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/.

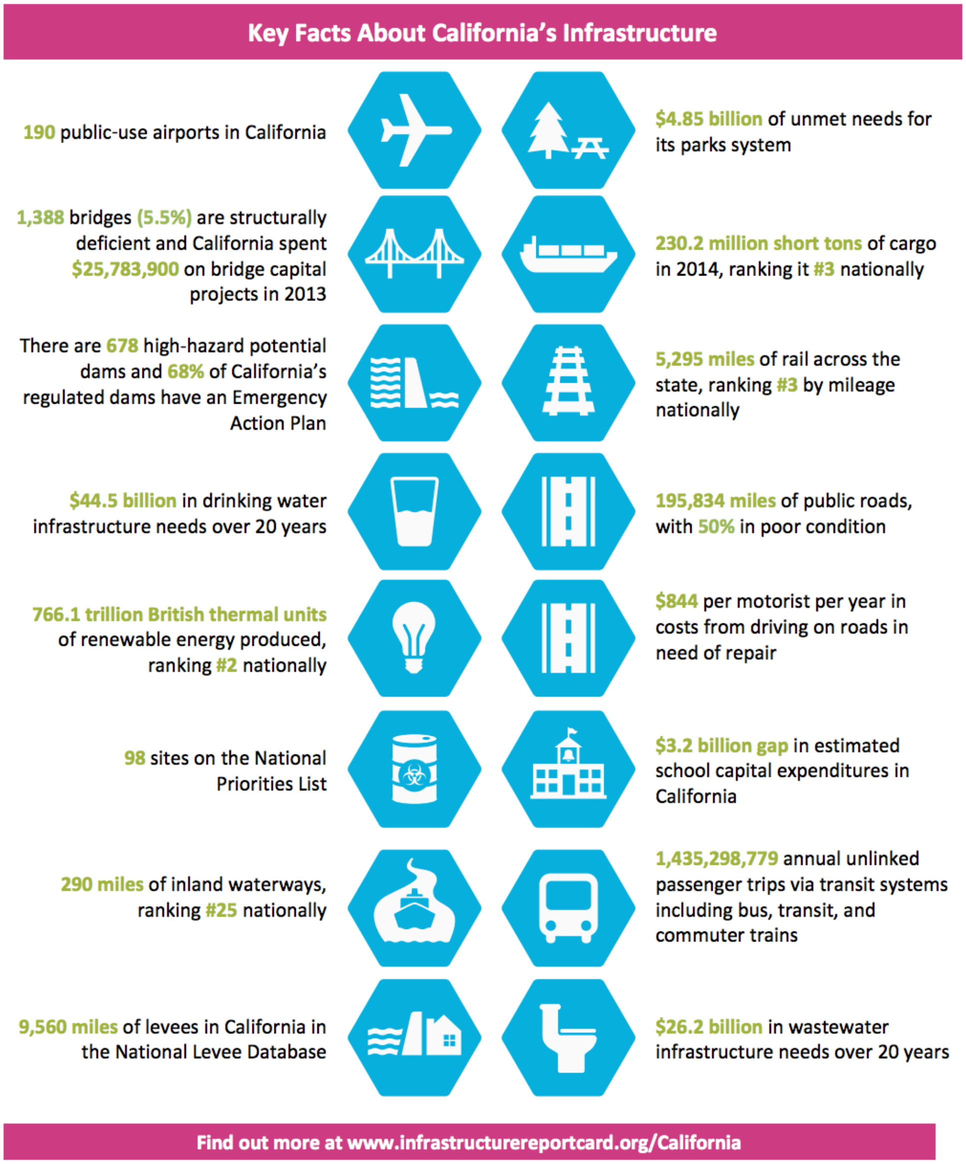

Figure 3.2 The American Society of Civil Engineers' 2017 factsheet on California's infrastructure. The state fared better in some infrastructure categories than in others compared to other states (Source: ASCE 2017[7], used with permission)

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 infra-structure 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)

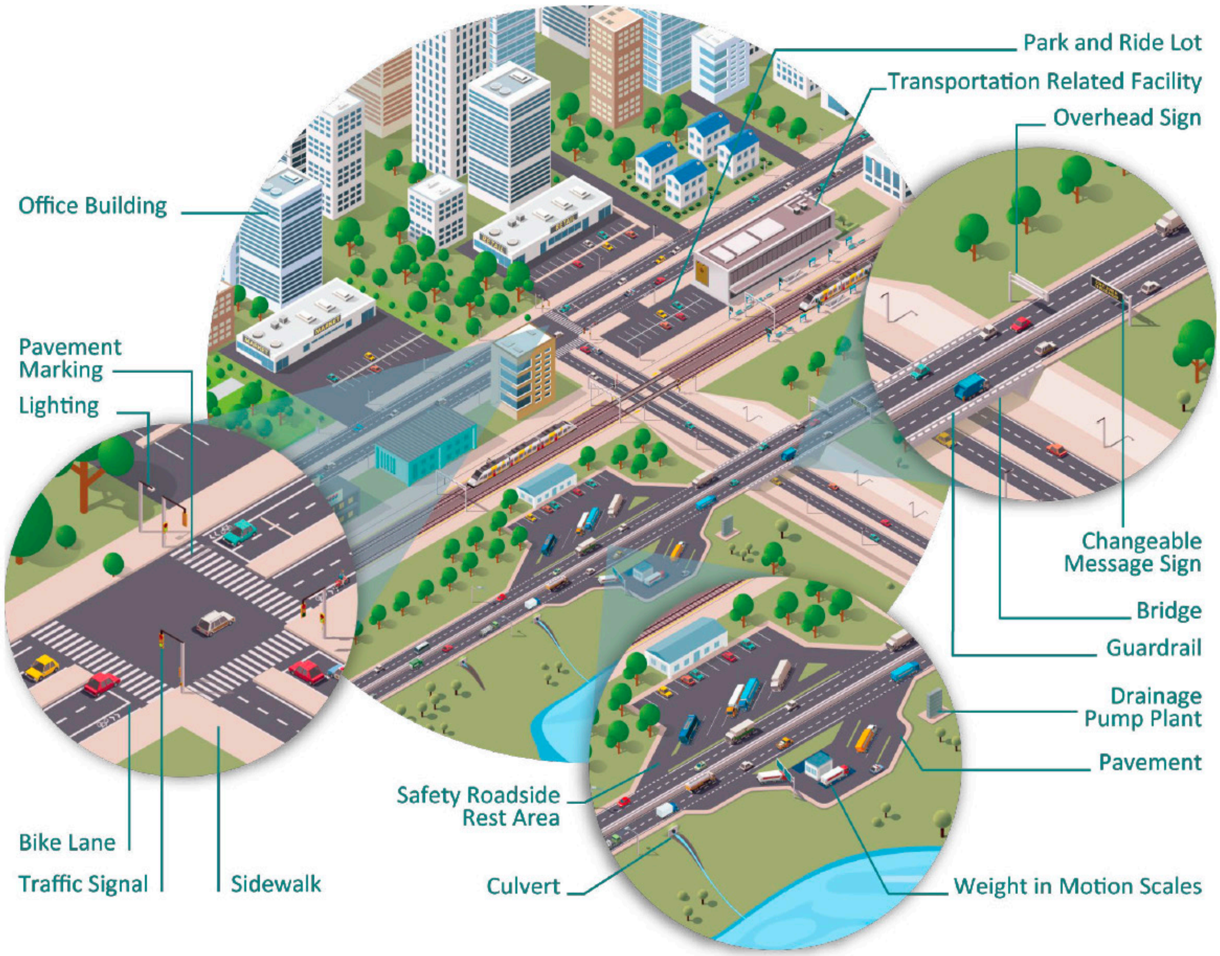

Figure 3.6 California's multi-modal transportation system faces a wide variety of threats from climate change (Source: Caltrans 2018[152], used with permission)

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.

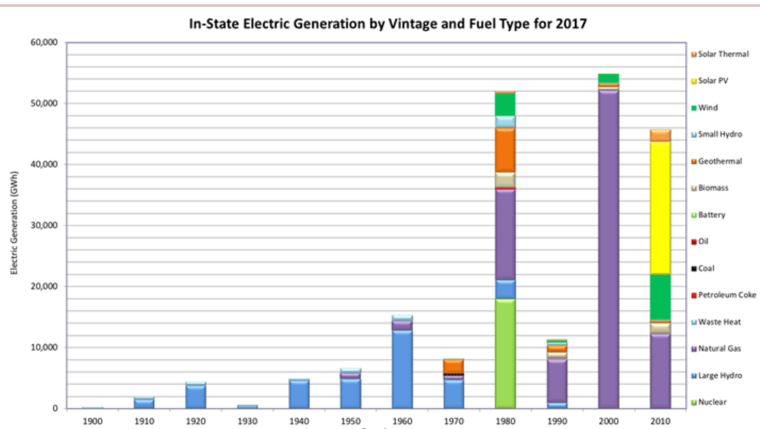

Figure 3.9 California's energy is generated in diverse types of power plants. This graphic shows the type of power generation by decade when it was built, indicating that a significant number of power plants are more than 50 years old by now (Source: CEC 2018[159], used with permission)

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].

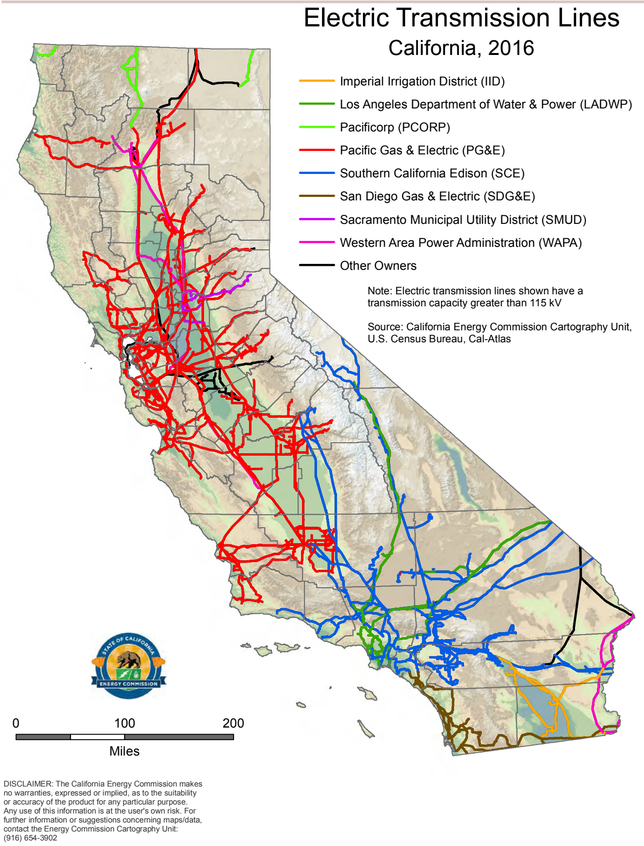

Figure 3.10 A deeply interwoven network of transmission lines connects California's power plants via substations to millions of electricity consumers. (Source: CEC 2016[161], used with permission)

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

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.

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)

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.

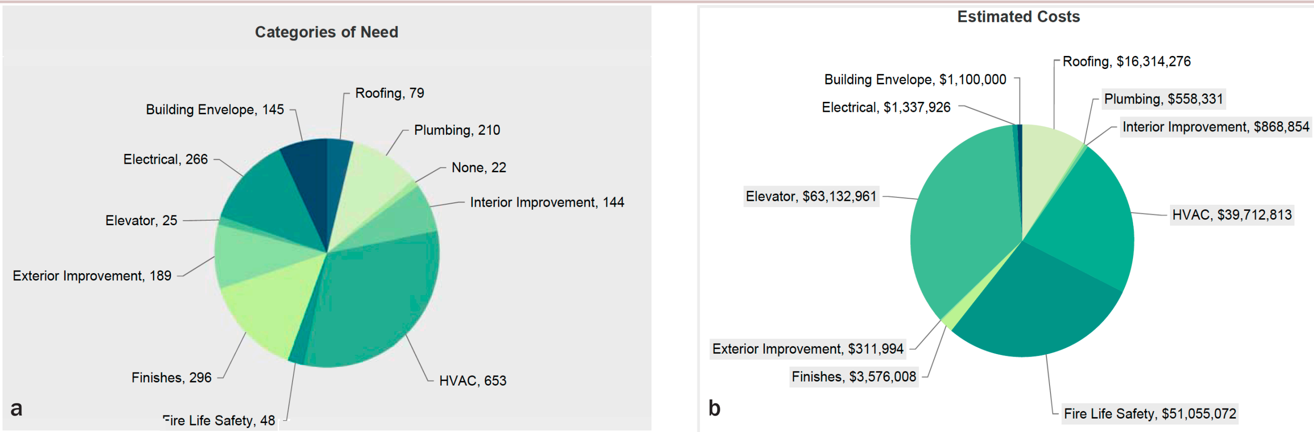

Figure 3.12 (a) California's Department of General Services estimates of the number of projects within DGS-managed buildings that fall under its deferred maintenance program. Many would improve energy efficiency, generate energy savings, and improve building occupants' health and well-being. (b) The 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)