grid Vulnerability to Extreme Heat. *California's Fourth Climate Change Assessment. Publication number: CCCA4-CEC-2018-013*. California Energy Commission: Sacramenton, CA.
165. Moser, S. and J. Finzi-Hart. 2018. The Adaptation Blindspot: Teleconnected and Cascading Impacts of Climate Change on the Electrical Grid and Lifelines in Los Angeles. *California's Fourth Climate Change Assessment Core Technical Reports. Publication number: CCCA4-CEC-2018-008*. California Energy Commission: Sacramento, CA.
166. California Energy Commission (CEC). 2018. *California Natural Gas Industry* (Available at: http://energy.ca.gov/almanac/naturalgas_data/).
167. Radke, J.D., et al. 2018. Assessing Extreme Weather-Related Vulnerability and Identifying Resilience Options for California's Interdependent Transportation Fuel Sector. *California's Fourth Climate Change Assessment. Publication Number CCCA4-CEC-2018-012*. California Energy Commission: Sacramento, CA.

168. California Energy Commission (CEC). 2016. *California's Oil Refineries* (Available at: http://www.energy.ca.gov/almanac/petroleum_data/refineries.html).
169. Bruzgul, J., et al. 2018. Potential Climate Change Impacts and Adaptation Actions for Gas Assets in the San Diego Gas and Electric Company Service Area. *California's Fourth Climate Change Assessment Core Technical Reports. Publication number CCCA4-CEC-2018-009*. California Energy Commission: Sacramento, CA.
170. Radke, J.D., et al. 2017. Assessment of Bay Area Natural Gas Pipeline Vulnerability to Climate Change. *White Paper for the California Energy Commission. Publication number: CEC-500-2017-008*. CEC: Sacramento, CA (Available at: http://www.energy.ca.gov/2017publications/CEC-500-2017-008/CEC-500-2017-008.pdf).
171. San Diego Gas & Electric Company. 2016. *Risk Assessment and Mitigation Phase: Report of San Diego Gas & Electric Company and Southern California Gas Company.* SDGE and SCG: San Diego and Los Angeles, CA Available at: https://www.sdge.com/regulatory-filing/20016/risk-assessment-and-mitigation-phase-report-sdge-socalgas).
172. Palmgren, C., et al. 2010. 2009 California Residential Appliance Saturation Study: Executive Summary. *Consultant Reports*. CEC: Sacramento, CA (Available at: https://www.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-V1.PDF).
173. U.S. Green Building Council (USGBC). 2005. *The New Orleans Principles: Celebrating the Rich History of New Orleans Through Commitment to a Sustainable Future* USGBC: Washington, DC (Available at: https://www.usgbc.org/resources/new-orleans-principles-celebrating-rich-history-new-orleans-through-commitment-sustainable).
174. Wilson, A. 2009. Green building: Passive survivability and building codes. *ICC eNews*, 6(9): 3 pp. (Available at: http://media.iccsafe.org/news/eNews/2009v2006n2009/greenbuilding.pdf).
175. Rutgers University. 2011. *Green Building Code (New Commercial Buildings)* Rutgers University: New Brunswick, NJ (Available at: http://greenmanual.rutgers.edu/newcommercial/strategies/survivability.pdf).
176. ASCE Committee on America's Infrastructure. 2012. *California Infrastructure Report Card 2012: A Citizen's Guide.* ASCE: Reston, VA (Available at: http://2013.infrastructurereportcard.org/california/california-infrastructure/).
177. Durairajan, R., C. Barford, and P. Barford. 2018. *Lights Out: Climate Change Risk to Internet Infrastructure. in ANRW '18 - Applied Networking Research Workshop.* Montreal, QC, Canada: ACM (Available at: http://ix.cs.uoregon.edu/~ram/papers/ANRW-2018.pdf).
178. ASCE Committee on Adaptation to a Changing Climate. 2015. *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*, J.R. Olsen, Editor. American Society of Civil Engineers Reston, VA (Available at: http://theicnet.org/wp-content/uploads/2015/07/2015-07-ASCE-Practice-to-Climate-Change-2015.pdf).
179. Minsker, B., et al. 2015. Progress and Recommendations for Advancing Performance-Based Sustainable and Resilient Infrastructure Design. *Journal of Water Resource Planning & Management*, 141(12): A4015006-4015001 - A4015006-4015016 (Available at: https://ascelibrary.org/doi/10.1061/%28ASCE%29WR.1943-5452.0000521).
180. Read, L.K. and R.M. Vogel. 2015. Reliability, return periods, and risk under nonstationarity. *Water Resources Research*, 51(8): 6381-6398 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2015WR017089).
181. Wallace, B., D. Ellison, and R. Daugherty. 2017. *Delivering Safe, Cost-Effective, Sustainable Civil Infrastructure Projects Under Conditions of Non-Stationarity, in International Conference on Sustainable Infrastructure 2017.* ASCE: New York, NY (Available at: https://ascelibrary.org/doi/book/10.1061/9780784481219).
182. Dahl, K., et al. 2018. *Underwater: Rising Seas, Chronic Floods, and the Implications for US Coastal Real Estate.* Union of Concerned Scientists: Cambridge, MA (Available at: https://www.ucsusa.org/global-warming/global-warming-impacts/sea-level-rise-chronic-floods-and-us-coastal-real-estate-implications#.W3grCOhKh3g).
183. Dahl, K.A., et al. 2017 Effective inundation of continental United States communities with 21st century sea level rise. *Elem Sci Anth*, 5: [art.37] (Available at: http://www.ucsusa.org/sites/default/files/attach/2017/2007/when-rising-seas-hit-home-elementa-research-article.pdf).
184. Hauer, M.E. 2017. Migration induced by sea-level rise could reshape the US population landscape. *Nature Climate Change*, 7(5): 321-325 (Available at: https://www.nature.com/articles/nclimate3271).
185. Luber, G., et al. 2014. *Ch. 9:* Human Health, in *Climate Change Impacts in the United States: The Third National Climate Assessment*, J.M. Melillo, T.T.C. Richmond, and G.W. Yohe, Editors. U.S. Global Change Research Program: Washington, DC. pp. 220-256 (Available at: https://www.globalchange.gov/nca3-downloads-materials).
186. Smith, K.R., et al. 2014. Human health: impacts, adaptation, and co-benefits, in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* C.B. Field, et al., Editors. Cambridge University Press: Cambridge, UK and New York, NY. pp. 709-754 (Available at: http://www.ipcc.ch/report/ar5/wg2/).
187. California Workforce Development Board. 2016. *Unified State Plan 2016-2019: Skills Attainment for Upward Mobility; Aligned Services for Shared Prosperity. California's Unified Strategic Workforce Development Plan under the Workforce Innovation and Opportunity Act (WIOA).* California Workforce Development Board: Sacramento, CA. 167 pp. (Available at: https://cwdb.ca.gov/plans_policies/wioa_unified_strategic_workforce_development_plan/)
188. Transportation Research Board (TRB). 2003. *The Transportation Workforce Challenge: Recruiting, Training, and Retaining Qualified Workers for Transportation and Transit Agencies*, Committee on Future Surface Transportation Agency Human Resource Needs, Editor. National Academies Press: Washington, DC. 186 pp. (Available at: https://www.

nap.edu/catalog/10764/the-transportation-workforce-challenge-recruiting-training-and-retaining-qualified-workers-for-transportation-and-transit-agencies)
189. The U.S. Department of Labor Employment and Training Administration. 2007. *Identifying and Addressing Workforce Challenges in America's Energy Industry, in High Growth Job Training Initiative*. DLETA: Washington, DC. 25 pp. (Available at: https://www.doleta.gov/BRG/pdf/Energy%20Report_final.pdf)
190. Cronin, B., et al. 2012. *Attracting, Recruiting and Retaining Skilled Staff for Transportation System Operations and Management.* Transportation Research Board: Washington, DC (Available at: http://www.trb.org/Main/Blurbs/166342.aspx).
191. Cronin, C.B., et al. 2013. *Building a Sustainable Workforce in the Public Transportation Industry – A Systems Approach.* Transportation Research Board: Washington, DC (Available at: https://www.nap.edu/catalog/22489/building-a-sustainable-workforce-in-the-public-transportation-industry-a-systems-approach).
192. National Infrastructure Advisory Council (NIAC). 2014. *Critical Infrastructure Security and Resilience National Research and Development Plan: Final Report and Recommendations*. NIAC Washington, DC. 245 pp. (Available at: https://www.dhs.gov/sites/default/files/publications/NIAC-CISR-RD-Plan-Report-Final-508.pdf)
193. Quadrennial Energy Review (QER) Task Force. 2017. *Electricity Workforce of the 21st Century: Changing Needs and New Opportunities, in Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review*, Quadrennial Energy Review (QER) Task Force, Editor. U.S. Department of Energy, Office of Policy: Washington, DC. pp. 5-1 - 5-37 (Available at: https://www.energy.gov/policy/initiatives/quadrennial-energy-review-qer).
194. Moser, S. 2016. *Framing and Measuring Adaptation Success. Presentation to the DOI Sandy Technical Team.* Webinar, January 8, 2016 (available upon request from author).
195. Los Angeles County Metropolitan Transportation Authority (LA Metro). 2015. *Resiliency Indicator Framework.* LA Metro (Available at: media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf) Los Angeles. 54 pp.
196. Rogers-Gibson, J. 2018. *Why Climate Change and Equity Matter for Infrastructure: An Interview with Chione Flegal of PolicyLink*, Union of Concerned Scientists. Oakland, CA (Available at: https://blog.ucsusa.org/jamesine-rogers-gibson/why-climate-change-and-equity-matter-for-infrastructure-an-interview-with-chione-flegal-of-policylink).
197. Fairchild, D. and K. Rose. 2018. *Inclusive Procurement and Contracting: Building a Field of Policy and Practice.* PolicyLink and Emerald Cities Collaborative: Oakland, CA (Available at: http://files.emeraldcities.org/media/news/Inclusive_procurement_final_03.05.18_3.pdf).
198. Pathways to Resilience (P2R) Partners. 2015. *Pathways to Resilience: Transforming Cities in a Changing Climate. P2R Partners (Movement Strategy Center, Movement Generation,* The Praxis Project, Reimagine! RP&E and the Kresge Foundation): Oakland CA (Available at: https://kresge.org/sites/default/files/Pathways-to-resilience-2015.pdf).
199. California Natural Resources Agency (CNRA). 2018. *Safeguarding California Plan: 2018 Update. California's Climate Adaptation Strategy.* CNRA: Sacramento, CA (Available at: http://resources.ca.gov/docs/climate/safeguarding/update2018/safeguarding-california-plan-2018-update.pdf).
200. PolicyLink and USC Program for Environmental and Regional Equity (PERE). 2018. *Advancing Health Equity and Inclusive Growth in the Sacramento Region.* PolicyLink and PERE: Oakland, CA and Los Angeles, CA (Available at: https://dornsife.usc.edu/pere/partnership/).
201. United Nations Office of the High Commissioner for Human Rights (UNOHCHR). 2018. *Human Rights and Climate Change. 8/9/2018* (Available at: https://www.ohchr.org/EN/Issues/hrandclimatechange/Pages/hrclimatechangeindex.aspx).
202. PolicyLink and USC Program for Environmental and Regional Equity (PERE). 2017. *Advancing Health Equity and Inclusive Growth in Fresno County.* PolicyLink and PERE: Oakland, CA and Los Angeles, CA (Available at: https://dornsife.usc.edu/pere/partnership/).
203. PolicyLink and USC Program for Environmental and Regional Equity (PERE). 2017. *An Equity Profile of the Nine-County San Francisco Bay Area Region*. PolicyLink and PERE: Oakland, CA and Los Angeles, CA (Available at: https://dornsife.usc.edu/pere/partnership/).
204. PolicyLink and USC Program for Environmental and Regional Equity (PERE). 2017. *An Equity Profile of the Los Angeles Region*. PolicyLink and PERE: Oakland, CA and Los Angeles, CA (Available at: https://dornsife.usc.edu/pere/partnership/).
205. PolicyLink and USC Program for Environmental and Regional Equity (PERE). 2017. *An Equity Profile of the Five-County San Francisco Bay Area Region: 2017 Updated Analyses and Projections.* PolicyLink and PERE: Oakland, CA and Los Angeles, CA (Available at: https://dornsife.usc.edu/pere/partnership/).
206. Brown, C., et al. 2012. Decision scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector. *Water Resources Research*, 48(9): 12 pp. (Available at: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011WR011212).
207. Poff, N.L., et al. 2015. Sustainable water management under future uncertainty with eco-engineering decision scaling. *Nature Climate Change*, 6: 25-34 (Available at: https://www.nature.com/articles/nclimate2765).
208. Steinschneider, S., et al. 2015. Expanded decision-scaling framework to select robust long-term water-system plans under hydroclimatic uncertainties. *Journal of Water Resources Planning and Management*, 141(11): 04015023 (Available at: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%29WR.1943-5452.0000536).

209. Luke, A., et al. 2017. Predicting non-stationary flood frequencies: Evidence supports an updated stationarity thesis in the United States. *Water Resources Research*, 53(7): 5469-5494 (Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2016WR019676).
210. Vahedifard, F., et al. 2017. Resilience of MSE walls with marginal backfill under a changing climate: Quantitative assessment for extreme precipitation events. *Journal of Geotechnical and Geoenvironmental Engineering*, 143(9): 04017056 (Available at: http://amir.eng.uci.edu/publications/17_JGGE_MSE_IDF.pdf).
211. Vahedifard, F., A. AghaKouchak, and N.H. Jafari. 2016. Compound hazards yield Louisiana flood. *Science*, 353(6306): 1374 (Available at: http://science.sciencemag.org/content/353/6306/1374.1).
212. Robinson, J.D., F. Vahedifard, and A. AghaKouchak. 2017. Rainfall-triggered slope instabilities under a changing climate: Comparative study using historical and projected precipitation extremes. *Canadian Geotechnical Journal*, 54: 117-127 (Available at: http://www.nrcresearchpress.com/doi/10.1139/cgj-2015-0602#.W3IgnehKh3g).
213. Gallien, T.W., B.F. Sanders, and R.E. Flick. 2014. Urban coastal flood prediction: Integrating wave overtopping, flood defenses and drainage. *Coastal Engineering*, 91: 18-28 (Available at: https://www.sciencedirect.com/science/article/pii/S0378383914000775).
214. Lopez-Cantu, T. and C. Samaras. 2018. Temporal and spatial evaluation of stormwater engineering standards reveals risks and priorities across the United States. *Environmental Research Letters*, 13: 074006 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/aac696).
215. Thorne, J., J. Bjorkman, and N. Roth. 2012. *Urban Growth in California: Projecting Growth in California (2000–2050) Under Six Alternative Policy Scenarios and Assessing Impacts to Future Dispersal Corridors, Fire Threats and Climate-Sensitive Agriculture. Publication number: CEC-500-2012-009*. California Energy Commission: Sacramento, CA (Available at: https://uc-ciee.org/downloads/Projecting%20Growth%20in%20California%20Under%20Six%20Policy%20Scenarios.pdf).
216. Wilbanks, T.J. and S.J. Fernandez. 2013. *Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the US Department of Energy in Support of the National Climate Assessment* Island Press: Washington, DC (Available at: http://www.ourenergypolicy.org/wp-content/uploads/2014/03/document_cw_01.pdf).
217. Thorne, J.H., et al. 2017. Does infill outperform climate-adaptive growth policies in meeting sustainable urbanization goals? A scenario-based study in California, USA. *Landscape and Urban Planning*, 157: 483-492 (Available at: https://www.infona.pl/resource/bwmeta1.element.elsevier-024c251a-94ff-3a9d-a381-e0ae8f0564ba).
218. Thorne, J., et al. 2014. The use of regional advance mitigation planning (RAMP) to integrate transportation infrastructure impacts with sustainability; A perspective from the USA. *Environmental Research Letters*, 9(6): 065001 (Available at: http://iopscience.iop.org/article/10.1088/1748-9326/9/6/065001).
219. Department of Water Resources (DWR) and Climate Change Technical Advisory Group (CCTAG). 2015. *Perspectives and Guidance for Climate Change Analysis.* DWR: Sacramento, CA (Available at: http://wdl.water.ca.gov/climatechange/cctag.cfm).
220. Department of Water Resources (DWR) and Climate Change Technical Advisory Group (CCTAG). 2016. *One Year Later: Influencing Climate Change Analysis throughout California*. DWR: Sacramento, CA (Available at: http://wdl.water.ca.gov/climatechange/cctag.cfm).
221. Buizer, J.L., et al. 2013. *Preparing the Nation for Change: Building a Sustained National Climate Assessment Process.* National Climate Assessment and Development Advisory Committee: Washington, DC (Available at: http://downloads.globalchange.gov/nca/NCADAC/NCADAC_Sustained_Assessment_Special_Report_Sept2013.pdf).
222. Buizer, J.L., et al. 2016. Building a sustained climate assessment process. *Climatic Change*, 135(1): 23-37 (Available at: https://www.researchgate.net/publication/283943201_Building_a_sustained_climate_assessment_process).
223. Sims, D., et al. 2016. *Taking the High Road to More and Better Infrastructure in the United States.* Natural Resosurces Defense Council: Washington, DC (Available at: https://www.nrdc.org/resources/taking-high-road-more-and-better-infrastructure-united-states).
224. Re:focus. 2015. *A Roadmap for Resilience: Investing in Resilience, Reinvesting in Communities.* RE:invest collaborative (Bechtel Corporation, Akin Gump Strauss Hauer & Feld, Wall Street Without Walls) (Available at: http://www.refocuspartners.com/reinvest/).
225. Northcross, M., et al. 2017. *Finance Guide For Resilient By Design Bay Area Challenge Design Teams: Final Version 1.0.* NHA Advisors: San Rafael, CA (Available at: http://www.resilientbayarea.org/finance-tools/).
226. 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: Washington, DC (Available at: https://www.gao.gov/products/GAO-17-3).
227. Hallegatte, S., et al. 2012. *Investment Decision Making Under Deep Uncertainty: Application to Climate Change, in Policy Research Working Paper.* World Bank: Washington, DC (Available at: https://openknowledge.worldbank.org/handle/10986/12028).
228. Ray, P.A. and C.M. Brown. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design: The Decision Tree Framework.* The World Bank: Washington, DC (Available at: https://openknowledge.worldbank.org/handle/10986/22544).

229. Boston Planning and Development Agency. 2017. *Climate Change Resiliency and Preparedness Checklist*. Boston Planning and Development Agency: Boston, MA (Available at: http://www.bostonplans.org/planning/planning-initiatives/article-37-green-building-guidelines).
230. Office of Planning and Research (OPR). 2018. *Planning and Investing for a Resilient California: A Guidebook for State Agencies*. OPR: Sacramento, CA (Available at: http://opr.ca.gov/docs/20171115-Building_a_Resilient_CA.pdf).
231. ASCE and Eno. 2017. *Maximizing the Value of Investments Using Life Cycle Cost Analysis.* ASCE and Eno: Reston, VA and Washington, DC (Available at: http://www.asce.org/life_cycle_cost_analysis_report/).
232. Solecki, W., et al. 2010. Climate protection levels. *Annals of the New York Academy of Sciences*, 1196(1): 293-352 (Available at: https://www.researchgate.net/publication/44670904_Climate_protection_levels_incorporating_climate_change_into_design_and_performance_standards_New_York_City_Panel_on_Climate_Change).
233. Schwartz, P. 1996. *The Art of the Long View*. New York, NY: Doubleday (Summary available at: https://www.slideshare.net/ramadd1951/summary-the-art-of-the-long-view).
234. Lempert, R., et al. 2013. *Making Good Decisions Without Predictions: Robust Decision Making for Planning Under Deep Uncertainty.* RAND Corporation: Santa Monica, CA (Available at: https://www.rand.org/pubs/research_briefs/RB9701.html).
235. Lempert, R.J., S.W. Popper, and S.C. Bankes. 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Longer-Term Policy Analysis*. Santa Monica, CA: RAND (Available at: https://www.rand.org/content/dam/rand/pubs/monograph_reports/2007/MR1626.pdf).
236. Lempert, R.J. and M.T. Collins. 2007. Managing the risk of uncertain threshold responses: Comparison of robust, optimum, and precautionary approaches. *Risk Analysis,* 27: 1009-1026 (Available at: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.2007.00940.x).
237. Brown, C. and R.L. Wilby. 2012. An alternate approach to assessing climate risks. *Eos, Transactions American Geophysical Union*, 92(41): 401-402 (Available at: http://www.value-cost.eu/sites/default/files/BrownWilby2012EO410001_rga.pdf).
238. Haasnoot, M., et al. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2): 485-498 (Available at: https://www.sciencedirect.com/science/article/pii/S095937801200146X).
239. Neufville, R.d. and S. Scholtes. 2011. *Flexibility in Engineering Design*. Cambridge, MA: The MIT Press.
240. Walters, C. 1986. Adaptive Management of Renewable Resources. New York: MacMillan Publishing Co.
241. Gunderson, L.H. 1999. Resilience, flexibility and adaptive aanagement - Antidotes for spurious certitude? *Conservation Ecology*, 3(1): 7 (Available at: http://www.consecol.org/vol3/iss1/art7/).
242. UK Environment Agency. 2012. *Thames Estuary 2100 Plan: Managing flood risk through London and the Thames estuary.* UK Environment Agency: London (Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/322061/LIT7540_43858f.pdf).
243. da Silva, J., S. Kernaghan, and A. Luque. 2012. A systems approach to meeting the challenges of urban climate change. International *Journal of Urban Sustainable Development*, 4(2): 125-145 (Available at: http://www.tandfonline.com/loi/tjue120).
244. Satterthwaite, D. and D. Dodman. 2016. Towards resilience and transformation for cities within a finite planet. *Environment and Urbanization*, 25(2): 291-298 (Available at: http://journals.sagepub.com/doi/full/10.1177/0956247813501421).
245. Pallardy, R. 2018. *Deepwater Horizon oil spill of 2010* (Available at: https://www.britannica.com/event/Deepwater-Horizon-oil-spill-of-2010).
246. World Nuclear Association. 2018. *Fukushima Accident* (Available at: http://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-accident.aspx)
247. Chester, M.V. and B. Allenby. 2018. Toward adaptive infrastructure: Flexibility and agility in a non-stationarity age. *Sustainable and Resilient Infrastructure*: 1-19 (Available at: https://www.tandfonline.com/doi/abs/10.1080/23789689.2017.1416846).
248. Kim, Y., et al. 2017. Fail-safe and safe-to-fail adaptation: Decision-making for urban flooding under climate change. *Climatic Change*, 145: 387-412 (Available at: https://ideas.repec.org/a/spr/climat/v145y2017i3d10.1007_s10584-017-2090-1.html).
249. Möller, N. and S.O. Hansson. 2008. Principles of engineering safety: Risk and uncertainty reduction. *Reliability Engineering & System Safety,* 93(6): 798-805 (Available at: https://www.sciencedirect.com/science/article/pii/S0951832007001251).
250. Park, J., et al. 2013. Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, 33(3): 356-367 (Available at: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1539-6924.2012.01885.x).
251. Ahern, J. 2011. From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning*, 100: 341-343 (Available at: https://scholarworks.umass.edu/cgi/viewcontent.cgi?article=1008&context=larp_grad_research)

252. Tye, M.R., G.J. Holland, and J.M. Done. 2015. Rethinking failure: Time for closer engineer-scientist collaborations on design. Proceedings of the Institution of Civil Engineers - *Forensic Engineering*, 168: 49-57 (Available at: https://www.icevirtuallibrary.com/doi/abs/10.1680/feng.14.00004).
253. Ayyub, B.M., et al. 2018. *Climate Resilient Infrastructure: A Manual of Practice on Adaptive Design and Risk* Management. Reston, VA: ASCE (forthcoming).
254. Wright, K., K. Whitehouse, and J. Curti. 2017. *Voluntary Resilience Standards: An Assessment of the Emergent Market for Resilience in the Built Environment.* Report Prepared for the Energy, Kresge and Barr Foundations. Meister Consultants Group: Boston, MA (Available at: http://www.mc-group.com/voluntary-resilience-standards-an-assessment-of-the-emerging-market-for-resilience-in-the-built-environment/).
255. Moran, D. and E. Mihaly. 2018. *Climate Adaptation and Liability: A Legal Primer and Workshop Summary Report. Conservation Law Foundation* Boston Green Ribbon Commission: Boston, MA. 64 pp. (Available at: https://www.clf.org/wp-content/uploads/2018/01/GRC_CLF_Report_R8.pdf)
256. Supreme Court of California. 2015. *Randall Keith HAMPTON et al., Plaintiffs and Appellants, v. COUNTY OF SAN DIEGO, Defendant and Respondent*. San Francisco (Available at: https://caselaw.findlaw.com/ca-supreme-court/1720566.html).
257. Institute for Sustainable Communities (ISC) and American Society for Adaptation Professionals (ASAP). 2017. *New England Climate Network Workshop Proceedings in New England Climate Network Workshop: Funding, Finance, and Investment Solutions for Climate Adaptation.* 2017. ISC, ASAP.
258. Arndt, C. 2016. *Infrastructure Spending Trends*, Washington, DC: American Action Forum (AAF). (Available at: http://americanactionforum.org).
259. Gray, G. 2015. *Trends in Federal Infrastructure Spending,* AAF, Editor. Washington, DC: American Action Forum (Available at: https://americanactionforum.org).
260. Governing. 2015. *Public Infrastructure spending for state and local governments*. Governing (Available at: http://www.governing.com/gov-data/state-local-government-construction-spending.html).
261. Elmer, V. and A. Leigland. 2014. *Infrastructure Planning and Financing: A Smart and Sustainable Guide for Local Practitioners.* New York, NY: Routledge.
262. Taylor, M. 2011. *A Ten-Year Perspective: California Infrastructure Spending.* Legislative Analyst's Office (LAO): Sacramento, CA (Available at: https://lao.ca.gov/Publications/Detail/2509).
263. Rueben, K. and S. de Alth. 2005. *Infrastructure financing in California, in California 2025: Taking on the Future,* E. Hanak and M. Baldassare, Editors. Public Policy Institute of California: San Francisco, CA. pp. 83-112 (Available at: http://www.ppic.org/publication/california-2025-taking-on-the-future/)
264. Government Accounting Office (GAO). 2000. *U.S. Infrastructure: Funding Trends and Opportunities to Improve Investment Decisions,* Report to Congress. GAO: Washington, DC (Available at: https://www.gao.gov/products/RCED/AIMD-00-35).
265. Hanak, E. and D. Reed. 2009. *Paying for Infrastructure: California's Choices, in At Issue: Critical Facts on Critical Issues.* San Francisco, CA: Public Policy Institute of California (Available at: http://www.ppic.org/content/pubs/atissue/AI_109EHAI.pdf).
266. Department of Finance (DOF). 2018. *2018 California Five-Year Infrastructure Plan*. Sacramento, CA: DOF (Available at: http://www.dof.ca.gov/Reports/Other/).
267. Caltrans. 2015. *2015 Five-Year Maintenance Plan Final.* Caltrans: Sacramento, CA (Available at: http://www.dot.ca.gov/docs/2015_Five-Year_Maintenance_Plan.pdf).
268. Department of Finance (DOF). 2007. *2007 California Five-Year Infrastructure Plan*. Sacramento, CA: DOF (Available at: http://www.dof.ca.gov/Reports/Other/).
269. California Forward. 2015. *Financing the Future: How Will California Pay for Tomorrow?* (Available at: https://cafwd.app.box.com/s/wg15ym5keehsmugvyjz5hw4zr3g8246p): Sacramento, CA: California Forward.
270. Department of Finance (DOF). 2016. *2016 California Five-Year Infrastructure Plan.* Sacramento, CA: DOF (Available at: http://www.dof.ca.gov/Reports/Other/).
271. Targ, N.W. and D.R. Golub. 2014. *Enhanced Infrastructure Financing Districts (SB 628, Beall): A New Power Tool for Growth in California, in hklaw.com*. Holland & Knight Law Offices. (Available at: https://www.hklaw.com/Publications/Enhanced-Infrastructure-Financing-Districts-SB-628-Beall-611-612-2014/).
272. Silva, F. and M. Pisano. 2015. *A New Tool for Urban Economic Development: EIFDs demystified.* The Planning Report: Insider's Guide to Planning and Infrastructure (June): 7 pp. (Available at: https://www.planningreport.com/2015/2006/2003/new-tool-urban-economic-development-eifds-demystified).
273. Day, L. 2016. *A New Financing Tool for California: Enhanced Infrastructure Finance Districts, in Planetzen*. Planitzen Press: Los Angeles, CA (Available at: http://cceda.com/wp-content/uploads/EIFD-Resource-Guide-Feb-20161.pdf).
274. California Local Government Finance Almanac. 2018. *Local Revenue Measure Results*, June 2018. Davis, CA: California City Finance, 11 pp. (Available at: http://californiacityfinance.com/Votes1806final.pdf).
275. National Institute of Building Sciences (NIBS). 2017. *Natural Hazard Mitigation Saves: 2017 Interim Report.* Washington, DC: NIBS (Available at: https://www.nibs.org/page/mitigationsaves).

276. Moser, S.C., et al. 2014. Ch. 25: Coastal Zone Development and Ecosystems, in *Climate Change in the United States: The Third National Climate Assessment,* J.M. Melillo, T.T.C. Richmond, and G.W. Yohe, Editors. U.S. Global Change Research Program: Washington, DC. pp. 579-618 (Available at: https://www.globalchange.gov/nca3-downloads-materials).
277. Ayyub, B.M. 2014. *Risk Analysis in Engineering and Economics*. 2nd ed. Boca Raton, FL: Chapman and Hall/CRC Press.
278. Gilbert, S. and M. Ayyub Bilal. 2016. Models for the economics of resilience. ASCE-ASME *Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 2(4): 04016003 (Available at: http://ctsm.umd.edu/wp-content/uploads/2017/02/GilbertAyyub-ResilienceEcon2016.pdf).
279. Moser, S.C., et al. 2018. Adaptation Finance Challenges: Characteristic Patterns Facing California Local Governments and Ways to Overcome Them. *California's Fourth Climate Change Assessment. Publication number CCCA4-CNRA-2018-007*. California Natural Resources Agency: Sacramento, CA.
280. Moody's Investor Service. 2017. *Climate change is forecast to heighten US exposure to economic loss placing short- and long-term credit pressure on US states and local governments*. New York, NY: Moody's Investor Service (Available at: https://www.moodys.com/research/Moodys-Climate-change-is-forecast-to-heighten-US-exposure-to--PR_376056).
281. Standards & Poor's Ratings Services. 2014. *Climate Change Is A Global Mega-Trend For Sovereign Risk, in S&P's Ratings Direct*. New York, NY: S&P Ratings Services (Available at: http://www.maalot.co.il/publications/GMR20140518110900.pdf).
282. Office of the President. 2018. *Legislative Outline for Rebuilding Infrastructure in America*. Washington, DC: The White House (Available at: https://www.whitehouse.gov/wp-content/uploads/2018/02/INFRASTRUCTURE-211.pdf).
283. Galston, W.A. 2018. *Trump's infrastructure plan: The good, the bad, and the biblical.* Washington, DC: The Brookings Institute (Available at: https://www.brookings.edu/blog/fixgov/2018/02/12/trumps-infrastructure-plan-the-good-the-bad-and-the-biblical/).
284. Levy, D.L., et al. 2018. *Financing Climate Resilience: Mobilizing Resources and Incentives to Protect Boston from Climate Risks.* Sustainable Solutions Lab, UMass Boston Boston, MA. 64 pp. (Available at: http://www.umb.edu/editor_uploads/images/centers_institutes/sustainable_solutions_lab/Financing_Climate_Resilience_April_2018.pdf).
285. Arnott, J.C., S.C. Moser, and K.A. Goodrich. 2016. Evaluation that counts: A review of climate change adaptation indicators & metrics using lessons from effective evaluation and science-practice interaction. *Environmental Science & Policy,* 66: 383-392 (Available at: https://ideas.repec.org/a/eee/enscpo/v66y2016icp383-392.html).
286. Taylor, M. 2012. *Maximizing State Benefits From Public-Private Partnerships.* Sacramento, : Legislative Analyst's Office (LAO) (Available at: https://lao.ca.gov/reports/2012/trns/partnerships/P3_110712.pdf).
287. Holeywell, R. 2013. *Public-Private Partnerships Are Popular, But Are They Practical?* Governing the States and Localities, Available online at: http://www.governing.com/topics/transportation-infrastructure/gov-public-private-popular.html).
288. Ayyub, B.M. and L. Parker. 2011. Financing nuclear liability. *Science*, 334: 1494 (Available at: https://www.researchgate.net/publication/51884190_Financing_Nuclear_Liability).
289. Ayyub Bilal, M., A. Pantelous Athanasios, and J. Shao. 2016. Toward resilience to nuclear accidents: Financing nuclear liabilities via catastrophe risk bonds. ASCE-ASME *Journal of risk and uncertainty in engineering systems, Part B: Mechanical engineering*, 2(4): 041005 (Available at: https://ascelibrary.org/doi/abs/10.1115/1.4033518?src=recsys).
290. Milken Institute. 2018. *Growing the U.S. Green Bond Market. Volume 2: Actionable Strategies and Solutions. A Report from a Milken Institute Financial Innovations Lab.* Los Angeles: Milken Institute (Available at: https://www.treasurer.ca.gov/growing-the-u.s.-green-bond-mkt-vol2-final.pdf).
291. Milken Institute. 2017. *Growing the U.S. Green Bond Market. Volume 1: The Barriers and Challenges. A Report from a Milken Institute Financial Innovations Lab.* Los Angeles: Milken Institute (Available at: https://www.treasurer.ca.gov/greenbonds/publications/reports/1.pdf).
292. Morrison-Saunders, A., et al. 2015. Demonstrating the benefits of impact assessment for proponents. *Impact Assessment and Project Appraisal*, 33(2): 108-115 (Available at: https://www.tandfonline.com/doi/pdf/10.1080/14615517.2014.981049).
293. Bennett, M., P. James, and L. Klinkers, eds. 2017 (1999). *Sustainable Measures: Evaluation and Reporting of Environmental and Social Performance*. Routledge: London and New York.
294. Green, G.P. and A. Haines. 2015. *Asset Building & Community Development*. 4th ed. Thousand Oaks, CA: Sage.
295. Arena, M., et al. 2016. Social Impact Bonds: Blockbuster or Flash in a Pan? *International Journal of Public Administration*, 39(12): 927-939 (Available at: https://www.tandfonline.com/doi/abs/10.1080/01900692.2015.1057852).
296. Bohn, S. 2014. *California's Need for Skilled Workers*. PPIC: San Francisco, CA. 12 pp. (Available at: http://www.ppic.org/content/pubs/report/R_914SBR.pdf)
297. Terplan, E., et al. 2014. *Economic Prosperity Strategy: Improving Economic Opportunity for the Bay Area's Low- and Moderate-Wage Workers*. SPUR: San Francisco, CA (Available at: https://www.spur.org/publications/spur-report/2014-10-01/economic-prosperity-strategy).

298. Leiserowitz, A., et al. 2018. *Climate Change in the American Mind: March 2018*. New Haven, CT: Yale University, Yale Program on Climate Change Communication and George Mason University, Center for Climate Change Communication (Available at: http://climatecommunication.yale.edu/publications/climate-change-american-mind-march-2018/).
299. Hollander, R.D., F.F. Benya, and C.H. Fletcher. 2014. *The Climate Change Educational Partnership: Climate Change, Engineered Systems, and Society: A Report of Three Workshops*. Washington, DC: National Academies Press (Available at: http://nap.edu/18957).
300. Moser, S.C., J. Coffee, and A. Seville. 2017. *Rising to the Challenge, Together*. The Kresge Foundation: Troy, MI (Available at: https://kresge.org/content/rising-challenge-together).
301. Borrego, M. and J. Bernhard. 2011. The Emergence of engineering education research as an internationally connected field of inquiry. *Journal of Engineering Education*, 100(1): 14-47 (Available at: https://onlinelibrary.wiley.com/doi/abs/10.1002/j.2168-9830.2011.tb00003.x).
302. Halbe, J., J. Adamowski, and C. Pahl-Wostl. 2015. The role of paradigms in engineering practice and education for sustainable development. *Journal of Cleaner Production*, 106: 272-282 (Available at: http://professor.pucgoias.edu.br/SiteDocente/admin/arquivosUpload/10139/material/Seminario_23_11_2015_Santiago_Daniela.pdf).
303. Blaney, L., et al. 2018. Another grand challenge: Diversity in environmental engineering. Environmental Engineering *Science*, 35(6): 568-572 (Available at: https://www.liebertpub.com/doi/abs/10.1089/ees.2017.0337).
304. Shuman, L.J., M. Besterfield-Sacre, and J. McGourty. 2005. The ABET "professional skills" — Can they be taught? Can they be assessed? *Journal of Engineering Education,* 94(1): 41-55 (Available at: http://bioinfo.uib.es/~joe/semdoc/PlansEstudis/ABET_Criteria_PTE/AbetProfessionalSkills_JEE2005.pdf).
305. American Society for Engineering Education (ASEE). 2010 (1994). *The Green Report - Engineering Education for a Changing World.* Engineering Deans Council and Corporate Roundtable of the American Society for Engineering Education Washington, DC (Available at: https://www.asee.org/member-resources/reports).
306. Jesiek, B.K., et al. Boundary spanning and engineering: A qualitative systematic review. *Journal of Engineering Education*, online first. (Available at: https://onlinelibrary.wiley.com/doi/full/10.1002/jee.20219).
307. California Natural Resources Agency. 2009. *The California Climate Adaptation Strategy 2009. A Report to the Governor of the State of California (Draft)*. Natural Resources Agency: Sacramento, CA (Available at: http://resources.ca.gov/docs/climate/Statewide_Adaptation_Strategy.pdf).
308. California Emergency Management Agency (CalEMA) and California Natural Resources Agency (CNRA). 2012. *California Adaptation Planning Guide*. CalEMA and CNRA: Mather, CA and Sacramento, CA. 56 pp. (Available at: http://resources.ca.gov/docs/climate/01APG_Planning_for_Adaptive_Communities.pdf)
309. California Coastal Commission (CCC). 2015. *California Coastal Commission Sea Level Rise Policy Guidance: Interpretive Guidelines for Addressing Sea Level Rise in Local Coastal Programs and Coastal Development Permits, San Francisco*, CA: CCC (Available at: https://documents.coastal.ca.gov/assets/slr/guidance/August2015/0_Full_Adopted_Sea_Level_Rise_Policy_Guidance.pdf).
310. Legislative Analyst's Office (LAO). 2018. *Infrastructure Procurement Approaches: How does the state build infrastructure?* (Available at: https://lao.ca.gov/Infrastructure/Procurement).
311. Murdoch, J. and W. Hughes. 2007. *Construction Contracts: Law and Management.* 4th ed. London: Taylor & Francis E-library.
312. Moser, S.C. and J.A. Ekstrom. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the National Academy of Sciences of the United States of America*, 107(51): 22026-22031 (Available at: http://www.pnas.org/content/107/51/22026) (See also: http://www.energy.ca.gov/2011publications/CEC-500-2011-004/CEC-500-2011-004.pdf).
313. Moser, S.C., et al. 2018. Growing Effort, Growing Challenge: Findings from the 2016 CA Coastal Adaptation Needs Assessment Survey. *California's Fourth Climate Change Assessment. Publication Number CCCA4-EXT-2018-009*. California Natural Resources Agency

1 Assembly Bill No. 2800
Chapter 580

Link to Bill Language

An act to add and repeal Section 71155 of the Public Resources Code, relating to climate change.

[Approved by Governor September 24, 2016. Filed with Secretary of State September 24, 2016.]

LEGISLATIVE COUNSEL'S DIGEST

AB 2800, Quirk. Climate change: infrastructure planning.

Existing law requires the Natural Resources Agency, by July 1, 2017, and every 3 years thereafter, to update the state's climate adaptation strategy to identify vulnerabilities to climate change by sectors and priority actions needed to reduce the risks in those sectors.

This bill, until July 1, 2020, would require state agencies to take into account the current and future impacts of climate change when planning, designing, building, operating, maintaining, and investing in state infrastructure. The bill, by July 1, 2017, and until July 1, 2020, would require the agency to establish a Climate-Safe Infrastructure Working Group for the purpose of examining how to integrate scientific data concerning projected climate change impacts into state infrastructure engineering, as prescribed. The bill would require the working group to consist of registered professional engineers with specified relevant expertise from the Department of Transportation, the Department of Water Resources, the Department of General Services, and other relevant state agencies; scientists with specified expertise from the University of California, the California State University, and other institutions; and licensed architects with specified relevant experience. The bill would require the working group, by July 1, 2018, to make specified recommendations to the Legislature and the Strategic Growth Council.

Vote: majority   Appropriation: no   Fiscal Committee: yes   Local Program: no

THE PEOPLE OF THE STATE OF CALIFORNIA DO ENACT AS FOLLOWS:

SECTION 1. The Legislature finds and declares all of the following:

(a) The impacts of climate change are already being felt in California and include record-breaking drought, wildfires, flooding, sea level rise, coastal erosion, and heat waves. These impacts are projected to worsen with a future punctuated by what are now considered extreme weather events.

(b) As the climate warms, California will need to design and maintain infrastructure, including, but not limited to, roads, bridges, buildings, and water systems, to withstand increasingly severe impacts.

(c) The scientific community is developing sound scientific understanding of projected impacts from climate change. The engineers responsible for overseeing, designing, and building state infrastructure must consider the influence of climate change impacts on siting and design standards and specifications.

(d) As California spends billions of dollars on infrastructure, expecting it to last many decades, state engineers should be provided with practicable information on projected climate change impacts that they should consider when establishing standards and planning and designing structures that are critical to California's economy and public safety.

(e) Prolonged heat waves, extreme precipitation events, severe drought, increasing wildfires, and other potentially dangerous climate change impacts will require significant changes in designing and building projects, such as roads, bridges, buildings, and water infrastructure, and require planning for the resilience and restoration of natural systems.

(f) There is a significant body of climate science being developed and continually updated to inform decisionmakers and provide guidance on the predicted impacts. Infrastructure project planning and design must incorporate design standards and specifications for climate change impacts.

(g) Due to Executive Order B-30-15, current efforts by state agencies provide built-in resources, processes, and expertise that can be utilized to provide coordination between scientists and those responsible for designing, building, and overseeing critical state infrastructure.

SEC. 2. Section 71155 is added to the Public Resources Code, to read:
71155. (a) Consistent with this part, state agencies shall take into account the current and future impacts of climate change when planning, designing, building, operating, maintaining and investing in state infrastructure.

(b) (1) By July 1, 2017, the agency shall establish a Climate-Safe Infrastructure Working Group for the purpose of examining how to integrate scientific data concerning projected climate change impacts into state infrastructure engineering, including oversight, investment, design, and construction.

(2) The working group shall consist of the following:
(A) Professional engineers registered in accordance with Chapter 7 (commencing with Section 6700) of Division 3 of the Business and Professions Code with relevant expertise in state infrastructure design from the Department of Transportation, the Department of Water Resources, the Department of General Services, and other relevant state agencies, as applicable.

(B) Scientists from the University of California, the California State University, and other institutions who have expertise in climate change projections and impacts across California.

(C) Licensed architects with relevant experience in state infrastructure design, as applicable.

(3) The two groups specified in subparagraphs (A) and (B) of paragraph (2) shall be equitably represented in the membership of the working group, to the extent reasonable and appropriate.

(4) The working group shall work in coordination with other state climate adaptation planning efforts and shall consider and build upon existing information produced by the state, including information from the most recent California Climate Change Assessment conducted pursuant to Executive Order S-3-05, the plan, and the State of California Sea-Level Rise Guidance Document completed pursuant to Executive Order S-13-08, among other resources.

(5) The working group shall work in coordination with other state agencies that advance sustainability in infrastructure, including the council and the Government Operations Agency.

(c) The working group shall consider and investigate, at a minimum, the following issues:
(1) The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design.

(2) The critical information that engineers responsible for infrastructure design and construction need to address climate change impacts.

(3) How to select an appropriate engineering design for a range of future climate scenarios as related to infrastructure planning and investment.

(d) (1) By July 1, 2018, the working group shall make recommendations to the Legislature that address the issues listed in subdivision (c), including recommendations for all of the following:
(A) Integrating scientific knowledge of projected climate change impacts into state infrastructure design.

(B) Addressing critical information gaps identified by the working group.

(C) A platform or process to facilitate communication between climate scientists and infrastructure engineers.

(2) By July 1, 2018, the recommendations submitted pursuant to paragraph (1) also shall be submitted to the council to inform its review, conducted pursuant to Section 75125, of the five-year infrastructure plan developed pursuant to Article 2 (commencing with Section 13100) of Chapter 2 of Part 3 of Division 3 of Title 2 of the Government Code.
(e) This section shall become inoperative on July 1, 2020, and, as of January 1, 2021, is repealed, unless a later enacted statute, that becomes operative on or before January 1, 2021, deletes or extends the dates on which it becomes inoperative and is repealed.

2 Climate-Safe Infrastructure Working Group Members, Project Team & Co-Facilitators

Climate Safe Infrastructure Working Group Members

Dr. Amir Aghakouchak, P.E., University of California, Irvine
Amir AghaKouchak is an Associate Professor of Civil and Environmental Engineering at the University of California, Irvine. His research focuses on climate extreme and crosses the boundaries between hydrology, climatology, remote sensing. Amir is the principal investigator of several research grants funded by the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), and the United States Bureau of Reclamation (USBR). Website: http://amir.eng.uci.edu/

Nancy Ander, P.E., California Department of General Services
Nancy Ander is the Deputy Director of the Office of Sustainability at the Department of General Services (DGS). She is responsible for greening state facilities. Her responsibilities include the development of sustainability policies and implementation of energy efficiency improvements, solar and wind installations, electric vehicle infrastructure development, recycling and other areas within state facilities. Nancy's team strives to ensure that state buildings are leading by example in advancing California's clean energy and sustainability goals.

Prior to this role, Nancy was a Principal Manager at Southern California Edison (SCE), one of the state's four major investor-owned utilities. At SCE, Nancy led the overall strategy for SCE's energy efficiency and demand response programs in alignment with regulatory requirements and in consideration of grid implications. Additionally, Nancy oversaw the development of climate action plans at local governments and large institutions.
Before coming to SCE, Nancy supported public policy at the California Energy Commission (CEC). At the CEC she developed energy codes and managed research to develop innovative technologies in Renewables and Energy Efficiency. Most notably, Nancy developed and managed the first Public Interest Research program for energy efficiency at the CEC and helped to lead the program to national prominence. Nancy has a bachelor's degree in Civil Engineering and is a registered CA engineer.

John Andrew, P.E., California Department of Water Resources

John T. Andrew is Assistant Deputy Director of the California Department of Water Resources, where since 2006 he has overseen the Department's climate change activities. His previous organizational affiliations include the Stege Sanitary District, the CALFED Bay-Delta Program, the California Department of Health Services, the Lawrence Berkeley National Laboratory, and the US Environmental Protection Agency. Andrew has over 25 years of experience in water resources and environmental engineering and holds degrees in Civil Engineering and Public Policy from the University of California at Berkeley.

Gurdeep Bhattal, P.E., California Department of Transportation

Gurdeep Bhattal is currently working as a Senior Transportation Engineer in the Hydraulics and Stormwater Branch within the California Department of Transportation (Caltrans) Headquarters Division of Design. As both a registered Civil and Mechanical Engineer, Gurdeep provides support to Caltrans Districts Statewide by developing guidance, policies, procedures, and standards for hydraulic designs for roadways and associated facilities. During 19 years with Caltrans, he designed drainage facilities, addressed failures of drainage facilities, and provided drainage designs for highway projects. During 10-years as a Project Engineer with a sugar manufacturing company, he developed designs for fluid flows involving pumping/piping/heat exchanger systems, developed pump curves, completed mass balances of fluid flows, stream flows and related power generation at a 4.5 MW power plant.

Martha Brook, P.E., California Energy Commission

Martha has been at the California Energy Commission (CEC) for over two decades; there she has become a highly respected expert in long term energy demand forecasting, building energy efficiency standards, and research and development of energy efficient technologies for residential and commercial buildings. Martha is currently the technical advisor to Commissioner Andrew McAllister, where she provides support on all areas of building and appliance energy efficiency, as well as energy data collection, organization, analysis and publication.

Martha has a Bachelor of Science in Environmental Resources Engineering from California State University, Humboldt and is a California Professional Mechanical Engineer.

Dr. Dan Cayan, University of California, San Diego: Scripps Institution of Oceanography

Dr. Dan Cayan is a climate researcher at the Scripps Institution of Oceanography, UC San Diego. Cayan's work is aimed at understanding climate variability and changes over the Pacific Ocean and North America and how they affect the water cycle and related sectors over western North America. He has specific interests in regional climate in California and has played a leading role in a series of California climate vulnerability and adaptation assessments. He is also involved with programs to deliver improved climate information to decision makers: The California Nevada Applications Program (CNAP), sponsored by the NOAA RISA Program and the Southwest Climate Science Center, sponsored by the US Geological Survey, Department of Interior.

James Deane A.I.A., C.D.T., LEED AP, P.M.P., California High Speed Rail Authority; Parsons Brinckerhoff

James brings more than 28 years of experience in project, program, and enterprise management and has successfully led teams in the definition, design, documentation, and delivery of their vision across an expansive range of planning, infrastructure, and facility types. He has worked on several internationally significant programs and projects such as London 2012, Masdar, and Astana Expo 2017. As the Senior Supervising Architect of the Rail Operations Group, Development and Design Section for the California High-Speed Rail Authority, James is responsible for developing the program-wide station design delivery mechanisms and is keenly focused the integration of the States and the Authority's sustainability and resilience goals and objectives.

Dr. Noah Diffenbaugh, Stanford University: Stanford Woods Institute for the Environment

Dr. Noah Diffenbaugh is a Professor in the School of Earth, Energy and Environmental Sciences and Kimmelman Family Senior Fellow in the Woods Institute for the Environment at Stanford University. He studies the climate system, including the processes by which climate change could impact extreme weather, water resources, agriculture, and human health. Dr. Diffenbaugh is currently Editor-in-Chief of the peer-review journal Geophysical Research Letters. He has served as a Lead Author for Working Group II of the Intergovernmental Panel on Climate Change (IPCC), and has provided testimony and scientific expertise to the White House, the Governors of California and Indiana, and U.S. Congressional offices. Dr. Diffenbaugh is a recipient of the James R. Holton Award from the American Geophysical Union, a CAREER award from the National Science Foundation, and a Terman Fellowship from Stanford University. He has also been recognized as a Kavli Fellow by the U.S. National Academy of Sciences, and as a Google Science Communication Fellow.

Dr. David Groves, RAND Water and Climate Resilience; Pardee Rand Graduate School

David Groves is codirector of the RAND Water and Climate Resilience Center, a senior policy researcher at the RAND Corporation, and a professor at the Pardee RAND Graduate School. He is a key developer of new methods for decision-making under deep uncertainty, and works directly with natural resources managers worldwide to improve planning for the uncertain future. His primary practice areas include water resources management and coastal resilience planning, with an emphasis on climate adaptation and resilience.

Groves has worked with major water agencies throughout the United States, including the U.S. Bureau of Reclamation, California Department of Water Resources, Metropolitan Water District of Southern California, and Denver Water, helping them to address climate variability and change in their planning. He also works internationally, most recently in China, Peru, and Mexico. Groves also works on coastal sustainability issues, most notably in the Bay Delta, South Florida, and Coastal Louisiana. In particular, he led a RAND team that developed the planning framework and decision support tool used to formulate Louisiana's 50-year, $50 billion Coastal Master Plan.

Groves received degrees in Geological and Environmental Sciences (B.S.) and Earth Systems (M.S.) from Stanford University, an M.S. in Atmospheric Sciences from the University of Washington, and a Ph.D. in policy analysis from the Pardee RAND Graduate School.

Dr. Kristin Heinemeier, P.E., University of California, Davis: Energy Efficiency Center

Dr. Kristin Heinemeier is Principal Engineer with the University of California Davis' Energy Efficiency Center. For over 30 years, in different capacities, she has focused on the gaps between the way things are supposed to work and how they really work, and ways to realize efficiency in the real world. Her work seeks to improve programs, codes and standards, technologies and industry best practices by focusing on substantial transformation of the way that heating, ventilation, and air-conditioning system installation, maintenance, and service are delivered. Kristin was one of the founders of the Western HVAC Performance Alliance. Her other key partners include the California Community Colleges, California Energy Commission, California Public Utilities Commission, and utility Emerging Technology programs. Kristin was awarded the ASHRAE Fellow award, in recognition of many years of service to the industry. Prior to her appointment at UC Davis, she worked for Lawrence Berkeley National Lab, Honeywell International, Texas A&M University, and PECI. She received her Ph.D. in building science from the University of California, Berkeley and is a licensed mechanical engineer.

Dr. Robert Lempert, RAND Corporation: Frederick S. Pardee Center for Longer Rare Global Policy and the Future Human Condition

Robert Lempert is a principal researcher at the RAND Corporation and Director of the Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition. His research focuses on risk management and decision-making under conditions of deep uncertainty. Dr. Lempert's work aims to advance the state of art for organizations managing risk in today's conditions of face-paced, transformative, and surprising change and helping organizations adopt these approaches to help make proper stewardship of the future more commonly practiced. Dr. Lempert is co-PI of the NSF-funded Sustainable Climate Risk Management (SCRIM) research network and co-PI of a MacArthur-foundation funded project conducting urban climate risk management in several U.S. cities. Dr. Lempert is a Fellow of the American Physical Society, a member of the Council on Foreign Relations, a chapter lead for the Fourth US National Climate Assessments and a lead author for Working Group II of the United Nation's Intergovernmental Panel on Climate Change (IPCC). Dr. Lempert was the Inaugural EADS Distinguished Visitor in Energy and Environment at the American Academy in Berlin and the inaugural president of the Society for Decision Making Under Deep Uncertainty (http://www.deepuncertainty.org). A Professor of Policy Analysis in the Pardee RAND Graduate School, Dr. Lempert is an author of the book Shaping the Next One Hundred Years: New Methods for Quantitative, Longer-Term Policy Analysis.

Dr. Cris Liban, P.E., ENV SP, Los Angeles County Metropolitan Transportation Authority; City of Los Angeles; National Council for Environmental Policy and Technology, USEPA

Dr. Cris B. Liban is an internationally recognized expert in the field of resource management, energy technologies, transportation, environmental protection, and sustainability. Dr. Liban's work has been making a tremendous impact around the world as his visionary framework and processes of environmental stewardship is continually used as a model of many similar programs. His award-winning and ISO 14001:2015 certified environmental and sustainability program has become the US national template in the transportation industry. In this program of empowerment, he has directly inspired thousands of Angelenos (and many in the transit industry around the world) to become environmental and sustainability leaders not only in their place of work, but most importantly in their families, communities and beyond.

He is currently the Executive Officer for Environment and Sustainability at the LA County Metropolitan Transportation Authority. LA Metro is the 3rd largest transportation agency in the United States in the 20th largest economy in the world. He was appointed by President Barack Obama's US Environmental Protection Agency Administrator as a Council Member of the USEPA National Advisory Council for Environmental Policy and Technology where he and his colleagues provide policy guidance and future direction of the USEPA. Dr. Liban also holds concurrent Commissioner political appointments in the Los Angeles County Beach Commission and the City of Los Angeles Board of Transportation Commissioners. In those capacities, he contributes to the development and implementation of safe, resilient, equitable and environmentally protective policies throughout Southern California.

Dr. Kyle Meng, University of California, Santa Barbara: Bren School of Environmental Science and Management

Kyle Meng is an Assistant Professor at the Bren School and the Department of Economics at the University of California, Santa Barbara and a Faculty Research Fellow at the National Bureau of Economic Research. He studies environmental, energy, and natural resource economics with a focus on climate change impacts and policies. His research appears in leading economics and science journals, including the American Economic Review, Nature, and PNAS. He received his Ph.D. in Sustainable Development from Columbia University and his bachelor's in Civil and Environmental Engineering from Princeton University.

Dr. Deb Niemeier, P.E, NAE, University of California, Davis

For two decades, Deb Niemeier, Professor in the Dept. of Civil and Engineering and Professor in the School of Education at UC Davis, has focused on integrating models for estimating mobile source emissions with transportation modeling. Her primary research interest has been on developing highly accurate, accessible processes and emissions modeling and travel behavior models that can be used in the public sector, including the identification and modeling of environmental health disparities and improved understanding of formal and informal governance processes in urban planning.

She is currently working with collaborators in sociology and political science broadly examining the intersection of governance processes in regional planning and climate change outcomes, and better connecting urban planning processes with mitigation of environmental disparities. She is a member of the graduate faculty in Computer Science; Transportation, Technology, and Policy; Education, and Geography. She currently sits on the Executive Committee of the Graduate Geography Group. In 2014, she was named a Fellow of the American Association for the Advancement of Science (AAAS) for "distinguished contributions to energy and environmental science study and policy development." In 2015, she was named a Guggenheim Fellow for foundational work on pro bono service in engineering. In 2017, she was elected to the National Academy of Engineering.

Bruce Swanger, P.E., California Department of Transportation
Bruce Swanger has 26 years of experience with the California Department of Transportation (Caltrans) and is a licensed civil engineer in California, Nevada, and Arizona. His career focus has been predominantly in the hydrologic and hydraulic field associated with transportation infrastructure and the riverine and coastal environments. Mr. Swanger is currently the Caltrans State Hydraulics Engineer and is responsible for managing and developing the Caltrans statewide hydraulics and storm water design guidance, procedures, and standards for inclusion in the Caltrans Highway Design Manual and Project Planning and Design Guide. He has been involved with steady, unsteady, and two-dimensional hydraulic modeling of large culverts and bridges, preparing on-site and offsite hydrologic studies, designing rock and vegetated stream bank revetments, performing stream and habitat remediation design and analysis associated with fish and aquatic organism passage, analyzing sediment transport, assessing stream stability, performing scour and floodplain analysis, determining influences from tidal events coinciding with storm events on beachfront culverts and bridges, and performing wave-run-up studies.

Chester Widom, FAIA, California Department of General Services: Division of State Architect
Chester A. Widom, FAIA was the founding partner of WWCOT, a 185 person (at the time of his retirement from the firm) architectural, interior design, planning and forensics firm with four offices in California and an office in Shanghai, China. After leaving WWCOT, he served as the Senior Architectural Advisor for the Los Angeles Community College District's $6.1 Billion construction program. In December of 2011, Governor Brown appointed him California State Architect. As a former President of both the National American Institute of Architects (AIA) and the California Council AIA, Chet is recognized as an international leader in the profession. He has been awarded Honorary Fellowship by the Japan Institute of Architects, The Federacion Colegios de Arquitectos de la Republica de Mexicana and by the Royal Architectural Institute of Canada and, served as the 2011 Chancellor of the College of Fellows for the American Institute of Architects. He is the 2011 recipient of the AIA's Edward C. Kemper Award for service to the profession. Chet was the 16th recipient of the Distinguished Alumni Award by the School of Architecture at USC where he has taught and currently sits on the school's Board of Councilors. He has been a frequent guest lecturer at numerous universities including Harvard, Yale and UCLA. In addition to his leadership of both the National and California AIA, he previously served on the Building and Safety Commission, the City Planning Commission and the Elected Charter Reform Commission for the City of Los Angeles, and as a member of the Hospital Building and Safety Board for the State of California (OSHPD). In 2010 and 2011 he served as member of the Bond Oversight Committee for the Los Angeles Unified School District.

Project Team Members

Keali'i Bright

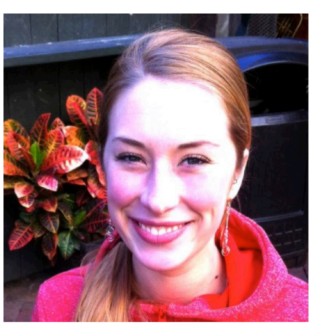
Keali'i Bright is the Deputy Secretary for Climate and Energy at the California Natural Resources Agency where he is responsible for agency related climate adaptation, natural and working land carbon management, energy and oil production and Salton Sea programs. Keali'i brings to this position over a decade of experience in state natural resources and environmental policy development. Prior to this appointment, he served the Brown Administration as the Deputy Secretary for Legislative affairs at the Natural Resources Agency which was preceded by his work for the Legislature as the principle consultant on natural resources, environmental protection, energy, transportation and other issues for the Assembly Budget Committee.

Guido Franco, P.E.

Guido Franco is the Team Lead for Climate Change and Environmental Research in the Energy Commission's Research Division. Mr. Franco led the preparation of the 1998 inventory of greenhouse gases for California that prompted the passage of a law requiring the periodic update of the inventory. He was the main author of the 2003 Climate Change Research Plan and he directed its implementation. He has been one of the main forces behind the three California Climate Assessments. The first one in 2006 was influential in the passage of Assembly Bill 32. He has been an Editor of two special issues of the prestigious journal Climatic Change on climate impacts and adaptation options for California. More recently, he was a member of the federal advisory committee that produced the National Climate Assessment delivered to the President and the US Congress on May 6, 2014. He is currently involved in the preparation of the 2018 National Climate Assessment and is co-led the preparation of California's Fourth Climate Change Assessment. Mr. Franco is a registered engineer in California and holds a Master's Degree in Engineering from UC Berkeley.

Joey Wraithwall

Joey is the Special Assistant for Climate Change at the California Natural Resources Agency. He was appointed to the position by Governor Jerry Brown after serving at the agency in several positions, including as associate governmental program analyst, staff services analyst, and executive fellow. Since 2014, Joey has assisted in the development and implementation of policies to adapt to and reduce the impacts of climate change. In his current position, Joey is the primary contact for the Safeguarding California Plan, the State's climate adaptation strategy, and is the agency lead for California's Fourth Climate Change Assessment. He supports and coordinates other climate adaptation activities and policies for the administration. Joey lives in Sacramento, California.



Elea Becker-Lowe

Elea Becker Lowe currently serves the Natural Resources Agency as an analyst in the Monitoring and Stewardship unit to track and monitor conservation projects across the state. She recently graduated from the Middlebury Institute of International Studies with a master's degree in International Environmental Policy. As a student she worked with the Natural Resources Agency's Climate Team to develop policy and practices to help the state of California adapt to the effects of climate change.

Co-Facilitators

Susi Moser, Ph.D., Director, Susanne Moser Research and Consulting

Dr. Susanne C. Moser, is an internationally renowned climate change adaptation expert and well known to the State of California for ongoing work with various state agencies since 1999. Since establishing an independent research and consulting firm in Santa Cruz in 2008, she has assisted the Energy Commission with synthesizing the Third Climate Change Assessment, CNRA with the drafting of the first Safeguarding California adaptation plan, the Ocean Protection Council with leading the public engagement effort informing the Update of the State's Sea-Level Rise Policy Guidance. In addition, she initiated in 2006 and has been a co-lead with Dr. Hart in the (now) longitudinal California Coastal Adaptation Needs Assessment and has contributed her own research to the state's Third and Fourth Climate Assessments. As part of the latter, she and Dr. Hart are conducting innovative research on the teleconnected and cascading impacts of climate change on interconnected infrastructure lifelines in the Greater LA region. Almost all of her work is trans-disciplinary, i.e., integrating multiple disciplines and the perspectives of decision-makers, to ensure the highest possible degree of practical use of integrative and robust knowledge. Creative facilitation of multi-stakeholder workshops is one of her signature strengths.

Juliette F. Hart, Ph.D., Director of Outreach, Coastal Climate Impacts team, USGS Pacific Coastal and Marine Science Center

Dr. Juliette Finzi Hart is an Oceanographer with the U.S. Geological Survey's Pacific Coastal and Marine Science Center in Santa Cruz. She is the Director of Outreach for the Coastal Climate Impacts team. Dr. Hart is a contributing author to the Coastal Effects chapter for the 4th National Climate Assessment (currently underway). At the CA state level, she has recently been appointed as a member of the Ocean Protection Council Science Advisory Team working group as co-author for the CA 4th Climate Assessment Oceans and Coasts report and, as noted above, is working with Dr. Moser on two projects that are part of the CA 4th Climate Assessment, as well as being the co-lead with her on the California Coastal Adaptation Needs Assessment. Dr. Hart specializes in translating complex scientific information to a wide array of audiences (from interested citizens to high level decision-makers). Her daily tasks entail working directly with policy- and decision-makers throughout the state to both understand and subsequently utilize the best scientific information in their decision-making. Prior to joining USGS in July 2016, Dr. Hart was the Marine & Climate Science Specialist at the University of Southern California Sea Grant for 10 years, following completion of her Ph.D. in Ocean Sciences from USC in 2006, along with a graduate certificate in Environmental Sciences, Policy, and Engineering; Sustainable Cities in 2004.

3 Webinar Series, Speakers and Resources

January 25, 2018
Inaugural Webinar: Setting the Standards and Context: Federal to Local Roles
Mike Sanio, Director of Sustainability, American Society of Civil Engineers
Kathryn Wright, Senior Associate, Meister Consultants Group/Cadmus Group
Peter Adams, Senior Policy Advisor, NYC Mayor's Office of Recovery and Resiliency

February 22, 2018
Webinar 2: Forward-Looking Climate Science for Use in Infrastructure Engineering: Possibilities and Limits
Dan Cayan, Ph.D., Researcher, Climate-Safe Infrastructure Working Group Member, Scripps Institution of Oceanography
Patrick Barnard, Ph.D., Research Geologist, USGS Pacific Coastal & Marine Science Center
Nicolas Luco, Ph.D., Research Structural Engineer, USGS Geologic Hazards Team
Morgan Page, Ph.D., Geophysicist, USGS Earthquake Science Center

March 21, 2018
Webinar 3: Mobilizing the Future: Infrastructure Challenges and Opportunities in the Transportation Sector
Gurdeep Bhattal, P.E., CalTrans, Climate-Safe Infrastructure Working Group Member
James Deane, AIA, CDT, LEED AP, PMP High-Speed Rail Authority, Climate-Safe Infrastructure Working Group Member
Cris Liban, Ph.D., P.E., ENV SP, LA Metro, Climate-Safe Infrastructure Working Group Member

March 22, 2018
Webinar 4: Rushing toward the Future: Infrastructure Challenges and Opportunities in the Water Sector
Kate White, Ph.D., P.E., Lead, Climate Preparedness and Resilience Community of Practice, US Army Corps of Engineers
Amir Aghakouchak, Ph.D., P.E., University of California, Irvine, Climate-Safe Infrastructure Working Group Member
Andrew Schwarz, P.E., California Department of Water Resources

April 6, 2018
Webinar 5: Green Infrastructure: Design and Integration for Climate-Safe Communities
Maya Hayden, Ph.D., Coastal Adaptation Program Leader, Point Blue
Jeff Odefey, Director, Stormwater Program, American Rivers
Tina Hodges, Sustainable Highways Initiative, US Department of Transportation, Federal Highway Administration

April 10, 2018
***Webinar 6: Governing Infrastructure: How Regulations, Standards, Codes and Guidelines* Are Set and Changed**
J. Alfredo Gomez, Director, Natural Resources and Environment Team, US Government Accountability Office
Stephen A. Cauffman, Community Resilience Group, National Institute of Standards and Technology
Ira Feldman, GHGMI Adaptation Leader; Adaptation Coordinator, ISO; President & Senior Counsel, Greentrack Strategies; Founder, Climate Adaptation Scholars™

April 18, 2018
Webinar 7: Energizing the Future: Challenges & Opportunities in the Building/Energy Sector
Nancy Ander, P.E., California Department of General Services, Climate-Safe Infrastructure Working Group Member
Tom Wells, FAIA, Principal Architect, California Department of General Services
Guido Franco, P.E., Technical Lead, Climate Change Research/Senior Engineer, California Energy Commission, Climate Safe Infrastructure Project Team
Martha Brook, P.E., CA Energy Commission, Climate-Safe Infrastructure Working Group Member
Kristin Heinemeier, Ph.D., P.E., Realized Energy, Climate-Safe Infrastructure Working Group Member

May 15, 2018
Webinar 8: Building the Future: Challenges & Opportunities in the Building Sector
Chester Widom, FAIA, California State Architect, California Department General Service, Climate-Safe Infrastructure Working Group Member
Jennifer Goldsmith-Grinspoon, Physical Scientist, Building Science Branch, Risk Management Directorate of Federal Emergency Managment Agency
Leslie Chapman-Henderson, President and CEO, Federal Alliance for Safe Homes (FLASH)

May 17, 2018
Webinar 9: Financing Climate-Safe Infrastructure I
Andreas Georgoulias, Ph.D., Research Director, Zofnass Program for Sustainable Infrastructure, Harvard University
Shalini Vajjhala, Founder & CEO, re:focus partners
David Dodd, CEcD, FM, Chairman & President, International Resilience Center

May 29, 2018
Webinar 10: Financing Climate-Safe Infrastructure II
John Cleveland, Executive Director, Boston Green Ribbon Commission and Innovation Network for Communities
Vladimir Antikarov, Principal, The Verea Group
Karl Schultz, Founder and Executive Chairman, Higher Ground Foundation

May 30, 2018
Webinar 11: Building a Climate-Safe Future for All: Social Equity and Inclusion in Infrastructure Planning
Deborah Moore, Western States Senior Campaign Manager, Union of Concerned Scientists
Chione Flegal, Senior Director, PolicyLink
Katie Grace Deane, Associate Director of Research and Field Development, Center for Community Investment, Lincoln Institute of Land Policy

June 6, 2018
Webinar 12: Enabling Scientists and Engineers to Work Together Effectively
Richard Moss, Senior Visiting Scientist, Columbia University
Susi Moser, Ph.D., Director, Susanne Moser Research & Consulting, Co-Facilitator of the Climate-Safe Infrastructure Working Group
Alex Wilson, President, Resilient Design Institute & CEO, BuildingGreen, Inc.

June 8, 2018
Webinar 13: Tools Supporting Climate-Safe Infrastructure Design
David Groves, Ph.D., RAND Water and Climate Resilience, Pardee Rand Graduate School, Climate-Safe Infrastructure Working Group Member
Wes Sullens, Director for Building Codes Technical Development, US Green Building Council
Kristin Baja, Climate Resilience Officer, Urban Sustainability Directors Network

June 11, 2018
Webinar 14: Monitoring Infrastructure Performance
Jennifer Jurado, Ph.D., Chief Resilience Officer, Division Director, Broward County
Peter Murdoch, Ph.D., Regional Science Advisor, U.S. Geological Survey Northeast Region
Andreas Georgoulias, Ph.D., Research Director, Zofnass Program for Sustainable Infrastructure, Harvard University

June 28, 2018
Webinar 15: Financing Climate-Safe Infrastructure III
Caitlin MacLean, Senior Director of Innovative Finance, Milken Institute
Brad Benson, Director of Special Projects, Port of San Francisco
Joyce Coffee, Founder and President, Climate Resilience Consulting

July 12, 2018
Webinar 16: Communicating Climate Change – Reaching Skeptical Audiences
Cara Pike, Director, Climate Access
Edward Maibach, MPH, Ph.D., Center for Climate Change Communication, George Mason University
Colin Wellenkamp, Esq., LLM, Executive Director, Mississippi River Cities and Towns Initiative

August 23, 2018
Capstone Webinar: The Findings and Recommendations of the CSIWG
Secretary John Laird, Natural Resources Agency
Jamesine Rogers Gibson, Senior Analyst, Union of Concerned Scientists
Working Group Members:
- Nancy Ander, P.E.
- John Andrew, P.E.
- Gurdeep Bhattal, P.E.
- Martha Brook, P.E.
- James Deane, A.I.A., C.D.T., LEED AP, P.M.P.,
- Noah Diffenbaugh, Ph.D.
- Cris Liban, P.E., ENV SP, Ph.D.

Susi Moser, Ph.D., Principal Researcher, Susanne Moser Research & Consulting; Co-facilitator of the Climate-Safe Infrastructure Working Group
Juliette Finzi Hart, Ph.D., Oceanographer, U.S. Geological Survey; Co-facilitator of the Climate-Safe Infrastructure Working Group

Webinar Details	Tool	Report	Other Resource
January 25, 2018 Setting the Standards and Context Michael Sanio		Adapting Infrastructure and Civil Engineering Practice to a Changing Climate; Committee on Adaptation to a Changing Climate; Edited by J. Rolf Olsen, Ph.D	.
January 25, 2018 Setting the Standards and Context Kathryn Wright		Voluntary Resilience Standards for Boston	
January 25, 2018 Setting the Standards and Context Kathryn Wright	Envision: Rating System for Sustainable Infrastructure		
January 25, 2018 Setting the Standards and Context Kathryn Wright	PEER Performance Excellence in Electricity Renewal		
January 25, 2018 Setting the Standards and Context Kathryn Wright	RELi Resiliency Action List		
January 25, 2018 Setting the Standards and Context Peter Adams	*Preliminary* Climate Resiliency Design Guidelines		
February 22, 2018 Possibilities and Limits Patrick Barnard	USGS Coastal Storm Modeling System		
February 22, 2018 Possibilities and Limits Patrick Barnard	USGS Hazard Exposure Reporting & Analytics		
February 22, 2018 Possibilities and Limits Patrick Barnard	UGSS CoSMoS-Coast, Coastal One-Line Assimilated Simulation Tool		
February 22, 2018 Possibilities and Limits Nicolas Luco		Induced Seismicity in Groningen: Assessment of Hazard, Building Damage and Risk	

Webinar Details	Tool	Report	Resource
March 21, 2018 Mobilizing the Future Cris Liban		Resilience Indicator Framework	
March 21, 2018 Mobilizing the Future Cris Liban		Building Resilience Los Angeles: A Primer for Facilities	
March 21, 2018 Mobilizing the Future Cris Liban		TCRP A-41 Improving the Resiliency of Transit Systems Threatened by Natural Disasters	
March 21, 2018 Mobilizing the Future Cris Liban		NCHRP SP20-101 Framework for Analyzing the Costs and Benefits of Adaptation Measures in Preparation for Extreme Weather Events and Climate Change	
March 22, 2018 Rushing Toward the Future Amir AghaKouchak		Compounding Effects of Sea Level Rise and Fluvial Flooding	
March 22, 2018 Rushing Toward the Future Amir AghaKouchak		Quantifying Changes in Future Intensity-Duration-Frequency Curves Using Multi-Model Ensemble Simulations	
April 6, 2018 Mobilizing the Future Maya Hayden		Case Studies of Natural Shoreline Infrastructure in Coastal California	
April 6, 2018 Mobilizing the Future Maya Hayden		Technical Report: California's Fourth Climate Change Assessment, California Natural Resources Agency. Publication number: CNRA-CCC4A-2018-3B	

Webinar Details	Tools	Report	Resource
April 6, 2018 Mobilizing the Future Jeffrey Odefey		Natural Security: How Sustainable Water Strategies are Preparing Communities for a Changing Climate	
April 6, 2018 Mobilizing the Future Jeffrey Odefey		Naturally Stronger: How Natural Water Infrastructure Can Save Money and Improve Lives	
April 6, 2018 Mobilizing the Future Tina Hodges			FHWA Resilience Website
April 6, 2018 Mobilizing the Future Tina Hodges		Vulnerability Assessment and Adaptation Framework	
April 6, 2018 Mobilizing the Future Tina Hodges		Engineering Guidance HEC 25	
April 6, 2018 Mobilizing the Future Tina Hodges		Engineering Guidance HEC 17	
April 6, 2018 Mobilizing the Future Tina Hodges		Synthesis of Approaches for Addressing Resilience in Project Development	
April 6, 2018 Mobilizing the Future Tina Hodges	FHWA Climate Change Adaptation Guide: For Transportation Systems Management, Operations, and Maintenance		
April 6, 2018 Mobilizing the Future Tina Hodges		Nature-based Resilience for Coastal Highways	
April 6, 2018 Mobilizing the Future Tina Hodges			FHWA Research Library

Webinar Details	Tools	Report	Resource
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-13-283 Limiting the Federal Government's Fiscal Exposure by Better Managing Climate Change Risks	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO -17-317 Progress on Many High-Risk Areas, While Substantial Efforts Needed on Others	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-16-37 A National System Could Help Federal, State, Local, and Private Sector Decision Makers Use Climate Information	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-17-3 Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-13-242 Future Federal Adaptation Efforts Could Better Support Local Infrastructure Decision Makers	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-18-206 DOD Needs to Better Incorporate Adaptation into Planning and Collaboration at Overseas Installations	
April 10, 2018 Governing Infrastructure Alfredo Gomez		GAO-14-446 DOD Can Improve Infrastructure Planning and Processes to Better Account for Potential Impacts	
April 10, 2018 Governing Infrastructure Stephen Caufman			NIST Website
April 10, 2018 Governing Infrastructure Stephen Caufman	NIST Community Resilience Planning Guide for Buildings and Infrastructure Systems I, II		

Webinar Details	Tools	Report	Resource
April 10, 2018 Governing Infrastructure Stephen Caufman	The Economic Decision Guide Software (EDGe$) Tool		
April 18, 2018 Energizing the Future Nancy Ander	CalAdapt Climate Adaptation Tools		
April 18, 2018 Energizing the Future Nancy Ander	CalEnviroScreen		
April 18, 2018 Energizing the Future Kristin Heinemeier	Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems		
May 15, 2018 Energizing the Future Chet Widom			7X7X7 Design Energy Water
May 15, 2018 Energizing the Future Jennifer Goldsmith-Grinspoon		Natural Hazard Mitigation Saves: 2017 Interim Report	
May 17, 2018 Infrastructure Financing I Andreas Georgoulias	Zofnass Economic Tool		
May 17, 2018 Infrastructure Financing I Shalini Vajjhala	Leveraging Catastrophe Bonds as a Mechanism for Resilient Infrastructure Project Finance		
May 17, 2018 Infrastructure Financing I Shalini Vajjhala	A Guide for Public-Sector Resilience Bond Sponsorship		
May 17, 2018 Infrastructure Financing I David Dodd	Resilient Infrastructure Public-Private Partnerships (PPPs): Contracts and Procurement The Case of Japan		

Webinar Details	Tools	Report	Resource
May 29, 2018 Infrastructure Financing II Vlad Antikarov	Vulnerability Reduction Credit (VRC) Standard Framework		
May 29, 2018 Infrastructure Financing II Karl Schultz	Pilot Implementation and Partnership Phase (PIPP)		
May 30, 2018 Infrastructure Financing II Chione Flegal		Pathways to Resilience: Transforming Cities in a Changing Climate	
May 30, 2018 Infrastructure Financing II Chione Flegal	Racial Equity Impact Assessments		
May 30, 2018 Infrastructure Financing II Chione Flegal	All in Cities Toolkit		
May 30, 2018 Infrastructure Financing II Chione Flegal	National Equity Atlas		
May 30, 2018 Infrastructure Financing II Chione Flegal	Inclusive Procurement and Contracting		
May 30, 2018 Infrastructure Financing II Chione Flegal			PolicyLink Perspectives (Blog and Newsletter)
May 30, 2018 Infrastructure Financing II Katie Grace Deane		Taking the High Road to More and Better Infrastructure in the United States. NRDC 16-06-A	

Webinar Details	Tools	Report	Resource
June 6, 2018 Enabling Scientists and Engineers Richard Moss		IPCC Reports	
June 6, 2018 Enabling Scientists and Engineers Richard Moss		Preparing the Nation for Climate Change: Building a National Climate Change Assessment	
June 6, 2018 Enabling Scientists and Engineers Susi Moser		Climate Change Educational Partnership: Climate Change, Engineered Systems, and Society	
June 6, 2018 Enabling Scientists and Engineers Alex Wilson		The New Orleans Principles: Celebrating the Rich History of New Orleans through Commitment to a Sustainable Future	
June 8, 2018 Tools Supporting CSI Design David Groves		Informing Decisions in a Changing Climate 2009	
June 8, 2018 Tools Supporting CSI Design Wes Sullens		Green Building and Climate Resilience: Understanding Impacts and Preparing for Changing Conditions	
June 8, 2018 Tools Supporting CSI Design Wes Sullens	LEED Climate Resilience Screening Tool		
June 8, 2018 Tools Supporting CSI Design Wes Sullens		Profiles of Resilience: LEED in Practice	
June 8, 2018 Tools Supporting CSI Design Wes Sullens			2018: LEED Recognition for California Projects

Webinar Details	Tools	Report	Resource
June 11, 2018 Monitoring Infrastructure Performance Jennifer Jurado		Unified Sea Level Rise Projection: Southeast Florida	
June 11, 2018 Monitoring Infrastructure Performance Jennifer Jurado		Southeast Florida Regional Climate Change Compact	
June 11, 2018 Monitoring Infrastructure Performance Peter Murdoch			Projects designed to provide ecosystem and community resilience to flooding, storm surge, SLR and increased storm events
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee		Climate Adaptation and Liability: A Legal Primer and Workshop Summary Report	
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			6 Steps for Building a "Sweet Spot" Where Social and Financial Equity Meet
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			Paying for Resilience: Market Drivers and Financial Means
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			Who Owns the Physical Risks from Climate Change? (And What One Move Can Make It Less Risky?)
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			Climate Disasters Hurt the Poor the Most. Here's What We Can Do About It.
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			10 Tips for a National Infrastructure Bank that Furthers Resilience Investments
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			The Next Era of Market Finance for Resilience

Webinar Details	Tools	Report	Resource
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee			Credit Rating Agencies Assess the Physical Risks of Climate Change
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee		Resilient by Design Finance Guide	
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee	Smart Cities Council Financing Guide		
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee	PWC Investor Ready Cities		
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee		UMB Financing Climate Resilience	
June 28, 2018 Financing Climate-Safe Infrastructure III Joyce Coffee	EEA Financing Urban Adaptation		
July 12, 2018 Communicating Climate Change Cara Pike			Communication and Engagement Resources at Climate Access
July 12, 2018 Communicating Climate Change Ed Maibach		Global Warming's Six Americas	

4 Climate Science Used Today

Appendix 1 provides summaries of the information currently used in infrastructure design and maintenance by different infrastructure sectors. This compilation begins the important task of identifying what information is currently used by state engineers and architects. The next important step will be to complete this list through a systematic survey of state engineers and architects. This could be an initial action taking by the proposed standing Climate-Safe Infrastructure Working Group.

Building Sector - Information Used for Current Planning, Design and Decision-Making

New & Existing Buildings, Parking Lots and Garages	• Ventilation requirements • Heating and cooling degree days for planning, including grid planning • Weather files • Hourly climate data • Historic weather data • Temperature: hourly min, max, average • Precipitation: hourly frequency and intensity, and duration • Wind: hourly min, max, average speed, direction, duration and 3 second gust • Air Quality: Ozone, VOC's, Particulate matter • Humidity: hourly min, max, average, dew point, USGS flood maps • ASHRAE Design Day: min/max dry bulb and dew point temperature • Zero Net Energy requirements & calculator
Energy Demand for Space Cooling	• Climate projections to estimate Cooling Degree Days
Energy Demand for Space Heating	• Climate projections to estimate Heating Degree Days

Transportation Sector - Information Used for Current Planning, Design and Decision-Making

Culvert Design	• NOAA Atlas 14 precipitation data (based on historical rainfall data) • Land use (based on stable historical conditions) • Material selection • Return frequency • Design life
Pavement Design	• Temperature extremes for material selection and expansion/contraction at bridge joints • Soil conditions for water saturation • Precipitation for design of bridges and culverts • Life-cycle cost • Maintenance operations
Bridge Design	• Temperature extremes for material selection and expansion/contraction at bridge joints • Soil conditions for water saturation • Precipitation for design of bridges and culverts • Life-cycle cost • Maintenance operations
Signals and Signage Design	• Temperature extremes for material selection • Precipitation for selection of control housing
Caltrans Buildings	• Temperature extremes for material selection and insulation • Precipitation for elevations, foundation and soil conditions • Energy usage for lighting and HVAC
Safety Rest Areas	• Temperature extremes for material selection and insulation • Precipitation for elevations, foundation and soil conditions • Energy usage for lighting and HVAC • Water table
Landscape Areas	• Soil conditions • Native plant species • Temperature • Precipitation • Water table
Roads and Bridges	Historic weather data: • Temperature: hourly min, max, average • Precipitation: hourly frequency and intensity, and duration • Wind: hourly min, max, average speed, direction, duration and 3 second gust • Air Quality: Ozone, VOC's, particulate matter • Humidity: hourly min, max, average, dew point

Water Sector - Information Used for Current Planning, Design and Decision-Making

Dams	• Landslide hazards • Rainfall and snowpack • Wind speed • Temperature, dewpoints • Historical storm and stream gauge data • Watershed ground cover and predominant soil types present • Digital Elevation Models / Terrain data • Lidar imagery • Stream networks • CEQA compliance • Downstream hazard assessment (population and infrastructure) • Water Rights Permit
Pipelines/Tunnels	• Hydrologic evaluations of watersheds • Hydraulic design of drainage facilities • Scour analyses • Head pressures • Groundwater table level • Fault locations and seismicity
Canals	• Hydrologic evaluations of watersheds • Flood routing through reservoirs, rivers and bypasses
Levees	• Hydrologic Evalauations of watersheds • Hydraulic design of drainage facilities • Flood routing through reservoirs, rivers and bypasses
Pumping/Generating Plants	• Occupancy requirements • Foundation suitability • Wind speed • Earthquake hazards • Groundwater table level • O&M requirements • Forebay/Afterbay water surface elevations

Energy Sector Information Used for Current Planning, Design and Decision-Making

Electrical Transmission Lines	• Historic maximum temperatures

5 Future Information Needs

The Climate-Safe Infrastructure Working Group (CSIWG) identified information needs for planning and designing climate-safe infrastructure under a changing climate. This Appendix provides summaries of these identified needs. This compilation provides important initial information to the State as agencies prioritize future research funding and investment. However, this Appendix only provides a first glimpse. A first task of the proposed standing CSIWG should include the development of a more comprehensive catalogue of climate and social science research and information needs, and then to prioritize identified information needs.

Building Sector - Information Needed for Future Planning, Design and Decision-Making

New & Existing Buildings, Parking Lots and Garages	• Temperature, precipitation, humidity, flooding, sea-level rise, ground water level, groundwater quality, hydrostatic pressure, ozone, VOCs, particulate matter • Need future forecasts (not historical data) for design days, heating and cooling degree days, weather files and hourly climate data • Need design day and hourly data for building energy system designs • Need to understand predicted variability around temperatures, wind speed/direction, solar radiation to better design high-performance building envelopes and hybrid (passive and active) heating/cooling systems • Need carbon design standard; need to design for future electrification
Energy Demand for Space Cooling	• Maximum and minimum daily temperatures
Energy Demand for Space Heating	• Maximum and minimum daily temperatures

Transportation Sector - Information Needed for Future Planning, Design and Decision-Making

Culvert Design	• How fast SLR will impact culvert and highways • Rates of coastal erosion • Change in return interval of storms • Temperature and precipitation increases over regions of state for various lifecycles of culverts • Identification of regions susceptible to wildfires
Pavement Design	• Review Caltrans map of Pavement Climate Regions and update map to reflect projected boundaries across the nine pavement regions • Projected precipitation data • Projected wildfire regions • Projected sea-level rise for protective measure design
Bridge Design	• Projected precipitation • Projected flows and velocities • Projected scour conditions, projected temperature increases for bridge expansion joint designs • Projected debris potentian • Projected wildfire regions in contributing watersheds • Sea-level rise for coastal highways
Signals and Signage Design	• Projected temperatures • Projected precipitation • Projected wildfire regions • Sea-level rise • Storm surge
Caltrans Buildings	• Projected temperatures for various regions of the state for the service life of buildings (which could project to year 2100) • Projected precipitation for the service life of the buildings • Projected wildfire regions of the state
Safety Rest Areas	• Projected temperatures for various regions of the state for the service life of buildings (which could project to year 2100) • Projected precipitation for the service life of the buildings • Projected wildfire regions of the state
Landscape Areas	• Projected temperatures • Projected precipitation • Projected wildfire regions • Sea-level rise • Storm surge
Roads and Bridges	Rate of change for: • Temperature • Precipitation • Humididty • Sea level • Groundwater level • Hydrostatic pressure • Groundwater quality • Ozone • Volatile Organic Compounds (VOCs) • Particulate matter

Water Sector - Information Needed for Future Planning, Design and Decision-Making

Dams	• Updated flood frequency distributions • Updated meteorological information (rainfall, snowpack, wind speed, temperature, dewpoint) • Updated stream gauge data • Impact of climate change on rainfall runoff, erosion, sediment and debris transport, potential for more frequent wildfires, and effects on utilities, facility access roads
Pipelines/Tunnels	• Updated meteorological information • Impact of climate change on rainfall runoff, erosion, sediment and debris transport
Canals	• Updated meteorological information • Impact of climate change on rainfall runoff, erosion, sediment and debris transport
Levees	• Updated flood frequency distributions • Updated meteorological information • Updated stream gage data • Impact of climate change on peak floodflows, erosion, debris deposition and durations of inundations
Pumping/Generating Plants	• Updated wind speeds • Updated water surface elevations • Understanding of expected debris at the intake • Updated seismicity
Watersheds	• Ecological, including forestry and wildfire, changes

Energy Sector Information Needed for Future Planning, Design and Decision Making

Electrical Transmission Lines	• Expected maximum ambient temperatures (for the life of the conductor)
Hydro Dams	• Timing and spatial pattern of precipitation patterns • Changes in snowpack
Power Plants	• Changes in cooling water temperature and availability • Changes in surface temperatures

6 CaliforniaDepartment of Water Resources

The Climate Change Technical Advisory Group

Producing Scientific and Strategic Guidance for California's Department of Water Resources
Poster for American Geophysical Union Annual Meeting (2015)
Provided by John Andrew, P.E. CSIWG Member

Producing Scientific and Strategic Guidance for California's Department of Water Resources:
The Climate Change Technical Advisory Group

Collaboration Overview

The California Department of Water Resources (DWR) runs the State Water Project (SWP), which provides drinking water for more than 25 million people, water for agriculture, flood control, power generation, recreation, fish and wildlife protection, and water quality improvements. Hydrologic impacts under a changing climate include reduced snowpack, increasing ratio of rain to snow, earlier snowmelt, higher temperatures, and rising seas; all of which impact the state's water supply. (See SWP and regional climate change vulnerabilities figure, below).

To improve the scientific basis for decisions and enhance the consistency of climate change approaches, DWR empaneled a Climate Change Technical Advisory Group (CCTAG) for guidance on the scientific aspects of climate change, its impacts on water resources, the use and creation of planning approaches and analytical tools for both DWR and for local water management supported by DWR, and the development of adaptation responses.

Diverse areas of expertise are needed to describe and assess the changing climate of California. Members were selected from multiple disciplines, including atmospheric science; hydrology; civil engineering/infrastructure; environmental science; climate data and statistics; social science; resource economics; land use planning; and climate modeling. DWR selected professional representatives from these disciplines by assessing applicants' knowledge, skills and experience. Membership was announced in February, 2012.

Meetings were held quarterly, with additional conference calls as needed, to discuss incorporating climate change into planning for DWR, as well as how DWR can best support the local water management community with climate change planning.

California Climate Change Vulnerabilities

Because of the economic, geographical, and biological diversity of California, vulnerabilities and risks due to current and anticipated future changes are best assessed on a regional basis. A few of the key climate vulnerabilities for each hydrologic region are indicated.

North Coast 1 Sea level rise may make tidal marshland susceptible to more frequent, longer and deeper flooding. • Longer drought periods would impact local fractured rock groundwater supplies.

Sacramento River 2 Increased air and water temperatures would place additional stress on sensitive ecosystems and species. • Loss of snowpack storage may reduce reliability of surface water supplies and result in greater demand on groundwater resources.

North Lahontan 3 Increased air and water temperatures would place additional stress on sensitive ecosystems and species. • Higher temperatures and longer dry seasons would increase wildfire risk.

San Francisco Bay 4 Sea level rise may increase the susceptibility of tidal wetlands to more frequent, longer and deeper flooding.

San Joaquin River 5 Increasing temperatures and variable precipitation patterns would affect agricultural crops by reducing winter chill-hours, increasing extreme heat days and increasing evapotranspiration.

Central Coast 6 Coastal infrastructure and nearshore ecosystems are vulnerable to increasing sea level and storm surges, while coastal aquifers could be affected by increasing salinity intrusion.

Tulare Lake 7 Loss of snowpack storage may reduce reliability of surface imported water supplies and replenishment of local supplies, and result in greater demand on groundwater resources. • Increased air and water temperatures would place additional stress on sensitive ecosystems and species.

South Lahontan 8 Higher temperatures and longer dry seasons would increase wildfire risk and impair water quality in local streams and lakes. • Reduced snowpack and changes in runoff timing would impact the winter-dependent economy supporting disadvantaged communities.

South Coast 9 Magnitude and frequency of extreme precipitation events may increase, resulting in greater flood risk, debris flows, and degradation of habitat for special-status species. • Higher temperatures and longer dry seasons would increase wildfire risk and impair water quality in local streams and lakes.

Colorado River 10 More frequent and longer droughts would reduce imported water supply reliability and decrease local water quality and habitat.

Mountain Counties • Loss of snowpack storage may reduce reliability of surface water supplies • Snowpack reduction may have significant impacts on the water-related tourism industry.

Sacramento-San Joaquin Delta • Sea level rise may increase stress on Delta levees and change water quality.

Authors and Affiliations:

John R Gyakum[1], Barney N Austin[2], David C Curtis[3], Michael Anderson[4], Holly Alpert[5], Sarah Young[6], Al Herson[7], Andrew Schwartz[4], ML Levent Kavvas[8], Ruth Langridge[9], Elissa Lynn[4], Jamie Anderson[4], Kelly T Redmond[10], Michael D Dettinger[11], Daniel R Cayan[12], and Matthew Correa[4], Konstantine P. Georgakakos[13] and Guido Franco[14]

(1) McGill University, Montreal, QC, Canada; (2) Aqua Strategies, Dripping Springs, TX, United States; (3) WEST Consultants, Inc., Folsom, California United States; (4) California Department of Water Resources, Sacramento, CA, United States; (5) Inyo-Mono Integrated Regional Water Management Program, Lafayette, CO, United States; (6) Santa Clara Valley Water District, San Jose, CA, United States; (7) The Sohagi Law Group, PLC, Sacramento, CA, United States; (8) University of California Davis, Civil, Environmental Engineering, Davis, CA, United States; (9) University of California Santa Cruz, Santa Cruz, CA, United States; (10) Desert Research Institute Reno, Western Regional Climate Center, Division of Atmospheric Sciences, Reno, NV, United States; (11) U.S. Geological Survey, La Jolla, CA, United States; (12) Scripps Institute of Oceanography, La Jolla, CA, United States; (13) Hydrologic Research Center, San Diego, CA, United States; (14) California Energy Commission, Sacramento, CA, United States.

Contact: Elissa Lynn, California Department of Water Resources, elissa.lynn@water.ca.gov, 916-651-0211

Process Overview:

DWR: CALL FOR Applications

REVIEWED BY Management Team

USING Criteria

SELECT Advisory Group (14 members)

First CCTAG meeting, in Sacramento, California, May 11, 2012.

ATTEND Meeting Program

PRODUCING Charter · Guidance · Methodology · Models · Understanding · Collaboration

Lessons Learned

- Climate change must be incorporated into DWR's planning and projects in a dynamic manner that is commensurate with updates to science and policy.
- Drafting DWR-specific recommendations for incorporating science was challenging both due to time constraints and understanding DWR business needs.
- Technical capacity to ingest climate data varies greatly among water managers and across DWR.
- The climate model selection process developed was more important in some ways than the actual list of models identified. Since the science is changing so rapidly, the process will likely have to be repeated every few years or so.
- Seeing the impact of assumptions made (e.g., through some type of appropriate integrative software or case studies and pilot projects on various scales, where such impacts have been studied or demonstrated) might achieve more useful and realistic guidance.
- Large-scale water distribution projects influence effective approaches to climate change adaptation, and depend more on the local characteristics (including institutional issues), demands and conditions, and less on the large-scale climate forcing.
- More time should be invested early in the process to develop a work plan for completing the final products and identify critical path items.
- Statewide adaptation can be hindered by a lack of mandating authority by DWR to influence planning at the local level. Providing incentives or technical assistance to increase water agencies' capacity to apply climate models for water resources planning would benefit statewide adaptation.
- Next steps should include implementation of the guidance and perspectives both scientifically and regarding support to local water management.

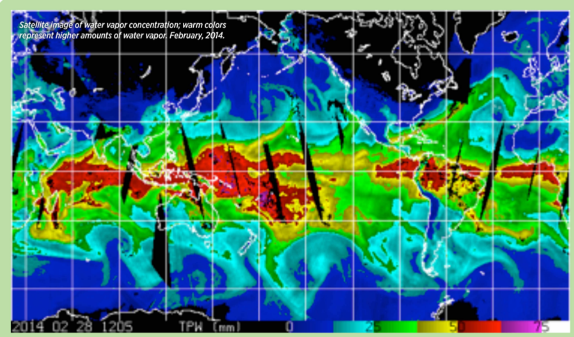
Positive Outcomes

The diverse professional team of scientists and practitioners tackled complicated water management issues regarding climate change impacts on California's water supply in *Perspectives and Guidance for Climate Change Analysis*, http://www.water. ca.gov/climatechange/ docs/2015/ Perspectives_Guidance_ Climate_Change_Analysis. pdf. This Technical Information Record represents the preliminary findings of the Advisory Group, on global climate model selection appropriate for California water resources, planning for extreme conditions, downscaling, and recommendations for future work.

A Dynamic Team with Diversity of Expertise

- The diversity of opinions and perspectives from technical fields, policy and practitioners from various local, regional, state and international affiliations was noted as a very positive aspect of this effort.
- External perspective was helpful as a counterbalance to DWR's internal perspective.
- The team effectively worked through challenging technical issues by holding frequent discussions, allowing DWR to advance its programs by incorporating the best science available.
- Effort showed that convergence to a practical planning guide for using climate information can be achieved even for complex multidisciplinary issues such as those tackled (see "Choosing Global Climate Models" figure to the right).
- The group conducted effective collaboration without many ground rules, fostering open, inclusive, and transparent discussion.
- A dynamic team brought expertise, energy and passion to the table, but had different communication styles, which could also be a challenge.
- DWR's longstanding engagement with the science community was broadened by the CCTAG process.
- The CCTAG offered members continuous learning opportunities and a venue for presenting and hearing differing views.

California's water supply is dependent upon annual and interannual weather and climate conditions. Determining the impact of climate change onto regular climate variability will be a challenge. The multi-disciplinary CCTAG members met regularly over the course of 3 years; in person and via webex, to discuss these important matters. The wide variety of perspectives allowed for the transfer of information and understanding between the science community and practitioners.



Satellite image of water vapor concentration; warm colors represent higher amounts of water vapor, February, 2014.

Choosing Global Climate Models to use for California Water Resources Planning

Criteria
- Scientists recommend using information from several Global Climate Models
- Using information from all available GCMs isn't practical
- Remove GCMs that fall short in representing historical climate and hydrologic processes important for California's water resources planning

Method

Start with 31[1] GCMs

Global — **Global Climatology Filter[2,3]**
Evaluate how each GCM represents global historical
- Solar Radiation
- Air Temperature
- Atmospheric Pressure, Wind

Remove ~10 GCMs

Western U.S. — **Western U.S. Climate & Hydrology Filter[4]**
Evaluate how each GCM represents Western US historical
- Air Temperature
- Precipitation
- Atmospheric Pressure Patterns
- El Niño Southern Oscillation Patterns

Remove ~5 GCMs

California — **California Hydrology & Extremes Filter**
Evaluate how each GCM represents California historical
- Dry and Wet Precipitation Extremes
- Heat Waves and Cold Snaps
- El Niño Spatial and Temporal Patterns

Remove ~5 GCMs

10 GCMs to use for CA water planning — **GCM Recommendations for California**
The remaining 10 GCMs are recommended for water resources planning because they represent important components of historical climate at global, regional, and statewide scales

References:
[1] CA-DWR Climate Change Technical Advisory Group analysis used GCMs available at the start of the investigation that met certain data requirements (2013).
[2] Gleckler, P. J., Taylor, K. E., and Doutriaux, C.: Performance metrics for climate models, J. Geophys. Res.-Atmos. (2008).
[3] IPCC, Climate Change 2013: The Physical Science Basis, Cambridge University Press, Cambridge, UK and New York (2013).
[4] Rupp, D. E., J. T. Abatzoglou, K. C. Hegewisch, P. W. Mote: Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA, J. Geophys. Res.-Atmos. (2013).

Model Selection

CCTAG provided guidance on a methodology to choose global climate models (GCMs), downscaling techniques, scenarios for extreme events, and further work needed to apply these elements. Specific unique work resulting from the CCTAG effort was related to GCMs:
- A 3-step evaluation approach was used to identify a tractable set of GCMs for California water resources planning.
- The identified GCMs will provide consistency for DWR planning projects.
- This methodology will inform the State's 4th Assessment Report, anticipated in 2018.

In Conclusion

- Substantial hydrologic climate changes will challenge current and future generations of Californians.
- CCTAG guidance and perspectives will help DWR improve the scientific basis for decisions and enhance the consistency of climate change approaches.
- DWR will be better able to provide guidance to local water managers on incorporating climate change into their planning.
- DWR and CCTAG members increased their understanding of climate change issues facing California, which will benefit the greater water management community.

7 Probabilistic Risk Assessment for Climate-Safe Infrastructure

Probabilistic Risk Assessment Process and Case Application

James R. Deane, AIA, CDT, LEED AP, PMP
Design and Development Section Supervising Architect
California High-Speed Rail
July 2018

1. Summary

1.1. Purpose

The purpose of this document is to define processes that agencies can employ to objectively assess climate change risks across their portfolio. This can be used when they have a need to either integrate climate change risk management into their current risk management plans or develop tools where none currently exist.

1.2. Disclaimer

The work presented within this document summarizes some of the work products developed as part of California High-Speed Rail and generalizes those processes as related to climate change adaptation but is not intended to represent CHSRA opinion or position on any issues.

2. Definitions

- **Threat:** An indication of imminent harm, danger or pain, e.g., shocks
- **Hazard:** Anything that can cause harm e.g. stressors
- **Risk:** A chance, probability or likelihood that harm may occur
- **Vulnerability:** An exposure to a hazard[1]
- **Event:** The hazard is realized

2.1. The Challenges

The challenge of developing climate-safe infrastructure begins with determining the type and intensity of future hazards and their likelihood of happening. This is achieved through five steps agencies can take:

1. Identify boundaries, assets and climate change-related hazards, e.g. flooding for their assets
2. Assess the risks by:
    - *Organizing* the risks into common categories for evaluation
    - *Quantifying* the risks for likelihood and severity
    - *Evaluating* the risks against their ability to manage them
3. Mitigate the risk to "As Low As Reasonably Practical" (ALARP)
4. Accept the residual risk
5. Monitor their decision-making against the evolving hazard

Climate change presents the design and engineering community with a unique challenge in that:

- The types of *hazards* are uncertain
- Their *severity* is uncertain
- Their *likelihood* is uncertain
- The *vulnerability* of the infrastructure is dependent on the uncertainty of the hazards

For governments, utility providers, planners and communities there are also additional challenges. These include: (1) that there is not enough funding for all the existing and new infrastructure projects; (2) there are not enough resources (e.g., land, steel or cement) to replace or build new, resilient infrastructure; (3) lack of action to address a hazard often creates or escalates environmental hazards; (4) unplanned reactions by the public or responses by government often have unintended social consequences; (5) lack of or poorly considered mitigation can negatively impact the local *economic* systems.

2.2. Where Does Risk Management Reside?

Most agencies will likely have some form of risk management processes already and can then focus on how to integrate climate risk into their existing processes. Risk management can occur at two levels of an agency:

- Program Risk Management: high level policy often bound by legal obligations of the Agency; and
- Project Risk Management: specific risks that occur because of taking an action, e.g., building a culvert.

[1] Vulnerability is variably defined as merely the exposure to a hazard as done here, or more as a combination of exposure, sensitivity and adaptive capacity.

Both influence, and are influenced by, the other in that the program provides for strategic decision making while the project provides tactical feedback as to the effectiveness of the strategy.

2.3. How Do You Analyze for Risk?

Risk can be *qualitatively* or *quantitatively* assessed. This document focuses on quantitative assessment. There are many tools to analyze for risk and an agency needs to evaluate their unique set of responsibilities and select a system that best provides a methodology for risk evaluation. Below are some of the methods:

- Fault Mode Effect Analysis;
- Fault Mode Effect and Criticality Analysis;
- Fault Hazard Analysis;
- Double Failure Matrix;
- Event Tree Analysis;
- Political, Economic, Social, Technological, Environmental and Legal Factors (PESTEL) Analysis; and
- Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analysis.

3. Risk Management

3.1. What Is Risk Management?

Risk management seeks to, in order of preference[2]:

- Avoid the risk by deciding not to start or continue with the activity that gives rise to the risk;
- Taking or increasing the risk to pursue an opportunity;
- Remove the risk source;
- Change the likelihood;
- Change the consequences;
- Share the risk with another party or parties (including contracts and risk financing); and/or
- Retain the risk by informed decision.

Risk management relative to climate hazards has evolved around the following similar concepts: eliminate, avoid, mitigate, absorb, resist or accept the hazards to the system.

The goal of a managed risk approach is to quantify the hazard severity and frequency and compare it against the vulnerability of a component or system to enable an agency to make reasoned decisions as to where to focus efforts with limited resources. The risk management process typically consists of the following steps[3] :

- Plan Risk Management
- Identify Risks,
- Perform Qualitative Risk Analysis,
- Perform Quantitative Risk Analysis,
- Plan Risk Responses, and
- Monitor and Control Risks.

The Planning and Investing for a Resilient California: A Guidebook developed by the Governor's Office for Planning and Research provides a similar structure for State agencies, but it is organized specifically around climate (Figure 1).

[2] ISO 31000:2009 – Risk management -- Principles and guidelines
[3] The Project Management Institute Body of Knowledge (PMBOK)

Figure 1: Climate Risk Management Steps. (Source: Planning and Investing for a Resilient California: A Guidebook for State Agencies, used with permission).

A more detailed breakdown of the risk assessment process is shown below in Figure 2.

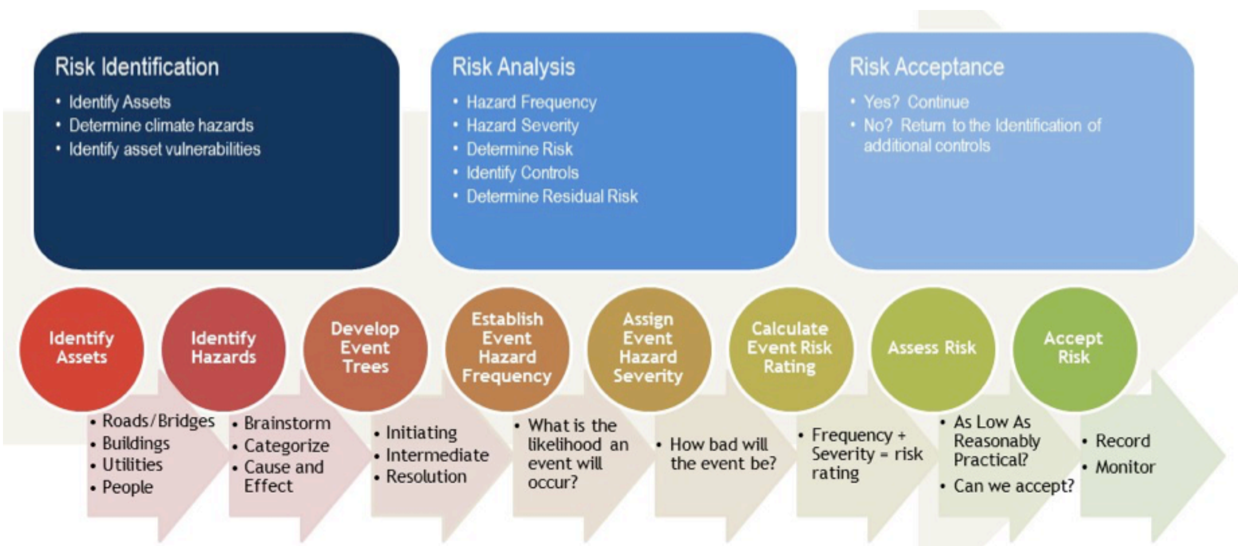


Figure 2: Risk Management Process.

The Network Rail Risk Assessment Process below (Figure 3) from Network Rail shows a functional risk assessment process.

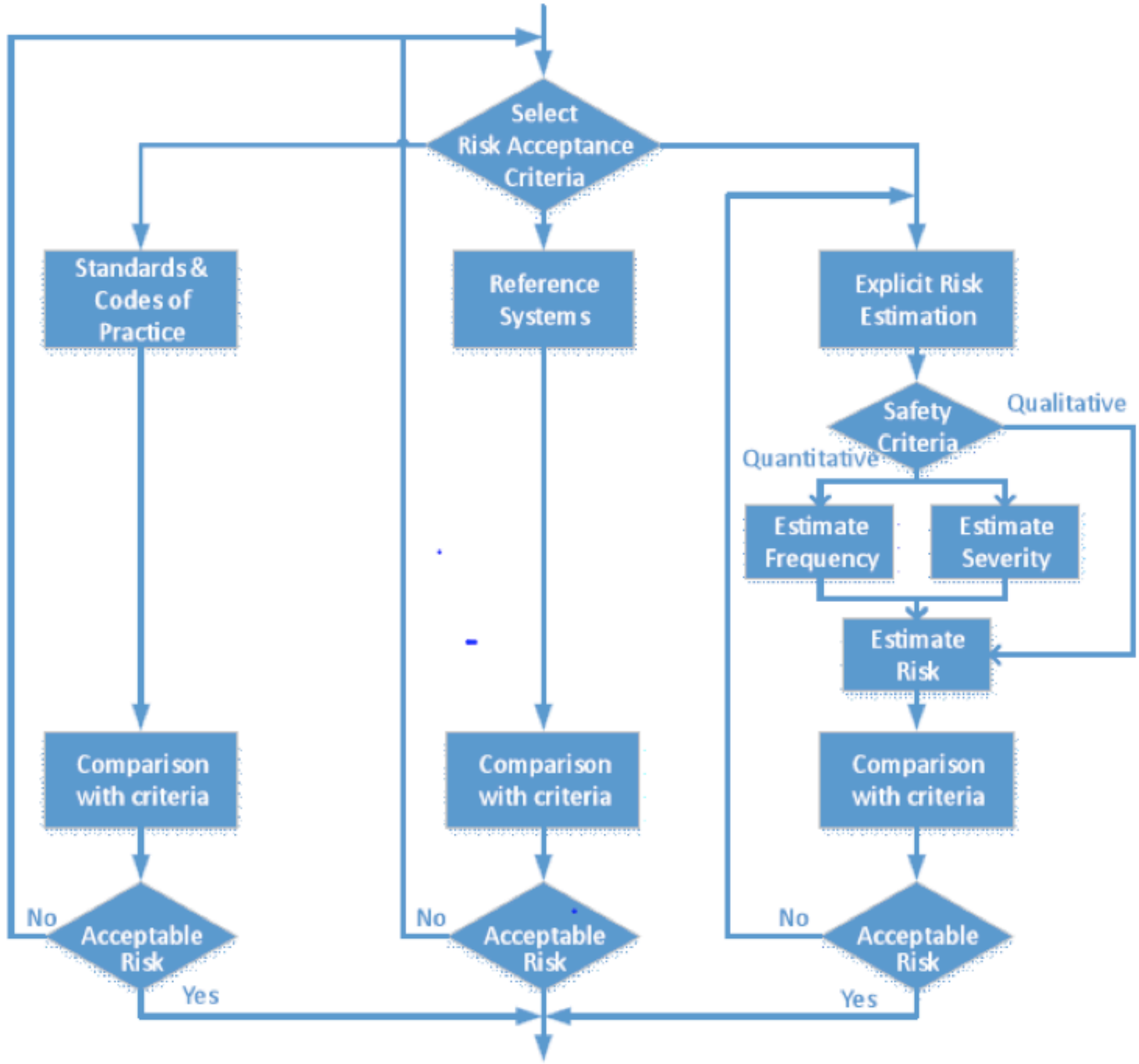


Figure 3: Network Rail Risk Assessment Process. (Source: Network Rail Risk Management Design, used with permission).

The Federal Highway Administration Adaptation Decision-Making Assessment Process (FHWA ADAP) below (Figure 4) provides detail on a more comprehensive process developed for the Federal Highway Administration and adopted by Caltrans.

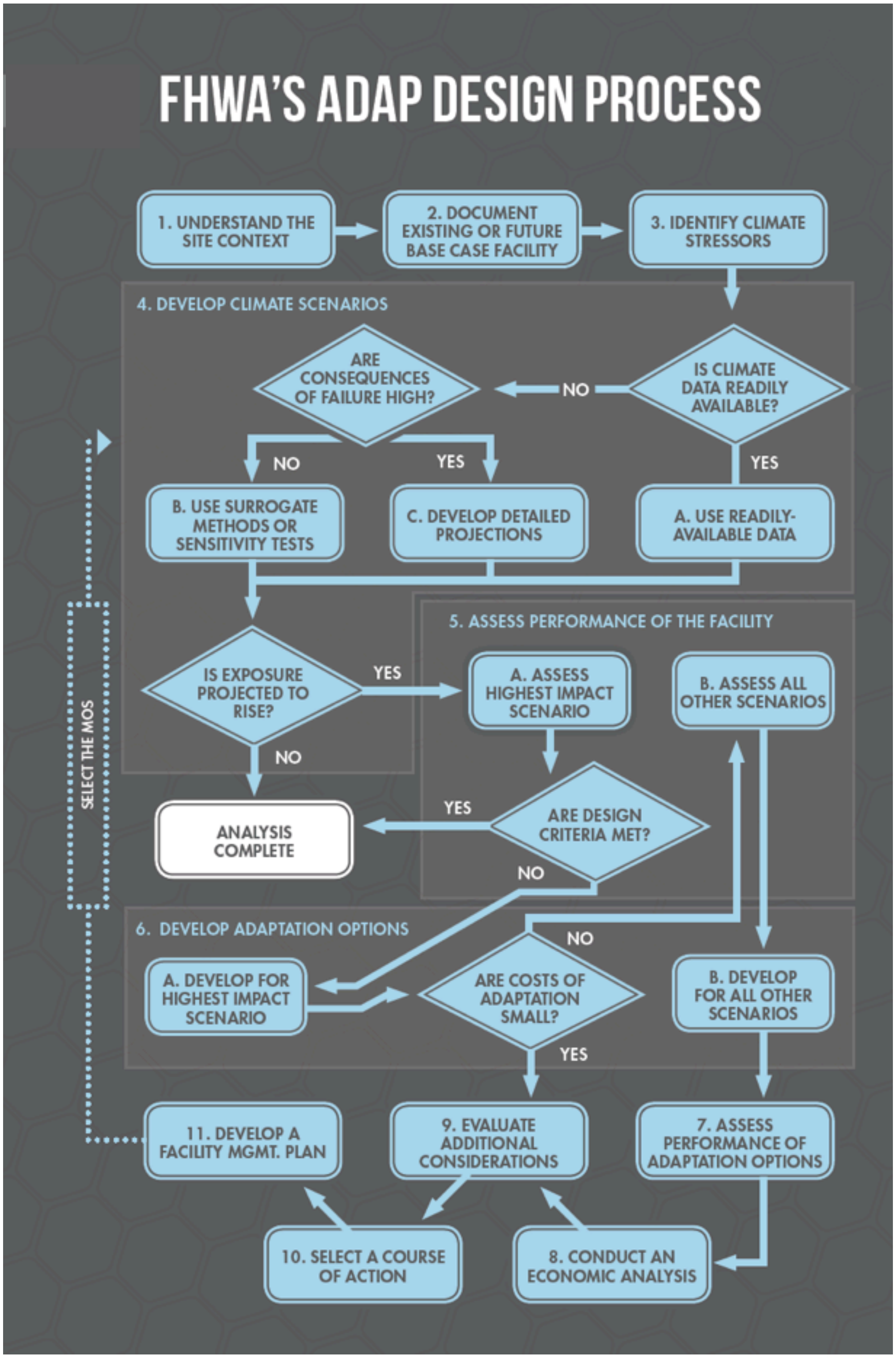


Figure 4: FHWA ADAP design process flow chart. (Source: D4 Caltrans Vulnerabiltiy Assessment v49, used with permission.)

3.2. Probabilistic Risk Assessment (PRA)

PRA is a process that allows for hazards to be identified, categorized, evaluated and mitigated based on their severity and frequency. PRA uses probability calculations to establish the likelihood of a hazard occurring and economic analysis to establish severity. PRA seeks to provide a quantifiable weighting to risk rather than subjective assessment. It uses a systems approach which encourages users to consider all aspects of their system and the interrelationships between pieces.

PRA is often expresses as a simple formula, several of which are listed below:

- Risk = Hazard Likelihood + Hazard Severity
- Risk = Hazard Likelihood x Hazard Severity
- Risk = Hazard Likelihood + Hazard Severity +Vulnerability
- Risk = Hazard Likelihood x Hazard Severity x Vulnerability
- Risk = Asset Value x Hazard Rating x Vulnerability Rating[4]

Likelihood or frequency establishes how often a hazard may occur. This is useful in climate adaptation as event frequency is often identified as a key indicator that change is occurring, e.g., a 1:100 precipitation event may become a 1:25 event, indicating that intense precipitation events of a certain magnitude are happening more frequently.

Severity can be identified quantitatively as:

- Cost of replacement for the component or system;
- Cost of damage to the system resulting from component failure; or
- Total cost of damage to life, environment, infrastructure damage, economic (loss of revenue), social fabric and reputation.

Vulnerability is useful for evaluating existing infrastructure as this allows one to focus on costs to upgrade a system.

4 Methodology

4.1. Plan

One of the first activities is to create a Risk Management Plan. This plan is used to:

- Document regulations, standards, and guidelines the agency will follow;
- Establish threshold for acceptance of risk and where action is required to mitigate a risk;
- Comprehensively document the types of hazards that may occur; and
- Identify response the agency will take should an event occur.

4.2. Identify

Many different methods can be used to identify requirements, assets, design criteria, threats, hazards and vulnerabilities:

- Historical records;
- Stakeholder interviews;
- Professional judgement;
- Brainstorming;
- Statistical modeling;
- Cause and effect analysis; and
- Strength Weakness Opportunity Threat (SWOT).

To complete a Risk Assessment there are three primary components that must be identified:

- Risk Acceptance Criteria: how much risk can we accept? (section 4.2.1)
- Asset identification: what do we own and what do we know about it? (section 4.2.2 and 4.2.3); and
- Hazard Identification: what can negatively impact our asset and how badly? (section 4.2.4).

[4] FEMA 428, Primer for Design Safe Schools Projects in Case of Terrorist Attacks (2003)

4.2.1. Identify Risk Acceptance Criteria

The chicken and egg dilemma with climate adaptation is that we often can't know how much we can accept until we have completed an evaluation. For this document, we place identifying risk acceptance criteria as the first step. If at the end of our analysis, we need to modify our criteria it can be accomplished as part of our monitoring activity. Because there are many potential risks to consider, PESTEL is useful for comprehensively identifying and organizing the risk into related categories:

- Political or governmental: What are the agencies' capabilities and how can it respond?
- Economic: What is the cost of mitigating a hazard versus accepting the impacts of the event?
- Societal: Who are we protecting and how will impacts affect their ability to continue to function?
- Technological or Infrastructure: What are the physical and virtual structures we seek to assess?
- Environmental: How will our natural systems be impacted?
- Legal: What is our ability to mandate change and will consequences of hazards be addressed by the courts?

The Risk Acceptance Criteria flor chart below is a representation of how risk acceptance criteria can be organized (Figure 5).

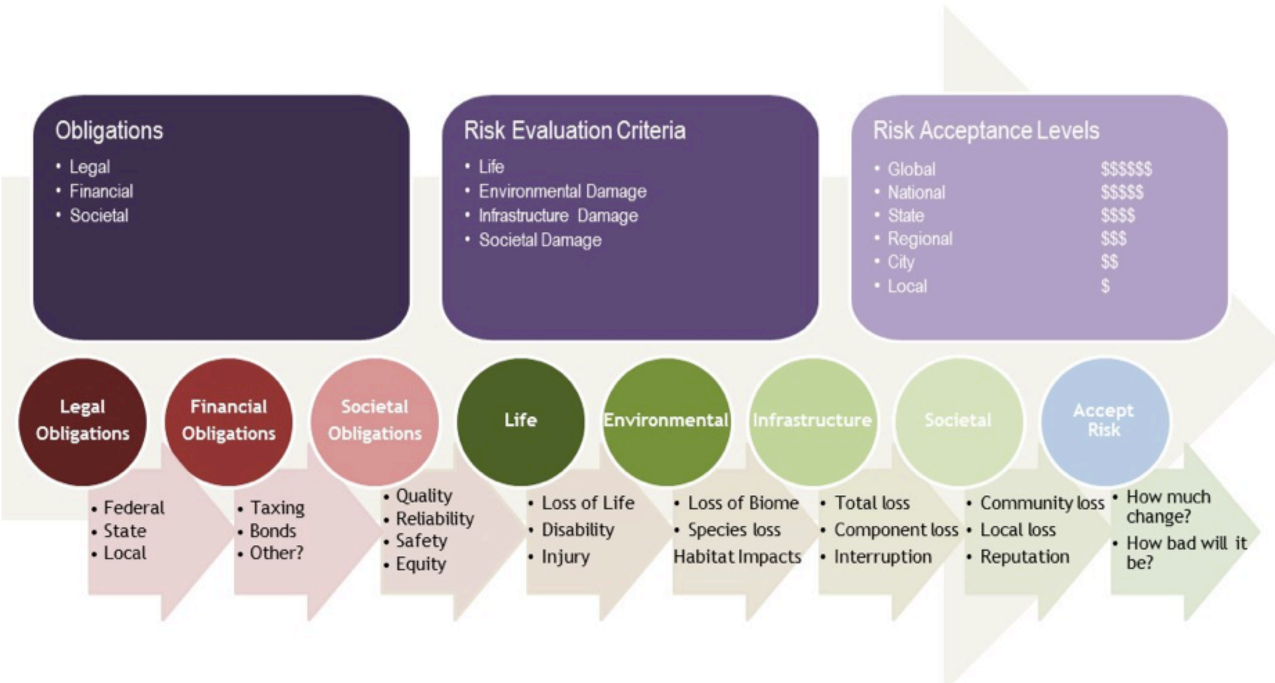


Figure 5: Risk Acceptance Criteria flow chart

4.2.2. Identify Design Criteria

Most agencies will be working with legacy regulatory structures that include design criteria that their assets must adhere to. Frequently, those design criteria do not address climate adaptation as a criteria or evaluation process. As part of the identification process it is important to understand how climate adaptation will be addressed. It is not uncommon to determine after a risk assessment that there are simple and effective mitigations that can be achieved by modifying the agencies design criteria. A new concept for agencies is that climate adaptation must be considered as part of the normal design process. Figure 6 provides a simple diagram to illustrate how to use a Design Criteria Assessment in decision-making around wildfire risk.

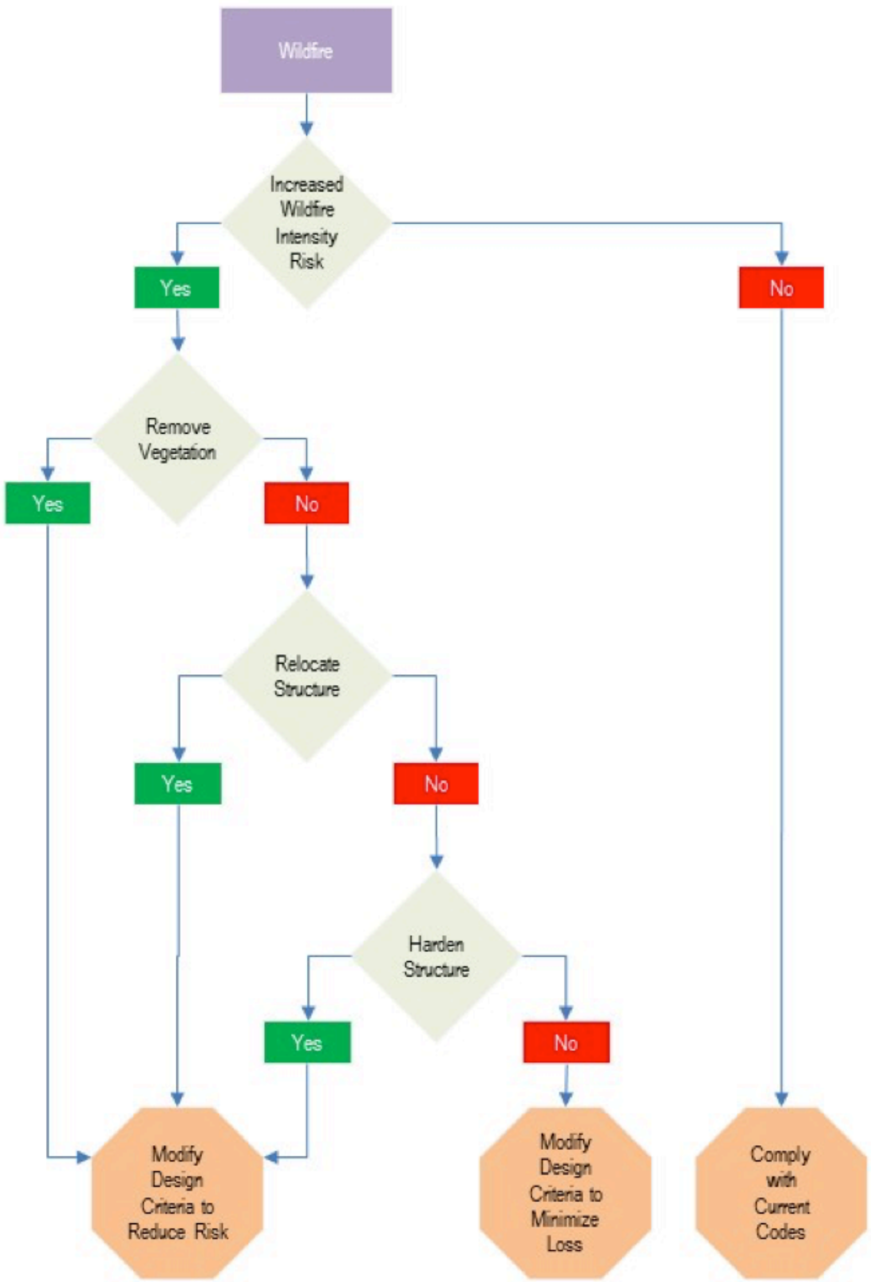


Figure 6: Design Criteria Assessment flow chart for a wildlife example

4.2.3. Identify Assets

Assets can exist in many forms:

- Physical infrastructure: buildings, roads, bridges, pipes, wires, dams, etc.
- Virtual Infrastructure: processes, software, etc.
- Human: staff, customers, communities, etc.
- Environmental: Inorganic (air, sea, land) and organic (plants, animals, habitats)

Who owns what is often a complex question due to the nature of funding, service agreements and regulatory authority. A key component of PRA is to establish a boundary for the analysis and this is also useful for cross-agency coordination so that all parties who influence a project also participate in the risk assessment. The example Risk Boundary Assessment below is one example of a simple boundary determination flow chart to illustrate how responsibility can be assigned (Figure 7).

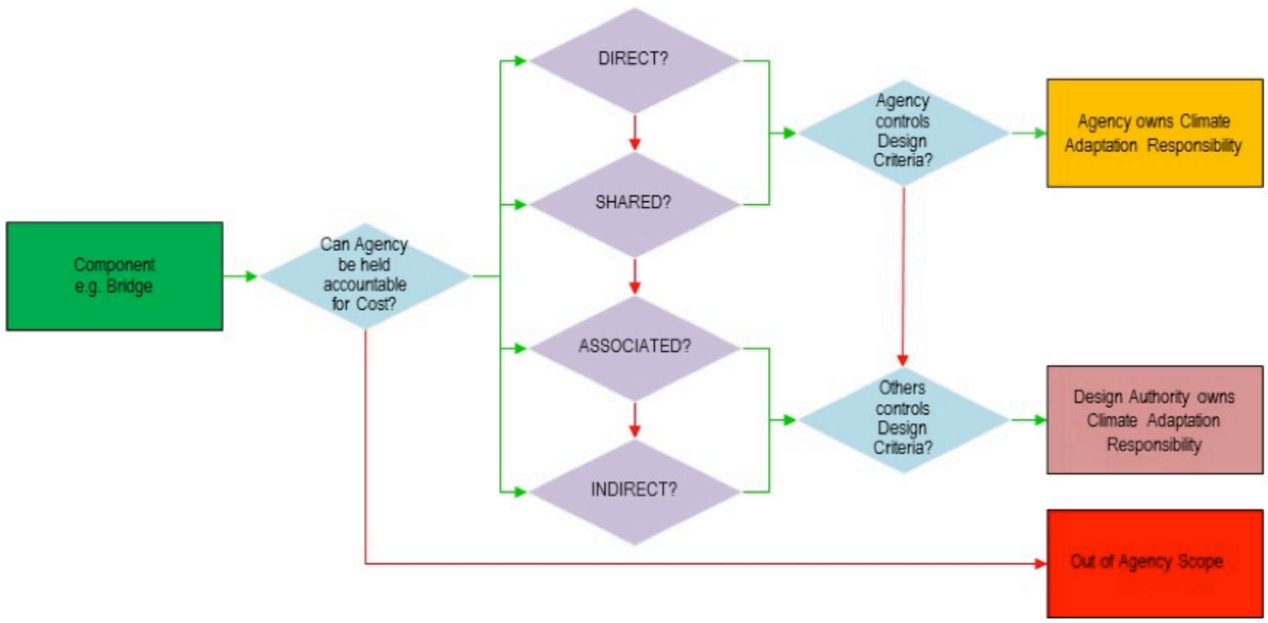


Figure 7: Risk Boundary Assessment flow chart

- Direct: Fully funded by Agency through purchase including design and construction activities directly related service;
  Agency owns the design criteria and directly benefits from construction
- Shared: Partial funding by Agency in support of others activities that benefit Agency;
  Agency Influences design criteria and directly benefits from construction
- Associated: Funded by Others and Agency directly benefits or manages;
  Agency does not influence design criteria but benefits from construction
- Indirect: Funded by others for their principal use but Agency indirectly benefits;
  The agency does not influence design criteria and does not directly benefit from construction

4.2.3.1. Physical Asset Identification

As this document is primarily focused on physical infrastructure, it is useful to discuss what kinds of data are important to be able to assess an asset. Relevent data include: asset name, function, location, age, service life, condition, design life, geographic conditions, climate zone, and biome. Note that much of this information is already captured by agencies (Table 1):

Table 1: Sample asset identification information

Temperature range						
Component	Design Life	Design standards	Impact	Severity	Justification	Mitigation
Foundations	80		No		Concrete piling is resilient to temperature change	N/A
Masts	60		No		Steel masts are resilient to temperature change	N/A
Small Part steel	40		Negligible	41	increased operational temperature range may increase maintenance frequency (items loosening)	Monitoring and inspection as part of maintenance regime
Contact Wire	30		Marginal	31	may reduce capacity and increase maintenance activities (stretch recovery)	Monitoring and inspection as part of maintenance regime
Messenger Wire	60		Marginal	31	may reduce capacity and increase maintenance activities (stretch recovery)	Monitoring and inspection as part of maintenance regime
Auxiliary wires	60		Marginal	31	may reduce capacity and increase maintenance activities (re-tensioning)	Monitoring and inspection as part of maintenance regime
Insulators	40		No		Ceramic	N/A
Section Insulators	15		No		Ceramic	N/A
Switches	30		Negligible	41	may require additional maintenance setup due to thermal expansion	Monitoring and inspection as part of maintenance regime

4.2.4. Identify Climate Hazards

Climate change is sometimes reduced to a single type of impact, such as: sea-level rise, but the changes affect the entire planetary system, including: atmosphere, hydrological systems, geology, ecological systems, natural biomes, species, human-made systems, agriculture, cities, transportation, utilities, and human systems.

Each of these systems can be further divided. For example, atmospheric system impacts include: temperature, humidity, precipitation, rain, snow, extreme weather such as hurricane, lightning, wind, extreme wind such as tornados, dust storms, fog, elevation and air pressure, air quality, aerosols, particulates, and UV radiation.

4.3. Prioritize: Organizing Hazards

From the initial identification process a more systematic method should be used to categorize events (hazards) to show relationships between events, to assign likelihood criteria, and to identify key hazards

Below is an example from California High-Speed Rail that shows how a working group brainstormed various events and then classified them into the Initiating Event Categories and Initiating Events (Table 2).

Table 2: Categorization of Climatic Events into Types of Initiating Events

Initiating Event Category	Initiating Event
Fires	FQ- On a train - in an on-board equipment room
	FO- On a train - in an on-board occupied area
	FX- On a train exterior
	FE- Within the tunnel but not on a train
Tunnel structure failure	CC- Tunnel structure failure
Tunnel blockage	CF- Tunnel flooding
	CD- Debris flow at tunnel portal
Trainset failure	CT- Trainset structure failure
	TE- On-board electrical system
	TB- Brake system
	TP- Pantograph
	TA- Automatic train control (ATC)
	TT- Traction power
	TW- Bogie / wheelset
Track and systems	CE- Overhead electrification structure failure
	CS- Track system failure
	II- Icing on overhead line electrification
	ID- Lineside intrusion detection
	IS- System short circuit
	IE- Earthquake detection and Landslide Detection?
	IP- Incoming power feed failure
	IN- Non-catastrophic safety integrity level (SIL) 4 event
Operator induced	OM- Manual wayside stop signal
	OA- Emergency general alarm activation
	OH- OCC shuts off overhead line electrification
	OB- On-board staff activates emergency stop
	OC- Operational control center issues stop instruction
	OD- Driver stops train (independently)
Passenger induced	PT- Traincrew advised of incident
	PO- External train door opened by passenger
	PV- Vandalism on train
	PB- Broken window
	PH- Train hi-jacked in cab
	PC- Cyber-attack on train
	PE- On-board emergency alarm triggered
	PF- Activation of fire alarm system (no fire)

Because harms resulting from hazards are often interrelated, their significance needs to be evaluated by comparing them to each other. Many mechanisms exist to organize hazards and to understand their linkage. These include, but are not limited to:

- Cause and Effect Diagrams (section 4.3.1);
- Fault Tree Analysis (section 4.3.2); and
- Event Tree Analysis (section 4.3.3).

4.3.1. Cause and Effect Diagrams

Cause and effect diagrams are useful for understanding the relationship of impacts to the larger issue of climate change. These diagrams are also useful for informing an agency where other hazards may exist that are not apparent using other techniques such as historical records. The diagram (Figure 8) shows the cause and effect relationship from fossil fuel consumption to coastal flooding. Note that a single hazard can create multiple additional hazards and that multiple hazards can combine to create new hazards.

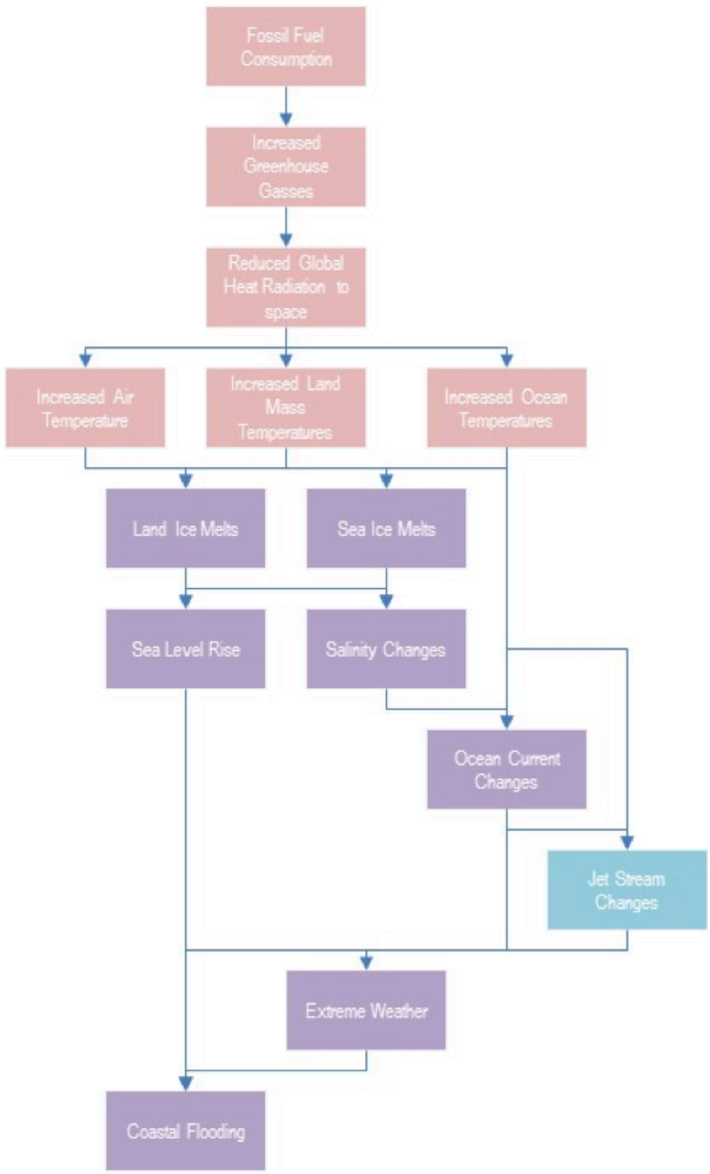


Figure 8: Cause and effect diagram on how fossil fuel consumption flooding can have ripple effects down the chain to coastal flooding

4.3.2. Hierarchical Risk Assessment: Root cause analysis

Probabilistic Risk Assessment processes use inductive and deductive processes to determine where hazards are and assigns a mathematical value to determine risk. There are two main methods for organizing and visualizing the hazards, Fault Tree Analysis (FTAn) and Event Tree Analysis (ETAn) (Figure 9).

Fault Tree Analysis is deductive modeling that looks backward for all events that can lead to a failure. This methodology can be useful for evaluating existing systems by working backward to predict how an element may fail and what are the resulting consequences for the system

Event Tree Analysis is inductive modeling that looks forward for consequences that may arise from events. They are useful for planning new systems especially where there are a range of possible responses. Root cause analysis Ishikawa, or fishbone diagrams, are often used to illustrate event trees. They all aim to roll back the layers of causality to better understand system function and get at the root causes of problemativ events.

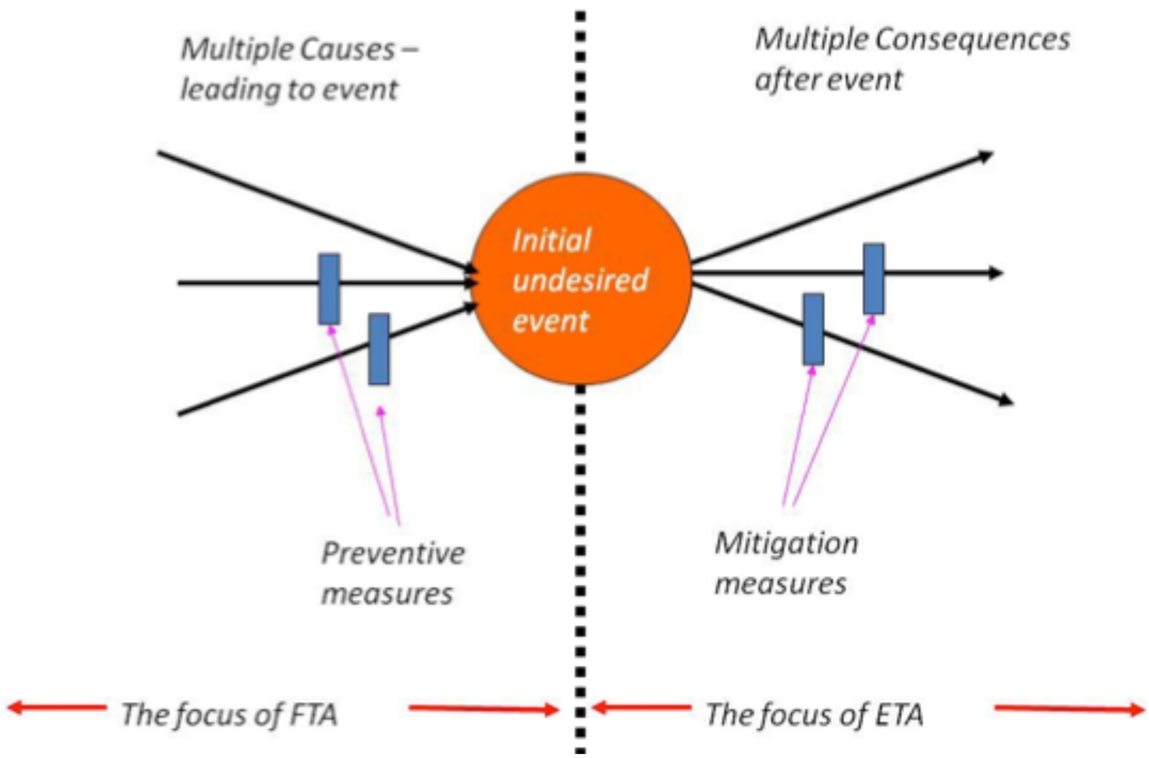


Figure 9: FTA versus ETA is useful in understanding the differences between the two processes. (Source: NEBOSH National Diploma - Unit A | Managing Health and Safety, used with permission)

4.3.3. Developing Event Trees

Event Tree Analysis allows us to start with climate change impacts and look forward to understand the hazards that it creates. Once each of the event scenarios are identified an event tree is developed to identify actions and responses and following each to a terminal action from which no further possible event branches occur. Steps to perform an event tree analysis (Clemens et al. 1998) include the following:

- Define the system: Define what needs to be involved or where to draw the boundaries.
- Identify the accident scenarios: Perform a system assessment to find hazards or accident scenarios within the system design.
- Identify the initiating events: Use a hazard analysis to define initiating events.
- Identify intermediate events: Identify countermeasures associated with the specific scenario.
- Build the event tree diagram.
- Obtain event failure probabilities: If the failure probability cannot be obtained, use fault tree analysis to calculate it.
- Identify the outcome risk: Calculate the overall probability of the event paths and determine the risk.
- Evaluate the outcome risk: Evaluate the risk of each path and determine its acceptability.
- Recommend corrective action: If the outcome risk of a path is not acceptable, develop design changes that change the risk.
- Document the event tree analysis: Document the entire process on the event tree diagrams and update for new information as needed.

Each event has a binary Yes or No action that leads to Resolution Event or another Intermediate Event. Three types of Resolution Events are considered:

- Non-Event: No risk occurs;
- Satisfactory Outcome: An identified action is taken to address the risk; or
- Unsatisfactory Outcome: Remaining risk that requires further action.

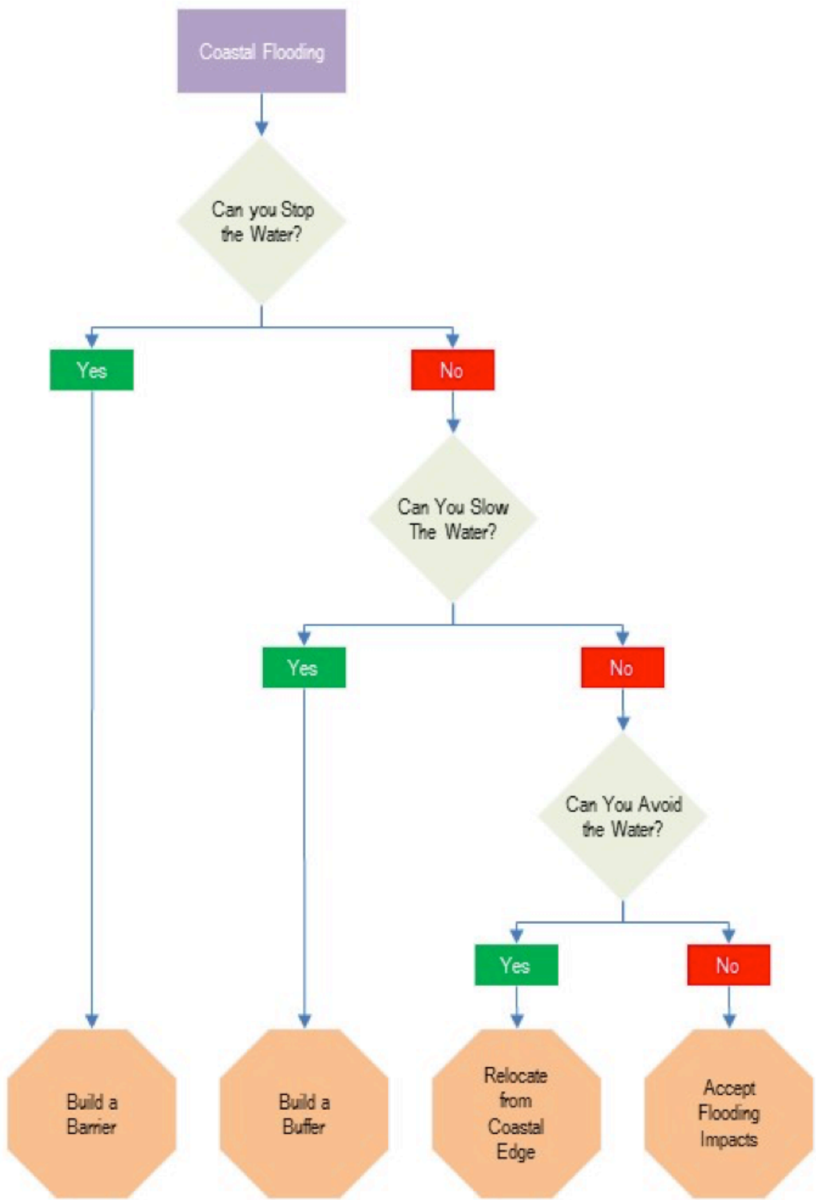


Figure 10: Example of an Event Tree Diagram

4.4. Risk Assessment

Using a methodology similar to the one shown in Figure 3 (Network Rail Risk Assessment Process), most risk assessment processes use some variation of a 4-step process:

- Establish Event Hazard Frequency: What is the likelihood an event will occur? (section 4.4.1);
- Assign Event Hazard Severity: How bad will the event be? (section 4.4.2);
- Calculate Event Risk Rating: What is the risk rating (frequency and severity)? (section 4.4.3); and
- Determine Risk Acceptance: Can we accept the risk? (section 4.4.4).

4.4.1. Establish Event Hazard Frequency

Once the event trees are completed, the team assigns frequency/likelihood of occurrence to the event based on historical data looking at past similar events against their systems relevant operational miles traveled. Hazard frequency is based on MIL-STD 882E and EN50126 Safety Integration Levels for probability of occurrence. Hazard Frequency is one example of how climate change may the risk calculations associated with each hazard type (Table 3).

4.4.2. Assign Event Hazard Severity

Hazard Severity categories are based on criteria defined in MIL-STD 882E (Table 4). California High Speed Rail has established criteria for determining the severity of an event or hazard for each of the following categories:

- Loss of life;
- Environmental Impact;
- Financial loss;
- Operational delays;
- Reputational harm;

For each, what are the consequences of risk being realized? Multiple factors often exist and interact, and each must be evaluated.

Table 3: Example hazard frequencies

Hazard Frequency Table

Frequency		Qualitative Definition	Qualitative Description for the System	Probability of Occurrence	Flooding	Drought	Wild Fire	Temperature Events	Temperature rise F	Sea Level rise ft.	Air Quality Index	Extreme Weather	Earthquake	Landslide
E	Highly Unlikely	These are events beyond planning and other mitigations- only impact responses are available- Infrastructure elements may fail completely	>500 Years	10-6 > p	1:1000	>7	>7 major fires/year	>7	>7	>7	300	1:1000	1:1000	1:1000
D	Remote	Physical systems have capacity to resist impact but significant damage may occur	>100 Years	10-3 > p > 10-6	1:500	7	7 major fires/year	7	7	7	200	1:500	1:500	1:500
C	Occasional	Physical systems have capacity to absorb impact- minor damage with minimal to no operation impacts	>50 Years	10-2 > p > 10-3	1:100	5	5 major fires/year	5	5	5	150	1:100	1:100	1:100
B	Probable	Other systems are used to mitigate risks	>25 Years	10-1 > p > 10-2	1:50	3	3 major fires/year	3	3	3	100	1:50	1:50	1:50
A	Frequent	Operational planning to cope with impact	<10 Years	p > 10-1	1:25	1	1 major fires/year	1	1	1	50	1:25	1:25	1:25

*Values are for illustration purposes only as the State should establish these values as a common standard for State agencies to work from.

Table 4: Hazard Severity Categories

Hazard Severity Table												
Severity	**Category**	**Life:**	**Natural Environment**	**Commentary**	**Economic:**	**Societal:**	**Commentary**	**Built Environment**	**Commentary**	**Geo significance**	**Recovery Time**	**Commentary**
5	Catastrophic	Loss of Life: Many- overwhelms HC infrastructure Injury: Many- overwhelms HC infrastructure	Extinction of species	habitat and/or species completely lost	Infrastructure: >$10B Resources: Businesses: Jobs:	Shutdown of services	All communities are affected	Infrastructure: Complete loss Critical infrastructure: Significant damage	Total loss of distribution Total loss of generation and reservoirs	State	>3 years	Arkstorm equivalent event
4	Critical	Loss of Life: Many- HC infrastructure accommodates Injury: Many- HC infrastructure accommodates	Loss of Biosphere	loss at location but biosphere exists elsewhere	Infrastructure: >$1B Resources: Businesses: Jobs:	Significant disruption	Many Communities are affected	Infrastructure: Significant damage to Critical infrastructure: Moderate damage to	Significant loss of distribution Significant loss of generation and reservoirs	Region	1-3 years	Northridge equivalent event
3	Moderate	Loss of Life: Few- HC infrastructure accommodates Injury: Many- HC infrastructure accommodates	Loss of species	Loss of some species at location but other species and partially functioning habitat remain	Infrastructure: >$100M Resources: Businesses: Jobs:	Limited disruption	Whole community is affected	Infrastructure: Moderate damage to Critical infrastructure: Limited damage to	Widespread loss of distribution Minimal loss of generation or reservoirs	County	6-12 months	
2	Marginal	Loss of Life: Few- HC infrastructure accommodates Injury: Many- HC infrastructure accommodates	Permanent change to habitat/species	permanent disruptions that species and habitat can adapt to e.g. change in migration patterns, change in flowering etc.	Infrastructure: >$10M Resources: Businesses: Jobs:	Limited disruption	Isolated portions of community are disrupted	Infrastructure: Moderate damage to Critical infrastructure: Limited damage to	Local loss of distribution No loss of generation or reservoirs	City	4-6 months	
1	Negligible	Loss of Life: None Injury: Few- HC infrastructure accommodates	Temporary changes	Temporary disruptions that species and habitat can recover from	Infrastructure:>$1M Resources: Businesses: Jobs:	No disruption	Community at large continues to function	Infrastructure: Limited damage to Critical infrastructure: No damage to	Isolated loss of distribution No loss of generation or reservoirs	Neighborhood	0-4 months	

***Values are for illustration purposes as the State should establish these values as a common standard for State agencies to work from.**

4.4.3. Calculate Event Risk Rating

Risk is assessed for frequency and severity and assigned a Risk Assessment Code (Table 5). Each type of hazard is assessed separately, and frequency and severity provide a single score.

Table 5: Risk Assessment Matrix

Risk Assessment Matrix					
Frequency / Severity	5 Catastrophic	4 Critical	3 Moderate	2 Marginal	1 Negligible
(E) Highly Unlikely	5E	4E	3E	2E	1E
(D) Remote	5D	4D	3D	2D	1D
(C) Occasional	5C	4C	3C	2C	1C
(B) Probable	5B	4B	3B	2B	1B
(A) Frequent	5A	4A	3A	2A	1A

Colors provide an indication of the risk level where:

- Red = High Risk
- Orange = Serious Risk
- Yellow = Medium Risk
- Green = Low Risk
- Blue = Eliminated Risk

*This table is for illustration purposes only; it is recommended the State establish these values as a common standard for State agencies to work from.

4.4.4. Determine Risk Acceptance

Once the Hazard Likelihood and Hazard Frequency are determined a score is generated for each evaluation criterion as shown in Table 6. The Risk Acceptance Criteria are developed at the beginning of the risk assessment process and they determine whether the agency can accept a risk. For instance, where the outcome has an "acceptable" risk rating, it may be accepted. If the outcome has a "tolerable" risk rating, the agency may consider other mitigation measures. If the outcome has an "undesirable" or "unacceptable" risk rating, the agency must develop additional mitigation measures until the subsequent branches have a tolerable or acceptable risk rating or the risk is eliminated.

Table 6: Risk Acceptance Matrix

Risk Acceptance Matrix			
Hazard Risk Index	Risk Rating	Action Required	Infrastructure Actions
5E	Catastrophic	Residual risks beyond those in critical category risks cannot be avoided	Accept Impacts
5D, 4E	Unacceptable	Risk must be reduced and managed	Resist Impacts
5B, 4C, 5C, 2D, 3D, 4D, 1E, 2E, 3E	Undesirable	Risk is acceptable only where further risk reduction is impracticable.	Absorb Impacts
4A, 5A, 2B, 3B, 4B	Tolerable	Apply mitigations where reasonably practicable. Risk can be tolerated and accepted with adequate controls.	Mitigate Impacts
1A, 2A, 3A, 1B	Acceptable	Current, normal management processes	Prepare for Impacts

4.4.5. Risk Mitigation

At a program level, it is appropriate to look at larger issues such as where to spend money or expend effort to mitigate risk if an agency is resource constrained. In the example below from the US EPA (Titus 2007), several criteria are identified that are useful for evaluating mitigation measures.

- Economic Efficiency: Will the initiative yield benefits substantially greater than if the resources were applied elsewhere?
- Flexibility: Is the strategy reasonable for the entire range of possible changes in temperatures, precipitation and sea level?
- Urgency: Would the strategy be successful if implementation were delayed ten or twenty years?
- Low Cost: Does the strategy require minimal resources?
- Equity: Does the strategy unfairly benefit some at the expense of other regions, generations or economic classes?
- Institutional feasibility: Is the strategy acceptable to the public? Can it be implemented with existing institutions under existing laws?
- Unique or Critical Resources: Would the strategy decrease the risk of losing unique environmental or cultural resources?
- Health and Safety: Would the proposed strategy increase or decrease the risk of disease or injury?
- Consistency: Does the policy support other national state, community or private goals?
- Private v. Public Sector: Does the strategy minimize governmental interference with decisions best made by the private sector?

4.4.6. Monitoring

Once a risk assessment is complete and all mitigation measures that can be taken have been identified, a risk baseline can be established. From this baseline, it is possible to evaluate climate change on an ongoing basis as new data becomes available, update assets as systems age and components are added or replaced, input actual frequencies and severities as events occur.

5. Reference Standards and Resources

Below, we identify reference standards that the California High-Speed Rail Authority uses for its planning and highlight additional resources that provide good examples of the components of PRA discussed above.

Standard EN50126 - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) EN50126 establishes design standards based on the use of the system under various conditions. It incorporates a comprehensive risk assessment/mitigation protocol to provide a system that achieves a safety level As Reasonably Low as Reasonably Practicable (ALARP). ALARP allows one to address uncertainty and acknowledge in a structured way where residual risk may still exist. Each system is assessed individually and is assessed as an overall interactive syste. California High-Speed Rail Authority (CHSRA) uses EN50126 to define its RAMS criteria and is now developing climate adaptation and resilience criteria into the program using this methodology.

MIL-STD-882E, DEPARTMENT OF DEFENSE STANDARD PRACTICE: SYSTEM SAFETY (11-MAY-2012)
This Standard is approved for use by all Military Departments and Defense Agencies within the Department of Defense (DoD). It is referenced in FRA 49 CFR Part 238 Subpart G (3). This system safety standard practice is a key element of Systems Engineering (SE) that provides a standard, generic method for the identification, classification and mitigation of hazards. Systems Engineering is a process that focus on the idea that all components of a system are interrelated and that there are cause and effect relationships that must be evaluated. California High-Speed Rail Authority (CHSRA) uses MIL-SDT-882E for risk identification, quantification, mitigation and acceptance measures.

NASA-STD-8739-8 NASA Systems Engineering Handbook SP-610S June 1995 This standard addresses risk management as part of its larger program management strategy. It also addresses probabilistic cost and effectiveness as it relates to uncertainty and modeling. NASA-STD-8739-8 deals with RAMS as part of the program management strategy and addresses measurement and verification which points to the need to be able to evaluate the completed work against the program and project goals to understand if what was done fundamentally works as it was intended. Finally this standard discusses the relationship of Event Tree Analysis to Probabilistic Risk Assessment.

Fault Tree Handbook NUREG-0492 United Stated Nuclear Regulatory Commission January 1981
The fault tree handbook provides a systems approach to decision making. It discusses Failure Mode Effect and Criticality Analysis as a method for identifying faults and their effects on the larger system and discusses Preliminary Hazard Analysis.

NASA Fault Tree Analysis (FTA): Concepts and Applications (Bill Vesely)
The document provides detailed examples of how an FTA is developed.

RRC Training NEBOSH Nation Diploma – Unit A: Managing Health and Safety element; A3-Identifying Hazards, Assessing and Evaluating Risks.

A Scalable Systems Approach for Critical Infrastructure Security Sandia National Laboratories Sand REPORT SAND2002-0877 April 2002
While focused primarily on security, the process is easily adaptable to climate assessment. It contains an extensive appendix of risk assessment tools for infrastructure.

How-To-Guide (FEMA386-5): Using Benefit-Cost Review in Mitigation Planning
This is a good example of using PESTEL (STAPLEE) in a qualitative risk assessment process.

ISO **31000:2009 – Risk management – Principles and guidelines**
ISO provides the global standard for risk management, and show how to integrate risk management with other ISO standards.

The New York City Panel on Climate Change Climate Protection Levels report
This is a good example of assigning probability to climate change events.

SSMP: California High-Speed Rail Safety and Security Management Plan
The SSHP is a good example of a risk management plan.

6. References

Clemens, P.L.; and Rodney J. Simmons (1998). "System Safety and Risk Management". *NIOSH Instructional Module, A Guide for Engineering Educators.* Cincinnati, OH: National Institute for Occupational Safety and Health: IX–3 – IX–7.

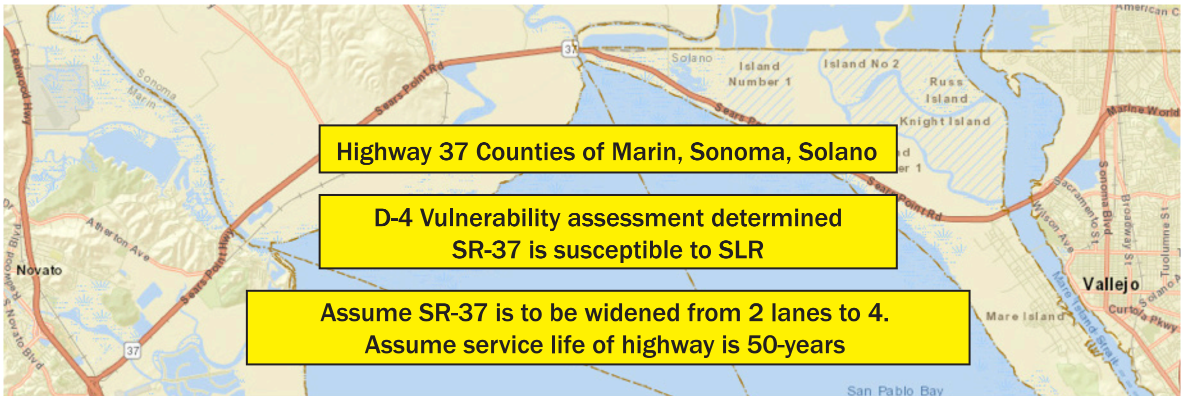
Titus, J.G. (2007) Strategies for adapting to the greenhouse effect. *Journal of the American Planning Association*. 56:311-323. (Available at: https://doi.org/10.1080/01944369008975775)

8 Sea Level Rise on State Route 37 Hypothetical Case Study

Accounting for the Threats from Sea-Level Rise (SLR) along State Route (SR-37): A Hypothetical Example

Gurdeep Bhattal, P.E.
Senior Transportation Engineer, Hydraulics and Stormwater Branch
July 2018

The following example from the transportation sector describes a challenge that infrastructure designers may face if they wish to account for climate change in their ongoing operations, maintenance or plans to build new infrastructure. While the section of Highway 37 that crosses Marin, Sonoma and Solano counties is a real-life example of stretch of road that is vulnerable to sea-level rise (SLR), Caltrans has not completed its analysis and plans. Thus, we consider this example still hypothetical.



SLR projections available vary by emissions scenario and model projections. For 50-year project life, select SLR for year 2070 using RCP 8.5 at 95th percentile and use the USGS Coastal Storm Modeling System (CoSMoS) model projections.

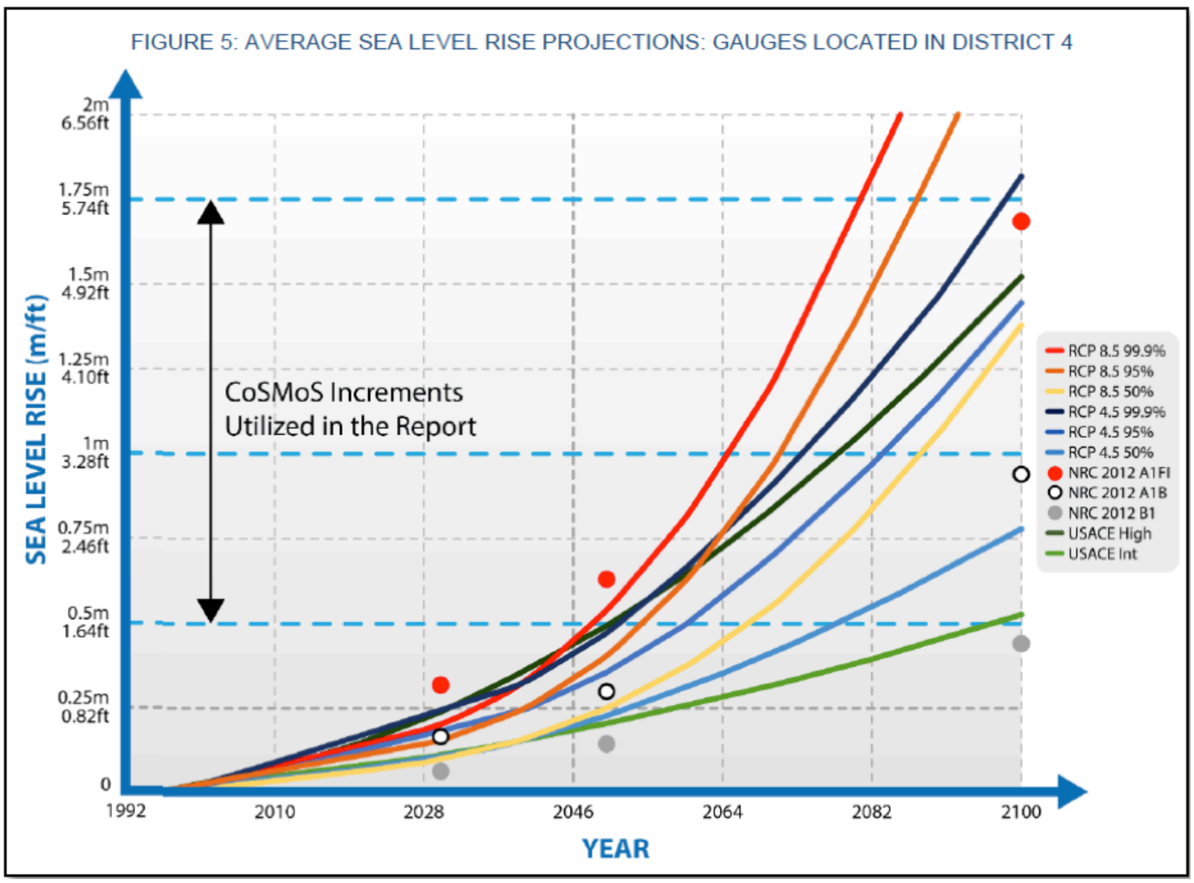


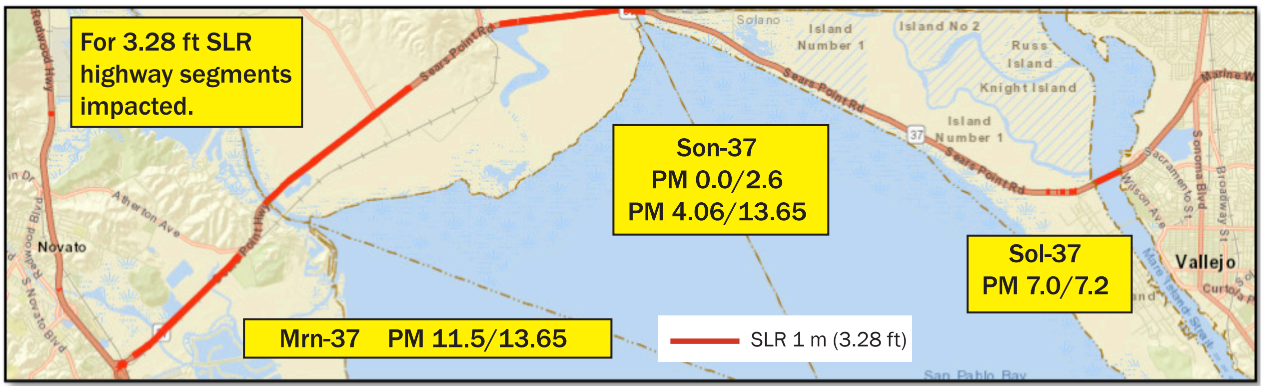
FIGURE 5: AVERAGE SEA LEVEL RISE PROJECTIONS: GAUGES LOCATED IN DISTRICT 4

Once SLR vulnerabilities are identified, a number of steps should be taken to assess and select strategies to mitigate SLR-related risks (occasional flooding, permanent inundation, erosion, saltwater intrusion and related corrosion.

Some Alternatives to Mitigate SLR

Partner with U.S. Army Corps of Engineers and other agencies (e.g., California Coastal Commission) and construct seawalls to protect low lying areas and build highway at existing elevations.

1. Build a viaduct to elevate the vulnerable segments of the highway above the projected SLR. If no additional measures are considered there may be potential impacts on ecological systems resulting from ocean waters encroaching onto the existing marsh land.
2. Construct an armored levee at the impacted segments of the highway and construct the highway on the levee. If no additional measures are considered there may be potential impacts on ecological systems resulting from ocean waters encroaching onto the existing marsh land.
3. Construct an armored levee along the coastline and realign the highway on the levee.
4. Evaluate various alternatives and select an alternative which is most feasible, cost effective and may be constructed within a reasonable schedule.



9 Building Energy Systems Design: Data, Standards & Practices

Case Study on Building Energy Systems Design

Martha Brook, P.E.
Technical Advisor, Commissioner Andrew McAllister,
July 2018

Building Energy Systems Design: Data, Standards & Practices

Engineered systems provide heating and cooling in buildings for indoor comfort and also ventilation for indoor air quality. These systems are designed to work within specific outdoor climate regimes. The data that characterizes these climate regimes is typically based on actual weather observed and recorded over time. Outdoor temperatures, humidity, solar radiation, wind speed and wind direction are recorded at weather stations around the globe.

National design standards and guidelines include statistics on temperature and humidity data and how to use this data to size heating and cooling systems. National standards also specify indoor temperature and humidity conditions that must be met for general human comfort. Buildings in California must adhere to the Energy Efficiency Standards, which include requirements to estimate the expected energy usage of the building design as part of the permitting process. This approach uses hourly weather data that is representative for the proposed building location. Further, national equipment energy efficiency standards include test procedures that must be completed and published by manufacturers before products can be sold in the U.S. These procedures specify the outdoor temperature and humidity levels that the equipment must be tested at, based on average weather conditions.

Typical engineering practices for building energy systems use historical weather data that will likely not be representative of the future climate conditions over the life of the buildings being designed, constructed and later renovated. Using climate patterns experienced in the past to design energy systems operating in the future limits the ability of these systems to provide critical building services in a future of climate change.

Changes Needed to Address Climate Resiliency

The building design community is beginning to acknowledge that past practices cannot be used to provide climate resilient building energy systems. Much more attention is needed from state and national standard setting bodies to establish design guidance and requirements that include attention to future climate expectations and levels of uncertainty.

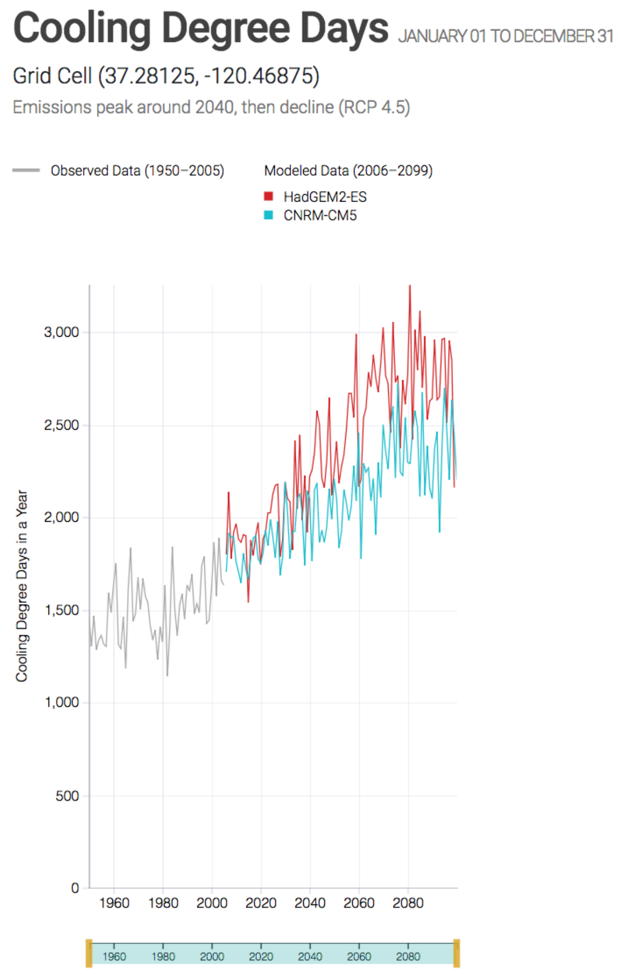
System Design Data Should Capture Future Climate Conditions

An important first step is to establish weather data used in energy system design that reflects future climate expectations. Design data should reflect expected changes in magnitudes, such as extreme temperatures, and changes in patterns, such as diurnal and seasonal fluctuations. Data on outdoor temperatures, solar radiation, wind speed and wind direction should reflect climate change futures.

Scientists have modeled global climate change over a broad range of scenarios and also downscaled these models for use by sub-national governments, such as California. The chart below exemplifies the climate projections that should be translated into energy system design guidance. The charted data is from the Cal-Adapt data portal, which has the objective of sharing scientific research on how climate change may affect California.

Designing For Uncertainty

Climate change promises an uncertain future. Therefore, building energy systems must be designed to perform well over a wider range of climate conditions. Engineers and other design professionals should select equipment and specify system controls to provide heating, cooling and ventilation efficiently over a broad range of possible climate futures. This will require scenario modeling of the energy systems, analogous to what has been done by climate scientists for critical climate variables.



Number of cooling degree days in a year for the Merced region under the RCP 4.5 scenario. These data are available via Cal-Adapt (http://cal-adapt.org/), used with permission.

10 Infrastructure Standards

As part of the work of the Climate-Safe Infrastructure Working Group (CSIWG), members compiled lists of standards, guidelines and other frameworks that guide how infrastructure in the state must be built. This compilation illustrates that there are dozens of standards, design manuals, bulletins, plans and specifications, design guidance, design criteria and references to rely on in any one infrastructure sector. This compilation begins the important task of identifying which standards are used most prevalently. The next important step will be to complete this list through a systematic survey of state engineers and architects and to identify which ones can accomodate climate change as they are currently written and which ones will need to be updated to safeguard against future climate impacts. This could be an initial action taking by the proposed standing CSIWG.

Building Sector Standards Identified by the CSIWG

New & Existing Buildings, Parking Lots and Garages	• Uniform Codes: Uniform Mechanical Code (UMC), Uniform Electrical Code (UEC), Uniform Plumbing Code (UPC) • California Codes: T-24 Part 6 (energy and water efficiency) – 3 year cycle, T-24 Part 11 (green building standards), T-20 – appliance and equipment standards • ASHRAE handbook of fundamentals: mechanical design • State Facilities Policy: Management memos, state administrative manual, Executive Orders, legislation (some of these include LEED by reference) • Regulators relating to grid reliability - CAISO, CPUC, CEC (power point siting, IOU regulations) • LEED certification requirements for new and existing buildings • State Administrative Manual (SAM) chapter 1800
Energy Demand for Space Cooling	• Cooling Degree Days are used to estimate changes in energy demand for long-term planning (~30 years).
Energy Demand for Space Heating	• Heating Degree Days are used to estimate changes in energy demand for long-term planning of the energy system.

Transportation Sector Standards Identified by the CSIWG

Culvert Design	• Caltrans Highway Design Manual (HDM) California Codes: T-24 Part 6 (energy and water efficiency) – 3 year cycle, T-24 Part 11 (green building standards), T-20 – appliance and equipment standards • FHWA Hydraulic Design of Highway Culverts (HDS-5) • FHWA Urban Drainage Design Manual (HEC-22) • FHWA Introduction to Highway Hydraulics (HDS-4) • Caltrans Standard Plans and Specifications • Caltrans Design Information Bulletins (DIB's)
Pavement Design	• Caltrans Highway Design Manual (HDM) • Design Information Bullettin (DIB) 79 Design Guides and Standards for Roadway Rehabilitation Projects • DIB-81 Capital Preventive Maintenance (CAPM) Guidelines • Caltrans Standard Plans • Standard Specifications
Bridge Design	• California Amendments to AASHTO LRFD Bridge Design • Seismic Design Specifications for Steel Bridges • Seismic Design Criteria • Bridge Design Details • Bridge Design Aids • Caltrans Highway Design Manual • Bridge Design Practice
Signals and Signage Design	• Overhead Sign Structure • Guide Caltrans Standard Plans
Caltrans Buildings	• California Building Standards Code • Title 24 Code of California Regulations • 2016 California Green Building Standards Code • California Energy Code • California Mechanical Code
Safety Rest Areas	• California Building Standards Code • Title 24 Code of California Regulations • 2016 California Green Building Standards Code • California Energy Code, California Mechanical Code • Highway Design Manual • Storm Water Project Planning and Design Guide
Landscape Areas	• Project Development Procedures Manual • Highway Design Manual • Storm Water Project Planning and Design Guide • Standard Environmental Reference
Roads and Bridges	• California Building Code
Rail System and Busways	• Metro Design Criteria, Technical Requirements, Specifications and Policies
Bus and Rail Maintenance Facilities	• Metro Design Criteria, Technical Requirements, Specifications and Policies
Electrified Fleet Infrastructure	• Metro Design Criteria, Technical Requirements, Specifications and Policies
Rail Cars and Buses	• Fleet Technical Requirements, Specifications and Policies

Water Sector Standards Identified by the CSIWG

Dams	• California Water Code • ASCE journals & publications • ASTM – American Society for Testing and Materials • ACI – American Concrete Institute • AISC – American Institute for Steel Construction • USACE – Engineering Manuals • NOAA – HMR Reports and Atlas 14 precipitation data • USBR Publications • FEMA Manuals • U.S. Geological Survey • NGA-West 2 ground motion prediction equations • CEQA – California Environmental Quality Act • Caltrans Standard Plans and Specifications • Uniform Building Code
Pipelines/Tunnels	• ASME B31.4 • ASME B31.8 • American Lifelines Alliance (seismic)
Canals	• NOAA - Precipitation Models and HMR Reports • HMR Reports • USBR - Design Standard
Levees	• USACE - Engineering Manuals • DWR - Levee Design Standards • HEC - H&H Modeling
Pumping/Generating Plants	• California Building Code • USACE - Engineering Manuals • DWR - Design Standards

Energy Sector Standards Identified by the CSIWG

Electrical Transformers	• National Electrical Manufactures Association (NEMA)

11 Barriers to Building Climate-Safe Infrastructure

AB 2800 stipulated, in Section 2 (c), that “[t]he Working Group shall consider and investigate, at a minimum, the following issues: (1) The current informational and institutional barriers to integrating projected climate change impacts into state infrastructure design.” The topic of barriers was considered throughout the Climate-Safe Infrastructure Working Group’s (CSIWG) deliberations and was also an integral part of the webinar series that supported the CSIWG’s work.

In this Appendix, we summarize and discuss the barriers we have identified throughout this project. We list the full list of barriers that were discovered, organized by the stages in the adaptation process[312] (which are similar to the stages in an infrastructure lifecycle) and by type of barrier (for example, informational, institutional, financial etc.).

Adaptation Process		Types of Barriers			
Phase	**Stage**	**Informational**	**Capacity/skill**	**Attitudinal**	**Political**
Understanding	Just becoming aware of climate change risks	• Inconsistent risk information (FEMA vs. other flooding info) • Lack of knowledge who is unaware/uninformed so outreach can target those groups • Lack of a national or state climate information system	• Lack of attention to and knowledge about CC in general • General lack of systems perspective on CC risks to interrelated infrastructure	• Climate skepticism among engineers • Climate skepticism among decision-makers (and public) • Assumptions about the public • No leadership to shape public opinion • Lack of education • Perceived lack of urgency • Lack of motivation to get interested in and knowledgeable about CC risks and resilience • Culture does not value long-term thinking	• Declined federal leadership reduces importance • Greater need for state leadership on adaptation • Lack of leadership outside government
	Gathering info to better understand risks	• Lack of centralized data/ information repository • Demographic shifts variably well understood • Cascading and teleconnected impacts poorly understood • Compound risks only partially known • Lack of certain climate risk data • Env. response to CC only partially understood (e.g., SLR > coastal geomorphology, bathymetry) • Reduced federal investment in research funding to generate relevant information • Lack of dynamically updated, central data depository	• Lack of sufficient upfront engagement of scientists and engineers and planners to assess information needs • Lack of guidance/requirements on data • Lack of knowledge about global climate models • Social equity not a consideration from the start • Lack of requirement to prioritize CC > if capacity is limited > back-burner • Inappropriate use of scientific info (e.g. conflating precision with accuracy)	• Difficulty of moving from scenario approaches (top-down) to bottom-up approaches (RDM, scaling) • Initial impact assessments can be scary and overwhelming, thwarting commitment to a fuller assessment • Social equity typically not a consideration from the start • Designers not included from the start • Cultural heritage and historical resources and structures frequently ignored still in adaptation planning	• Lack of political will to look into issue • Challenging political climate • Lack of political backing of non-state-owned infrastructure owners (e.g., ports, airports) from state (executive or legislative side) in pushing to overcome federal barriers • Diverse political opinions about climate change can hinder regional collaboration
	Completed assessment of climate change risks	• Certain forward-looking science not available (e.g., precipitation data, development) or available but not useful • Methodological gaps • Lack of roadmap for identifying critical infrastructure/facilities in each sector • Scientific info not actionable • Use of rules of thumb vs. use of data • Floodplain mapping for state infrastructure is incomplete/ missing	• Lack of requirements for process of using data • Lack of systems thinking/ perspective • Lack of knowledge of what to do with CC information • Inadequate education of engineers on climate change and on range of professional skills for effective stakeholder engagement and multi-disciplinary team work • Lack of training on how to deal with uncertainty	• Skepticism of climate models • Inadequate public engagement in risk/vulnerability assessment	• Lack of political will to use forward-looking climate science • Lack of list of “choke points” in each infrastructure sector prevents issue rising as political priority

Adaptation Process		Types of Barriers			
Phase	**Stage**	**Informational**	**Capacity/skill**	**Attitudinal**	**Political**
Planning	Brain-storming range of options	• Insufficient funding for strategic planning and regional coordination • Only limited funding options considered • Temporal misalignment of available funding programs (difficulty in combining sources)	• FEMA requirement to rebuild to pre-disaster design and function unless the prevalent local code is more progressive • NFIP exempts historical structures from flood protection requirements, thus undermining that risks are fully assessed, planned for and mitigated • Legislation often without technical input so can be ill-informed and needs to be corrected through procedural guidelines and regulation	• Limited technical assistance to date • Lack of long-term planning for facilities • Lack of partnerships, delayed coordination in G/NBI projects	
	Completed assessment of potential options	• Limits of existing CBA methods • Limited ability to value non-monetary risks and benefits • Cost effectiveness requirements of most options • Tradeoff: cost vs. risk • Perception/reality that jobs are at risk	• ADA may restrict certain options • Historic preservation (ditto) • Prevalent codes and standards • Design immunity only if following existing standards • Lack of clarity on liability for CC risks • Lack of incentives • Lack of policy guidance • No requirement to use life cycle assessment informed by CC	• Lack of process to value resilience • Limited (sometimes lacking) cross-jurisdictional coordination among local, state, federal entities • Zoning inflexibility can inhibit cross-sector coordination • Lengthy delays from assessments to implementation (up to 20 years)	• Greater difficulty of integrating CC considerations in retrofits of existing infrastructure than in new infrastructure
	Selected subset of adaptation options assessment of climate change risks	• Higher upfront cost of climate-resilient designs • Long-term funding uncertainty • Unfunded mandates • Restrictions on use of disaster funding • Discount rates devalue the future	• Tight connection between standards and professional liability (reinforces risk aversion, maintaining current practice, even if no longer best practice) • Lack of clarity on who is liable when deviating from existing standards	• Lack of forward-looking standards • Old backward-looking/static standards • Contradictory standards • Competing rating systems	

Adaptation Process		Types of Barriers			
Phase	**Stage**	**Informational**	**Capacity/skill**	**Attitudinal**	**Political**
Managing	Begun implementing options (design & construction)	• Insufficient or unclear funding sources for G/NBI and other infrastructure • Failure or inability to combine/ coordinate different funding sources/agencies • Cost escalation in construction undermines implementation of sustainability/ resilience measures	• Rating systems not adopted as code • Lack of technical standards to guide implementation • Lack of bid criteria • Unclear authority over multi-jurisdictional G/NBI projects • Too much flexibility in laws creates uncertainty for implementation; people are not willing to be the first to test legal limits • Inadequate implementation of codes and standards • Lack of code enforcement	• Need for partnerships to implement multi-jurisdictional projects (added workload and complexity) • Permitting delays • Loss of Community Redevelopment Authorities (loss of coordination, power) • Existing standards and guidelines too restrictive	• Industry lag time in adopting new practices
	Operating, maintaining and monitoring performance of actions	• Lack of money for longitudinal tracking/ monitoring • Lack of funding to implement evaluation	• Lack of accountability that repair/ replacement actually happens • Lack of technical standards to guide evaluation • Lack of requirement to evaluated projects for climate change	• Changes in building use • No process to evaluate evaluation • No process to assess/evaluate risk management process	• Need for more demonstration projects and monitoring of effectiveness
	Evaluating and reassessing options	• Difficulty of keeping infrastructure current and in state of good repair	• Lack of performance goals • Lack of professional standards/ standards of care • Lack of accountability (esp. long-term) • Disconnect of accountability of owner/developer from accountability of designer > becomes a public liability	• Competing rating systems (old, mandatory and newer, voluntary) • Externalization of certain consequences > ignores systemic consequences	

Political Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Development	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Lack of federal political leadership on climate change in general, resulting in de-prioritization at best and unhelpful controversy at worst, as well as inadequate progress on federal infrastructure investment						✓			✓	✓
Against a background of politicized debate and near-term priorities absorbing limited funds, lack of political will to prioritize climate change and commit to climate preparedness and adaptation										
Lack of political will to address past legacies of institutional racism, neglect of certain communities and to redress those infrastructure inequities now								✓	✓	
Inability to generate public support for infrastructure investment, including to effectively communicate costs and benefits										
Lack of commitment to aspects of infrastructure operation and maintenance (e.g. monitoring) if they don’t generate political benefits						✓		✓	✓	✓
Lack of support for novel infrastructure designs (e.g., green/ nature-based infrastructure)										

Legal/Regulatory Barriers	**Rec. 1** Climate Safe Path for All	**Rec. 2** Fund Climate Science	**Rec. 3** Engineering/ science interaction	**Rec. 4** Pre-develop-ment	**Rec. 5** Stakeholder Engagement	**Rec. 6** Climate-cognizant standards	**Rec. 7** Equitable finance + better economic tools	**Rec. 8** Workforce Develop-ment	**Rec. 9** Standing CSIWG	**Rec. 10** Policy for project translation
Lack of policy guidance on what to plan for and how				✓		✓			✓	✓
Lack of rules and regulations that would foster/require consideration of climate change (e.g., no requirement to assess exposure to climate change; no requirement to use certain data, no requirement to do a life cycle assessment)										
Lack of design criteria, standards, performance goals/targets and guidelines for inclusion of climate change in infrastructure design, implementation, monitoring and evaluation						✓		✓	✓	✓
Lack of professional standards of care										
Lack of regulatory incentives (e.g., accelerated permitting)						✓		✓	✓	✓
Rating systems are not adopted as code (i.e. don't have regulatory power)										
Lack of code enforcement, including exemptions after disaster or in other special circumstances, and lack of accountability for inadequate designs or maintenance								✓	✓	✓

Legal/Regulatory Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Develop-ment	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Unclear jurisdiction where infrastructure crosses jurisdictional lines (including the possibility that different jurisdictions have different priorities, capacities and needs)						✓			✓	✓
Different or even contradictory standards and risk assessment approaches (e.g., FEMA's recognition of certified levees only; NFIP's exemption of historical buildings from flood protection requirements even in high-hazard zones)										
Existing laws and regulations that could or have already been experienced as limiting the consideration of climate change, even if infrastructure owners have been willing to do so						✓			✓	✓

Institutional Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-development	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Development	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Differences in planning time horizons across levels of government or types of infrastructure				✓	✓			✓	✓	✓
General lack of longer-term planning										
Lengthy time from initiation to complete implementation of infrastructure projects (up to 20 years), (e.g. due to lengthy reviews and permitting)				✓		✓			✓	
Lack of processes for comprehensive valuation, evaluation, assessing the quality of risk assessment, risk management or evaluation approaches										
Competing rating systems (mandatory, voluntary) and competing standards (backward-looking/static standards, forward-looking standards)						✓			✓	
Externalization of certain consequences from systemic assessment										

Informational and Knowledge Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Develop-ment	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Lack of knowledge and understanding in certain areas, requiring more research (e.g., in methods, adaptive design, trade-offs, value/benefits of resilient design) or cross-disciplinary education on existing knowledge							✓		✓	
Lack of investment in certain types of research and monitoring (e.g., no benchmarks, no M&E hence no understanding of performance; lack of metrics)										
Existing knowledge and approaches are contested (i.e. experts do not agree on what is most credible or reliable); as a result, practitioners avoid new/contested approaches or rely on outdated information and methods						✓		✓	✓	✓
Lack of information in usable/ actionable/standardized formats (including incomplete or missing information, inconsistent information or information is not available at the right temporal/spatial scale)										
Lack of (easy) access to information either because the data is proprietary, help by individual researchers or not in a centralized repository										
Lack of guidance on, and familiarity with, how to use data/information/ tools/methods appropriately										

Capacity/skill barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Develop-ment	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Inadequate/narrow/siloed disciplinary or sectoral perspectives on what are in fact systemic, interconnected challenges										
Widespread lack of engagement of scientists and engineers on climate change issues										
Lack of training in and guidance on assessing and interpreting uncertainty and making decisions under uncertainty										
Lack of skills and staff capacity in tracking performance, assessing non-monetary benefits										
Insufficient capability of translating policy and guidance into standards and codes										
Lack of sufficient knowledge about climate change, climate models and lack of expertise in or guidance on how to appropriately use climate data										
Lack of awareness of/education about resilient, adaptive and sustainable designs (including green/ nature-based infrastructure options)										
Lack of training in and guidance on effective stakeholder engagement and other professional skills										
Lack of awareness, familiarity and skill in considering social equity issues in infrastructure planning and decision-making from the start										

Attitidunal Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Develop-ment	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Abiding skepticism of global climate models and sometimes even the reality of climate change										
Lack of acceptance of citizen science as valuable input to monitoring performance										
Neglect of social equity as a central concern, integrated from the start of infrastructure planning										
Perceived incompatibility of green/ nature-based infrastructure with prevailing professional norms										
Strict adherence to established professional norms resulting in resistance to innovation and experimentation										
Premature narrowing of the range of options considered due to assumptions about their public acceptance										
Lack of leadership and related, a pervasive lack of urgency about climate change and lack of commitment to invest in infrastructure										
Culturally prevalent attitudes that do not favor long-term thinking.										
Lack of willingness to pay for resilience (resulting from the above-mentioned attitudes)										
Lack of trust among stakeholders partly due to divergent values and priorities, partly due to past experience										
Varying levels of risk aversion/risk tolerance										

Financial Barriers	Rec. 1 Climate Safe Path for All	Rec. 2 Fund Climate Science	Rec. 3 Engineering/ science interaction	Rec. 4 Pre-develop-ment	Rec. 5 Stakeholder Engagement	Rec. 6 Climate-cognizant standards	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce Develop-ment	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Lack of funding for every stage in the infrastructure lifecycle, including inadequate resources for infrastructure-related research, strategic planning, building infrastructure in general and green/nature-based infrastructure in particular; difficulty of keeping infrastructure in state of good repair (high maintenance costs); and lack of funding for monitoring systems and long-term, ongoing data collection										
Higher upfront cost, particularly of climate-resilient infrastructure										
Long-term funding uncertainty										
Limited funding options available or considered										
Lack of coordination among funding agencies; inability to coordinate or combine funding sources and types due to disconnected timing or other factors; and lack of funding for coordination										
Unfunded mandates										
Lack of monetary incentives to plan for climate change										
Restrictions on use of funds (e.g., disaster recovery funding) or constraining eligibility criteria										
High discount rates that devalue the future										
Difficulties related to valuing risks and benefits and thus with making the economic case for infrastructure investment										

Other Barriers	Rec. 1 Climate Safe Path for All as Policy	Rec. 2 Fund climate science assess-ments	Rec. 3 Engineering/ science interaction	Rec. 4 Better pre-develop-ment	Rec. 5 Stakeholder engagement	Rec. 6 Climate-cognizant standards + governance	Rec. 7 Equitable finance + better economic tools	Rec. 8 Workforce development	Rec. 9 Standing CSIWG	Rec. 10 Policy for project translation
Until recently, lack of a catastrophic weather-related events of the magnitude of Hurricanes Katrina (2005), Sandy (2012) or Maria (2017) in California to generate sufficient media, public and political attention and support for action (recent drought, wildfires, landslides and flooding may raise sufficient awareness)					✓					
Physical limitations related to existing infrastructure (i.e., greater difficulty of integrating climate change considerations in retrofits than in new infrastructure)										
Industry lag time in adopting new practices in design and construction				✓	✓	✓				✓
A general lack of demonstration projects, including monitoring of their effectiveness										

12 Milestones in California Infrastructure Thinking, Planning and Policy-Making

The Climate-Safe Infrastructure Working Group and its main product – this report – were mandated by AB 2800. They join a series of previous state infrastructure-focused efforts and reports, some prepared by or for the State, others produced by outside interest groups that have had a significant impact on state infrastructure planning and thinking. We highlight key examples (without claiming completeness).

2017 Office of Planning and Research (OPR), Planning and Investing for A Resilient California: A Guidebook for State Agencies.

Guidebook provides a process for state agencies to integrate climate change into planning and investment decisions. Implementation of the guidance document is being coordinated with the Strategic Growth Council, the Government Operations Agency, and OPR's Integrated Climate Adaptation and Resiliency Program (ICARP).

2017 Gibson, J.R., Built to Last: Challenges and Opportunities for Climate-Smart Infrastructure in California, Union of Concerned Scientists

White paper summarizes interviews, literature and a workshop of experts which identified needs and barriers to integrating climate change in infrastructure planning and design. Calls for updating of design standards, improvements in the scientific and technical basis for decision-making, increased infrastructure funding and improved governance.

2015 Executive Order B-30-15 and AB 1482 (Gordon, Climate adaptation)

Among other things, the executive order and bill mandate that the Strategic Growth Council incorporate climate impacts into the Five-Year Infrastructure Plan; preference is given to natural/nature-based infrastructure where feasible.

2014 SB 628 (Beale, 2014), Enhanced Infrastructure Finance Districts (EIFDs)

Effective January 1, 2015, EFIDs are distinct districts that may be created by a city or county within a defined area to finance infrastructure projects with community-wide benefits. EFIDs fill the gap created by the dissolution of redevelopment agencies.

2010 Little Hoover Commission, Building California: Infrastructure Choices and Strategy

Calls for a strategy for statewide infrastructure investment that develops a vision for California's future; identifies needs across the different roles of government and prioritizes these needs according to where an investment can deliver the greatest value. Strongly advocated for rethinking how the state meets its infrastructure needs by relying more on demand-side management, expanded revenue sources for infrastructure and expanded use of public-private partnerships.

2009 Hanak, E. and D. Reed, Paying for Infrastructure: California's Choices. Public Policy Institute of California.

Paper argues for deep reforms of the ways in which California finances its infrastructure.

2009 Little Hoover Commission, Bond Spending: Expanding and Enhancing Oversight

Makes recommendations on how to improve efficient spending of bond funding and improve oversight.

2008 Dowall, D. and R. Reid, The California Infrastructure Initiative, Access 32(4): 18-25

Paper makes specific recommendations on how to further improve infrastructure planning and financing in the state.

2007 SB97, CEQA Amendments (effective as of March 18, 2010)

Requires that projects assess their impact on greenhouse gas emissions and hence on climate; lead agencies on projects must also analyze to what extent projects may be exposed to the impacts of climate change in proposed locations (see CEQA Guidelines § 15126.2(a)).

2006 Governor Schwarzenegger's first (20-year) Strategic Growth Plan

Proposes infrastructure funding priorities; also proposes to create two organizations to aid in managing infrastructure development in a more cost effective and accountable manner: Performance Based Infrastructure California (PBI California) and the Strategic Growth Council.

2005 Hanak, E. and M. Baldassare, California 2025: Taking on the Future, Public Policy Institute of California

An edited volume of research on California's population, economy, labor force, governance and infrastructure in 2025. It points to a greater focus on workforce and efficiency, rather than traditional supply-side infrastructure management.

2003 Update of Environmental Goals and Policy Report (initial report from 1973; previously updated in 1978)

Report aims "to articulate the state's policies on growth, development and environmental quality; to recommend specific state, local and private actions needed to carry out these policies; and to serve as the basis for the preparation of the state's functional plans (such as housing, transportation, air and water quality) and for locating major projects such as highways, water projects and university facilities.

2002 Governor Gray Davis delivers the first Five-Year Infrastructure Plan

Later plans are delivered irregularly. None of the released five-year plans have been formally considered by the Legislature.

2001 Commission on Building for the 21st Century, Invest for California: Strategic Planning for California's Future Prosperity and Quality of Life

A Commission established per executive order by Governor Gray Davis calls for infrastructure planning to be considered a shared responsibility of the state (leadership role), federal and local governments, regional agencies, private and philanthropic sectors and the people of California.

1999 Passage of California Infrastructure Planning Act

Act requires the governor, in conjunction with the Governor's Budget, to submit an annual five-year infrastructure plan to the Legislature that identifies the infrastructure needed and funding proposed for state agencies, schools and postsecondary education institutions.

1998 California Business Roundtable, Building a Legacy for the Next Generation

Report by the business community highlights California's lack of a "formal process for considering capital investment within a larger fiscal and policy framework."

1997 Department of Finance, Capital Outlay and Infrastructure Report

Report estimates state infrastructure needs over the next 10 years.

1996 AB 2660 (Aguiar), passage of the Infrastructure Finance Act

Allows local government authorities to utilize public-private partnerships to finance fee-producing infrastructure projects.

1994 Establishment of IBank, The California Infrastructure and Economic Development Bank

IBank's programs in 2018 include the Infrastructure State Revolving Fund (ISRF) Program; Bond Financing Program, including: 501(c)(3) Bonds, Industrial Development Bonds, Exempt Facility Bonds, and Public Agency Revenue Bonds.

1970 State Office of Planning is replaced by the State Policy Development Office

The office is later renamed the Office of Planning and Research; it reports directly to the governor.

1960s Spending on infrastructure peaks in the late 1950s and 1960s during Governor Pat Brown's administration

This is a time marked by increased federal spending, bipartisan support for infrastructure and a rise in tax revenues; the period is followed by declines in the 1970s and has increased through the early 2000s, but sharply declined during the Great Recession of 2007-9. Since then infrastructure funding has increased again.

1959 SB597, State Development Plan

Act creates the State Office of Planning within the Department of Finance; later dissolved and replaced (see 1970).

13 Water Storage Investment Program: California Water Commission and California Department of Water Resources

Project Summary

In 2014, the Water Quality, Supply, and Infrastructure Improvement Act (Proposition 1) was approved by voters. Proposition 1, Chapter 8, allocated $2.7 billion to the California Water Commission (Commission) to fund public benefits associated with water storage projects throughout California. The Commission is implementing requirements of Proposition 1 through the Water Storage Investment Program (WSIP). In developing the WSIP, the Commission wanted to consider the effects of climate change in the evaluation of projects for State investment. To support the Commission in their effort, the Department of Water Resources (DWR) created detailed climate projection datasets for the entire state of California to estimate how water resources are expected to change in the future due to climate change impacts.

Through its regulations, the WSIP considers climate change in two ways, directly into the quantification of public benefits and through an uncertainty analysis. Applicants must use the WSIP-provided climate projection datasets to calculate the public benefits of their project proposals in light of climate conditions in 2030 and 2070. Additionally, the applicants must also provide an uncertainty analysis that assesses how a project's public benefits may be affected by two specified sets of extreme climate conditions. Proposals, submitted in 2017, were reviewed and scored by Commission staff and State agencies responsible for administering the public benefits. The climate data and tools development took nine months and was the collaborative effort of staff members at DWR and Scripps Institution of Oceanography, with support from consultants. For the first time, California was able to produce complex data highlighting local downscaled information on climate and water for 6 km gridded cells across the entire state, which is not currently available in other tools. The datasets will continue to be refined to serve other programs such as supporting planning for local groundwater sustainability efforts.

Drivers

The driver for the tool development was the Water Commission and the public process used in developing the regulations. The Commission wanted to consider climate change while balancing the burden on the applicant and the uncertainties associated with forecasting into the future. The WSIP needed a tool and methodology that local jurisdictions could apply to their project specific operations and specific regional setting. The research and creation of datasets by DWR for WSIP were due to the level of detail that was required that was not available through any other tools or resources. The datasets produced detailed downscaled data that could be used in quantifying public benefits of proposed projects.

Climate Impact Area

Water throughout California is projected to be impacted by climate change. Precipitation patterns are expected to change with climate change, with increases in drought but also extreme storm events. These changes will ultimately affect water storage and also soil moisture throughout the state. As temperatures increase, snow pack in the Sierra Nevada is also projected to decrease substantially. WSIP aims for proposed projects to plan accordingly for localized changes.

Funding Source

The funding source for the climate data and tools development project was from WSIP's administrative costs (Proposition 1 allows up to 5% of funds allocated to a program for administrative costs). The WSIP climate data and tools development project cost approximately $490,000. These funds were a key element in the success of the project as they enabled many more resources and staff to contribute to the project. This comprehensive team included consultants, modelers and staff from DWR, including experts on sea-level rise, hydrology and climate change.

Research and Data

The datasets include downscaled (6 km gridded cell) projections for the climate conditions expected over the next 30 years (2016-2045) and at late mid-century (2056-2085). DWR also simulated State Water Project and Central Valley Project operations under future climate conditions to provide important information about future streamflow, water storage,and water delivery conditions. For project operations, DWR used the CalSim-II model (http://baydeltaoffice.water.ca.gov/modeling/hydrology/CalSim/), which is the standard water operations modeling tool for simulating the operations of the State Water Project and Central Valley Project. Proposals use the datasets to show how their projects will function under expected future conditions in order to show that the projects are resilient to climate impacts and will continue to provide public benefits under a range of uncertain future conditions.

Challenges

This was the first program to require the quantitative analysis of future climate conditions and their use as part of a decision-making process to award competitive funding. Projections of future conditions including climate, population, economics, etc. are inherently uncertain. During the development of program regulations, several parties commented on issues relating specifically to the climate uncertainties. Some commenters argued that the level of uncertainty was so great that the information should not be used for decision making purposes, while other commenters argued that additional analysis needed to be completed to fully explore the uncertainties. Ultimately, the Commission decided that the datasets and tools developed by DWR provided useful information about future condition uncertainty for their decision-making process and that additional analysis to fully explore uncertainties would place undue burden on applicants.

Additional challenges were encountered with the technical development of the datasets and tools. These challenges mostly related to the need to develop a statewide dataset. Historically, DWR has focused its water operations modeling on the major watersheds of the Sacramento and San Joaquin Rivers. DWR has considerable expertise and experience in these watersheds with less expertise and experience in other watersheds throughout the state. Moving to a statewide dataset involved methodological changes to the ways in which DWR has previously created future climate streamflow projections.

Outcome

The datasets were used by applicants for the WSIP funding. These datasets will be further developed and refined to be more user friendly for local water districts. Local jurisdictions complying with Sustainable Groundwater Management Act will be able to use this tool as a way to manage local groundwater under projected climate conditions as well.

The Climate-Safe Infrastructure Working Group

(in alphabetical order)
Dr. Amir AghaKouchak, P.E., University of California, Irvine
Nancy Ander, P.E., California Department of General Services
John Andrew, P.E., ENV SP, California Department of Water Resources
Gurdeep Bhattal, P.E., California Department of Transportation (alt)
Martha Brook, P.E., California Energy Commission
Dr. Dan Cayan, University of California, San Diego: Scripps Institution of Oceanography
James Deane AIA, CDT, LEED AP, PMP, California High Speed Rail Authority/WSP
Dr. Noah Diffenbaugh, Stanford University
Dr. David Groves, RAND Water and Climate Resilience Center, Pardee RAND Graduate School
Dr. Kristin Heinemeier, P.E., University of California, Davis: Energy Efficiency Center
Dr. Robert Lempert, RAND Corporation; Frederick S. Pardee Center for Longer Range Global Policy and the Future Human Condition (alt)
Dr. Cris B. Liban, P.E., ENV SP, Los Angeles County Metropolitan Transportation Authority
Dr. Kyle Meng, University of California, Santa Barbara
Dr. Deb Niemeier, P.E, NAE, University of California, Davis
Bruce Swanger, P.E., California Department of Transportation
Chester Widom, FAIA, California Department of General Services; Division of State Architect

Co-Facilitators and Report Authors

Dr. Susanne C. Moser, Susanne Moser Research & Consulting
Dr. Juliette Finzi Hart, U.S. Geological Survey

Project Support

Keali'i Bright, California Natural Resources Agency
Joseph Wraithwall, California Natural Resources Agency
Elea Becker Lowe, California Natural Resources Agency
Guido Franco, P.E., California Energy Commissions

Suggested citation: Climate-Safe Infrastructure Working Group (CSIWG). 2018. Paying it forward: The Path Toward Climate-Safe Infrastructure in California. Report of the Climate-Safe Infrastructure Working Group to the California State Legislature and the Strategic Growth Council. Sacramento, CA: CNRA, Publication number: CNRA-CCA4-CSI-001.

The full report is available at: http://resources.ca.gov/climate/climate-safe-infrastructure-working-group/

Cover photo credits (top to bottom, left to right): Paul Hanes (DWR), Susanne Moser, John Chacon (DWR), Don McCullough (flickr), Russell Mandy (flickr), Kate Costa (DOE), XFLaw (Wikimedia Commons), Jonathan Parfrey (Climate Resolve). **Back cover photo credit:** DWR

Acknowledgement. The work of the Working Group was funded through a grant from the California Natural Resources Agency to the Berkeley Energy and Climate Institute (BECI), a part of the California Institute for Energy and Environment (CIEE) at the University of California, Berkeley, and constitutes a contribution to the Fourth California Climate Assessment.