POTENTIAL IMPACTS OF CLIMATE CHANGE ON CALIFORNIA'S ENERGY INFRASTRUCTURE AND IDENTIFICATION OF ADAPTATION MEASURES

STAFF PAPER

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Potential Impacts of Climate Change on California's Energy Infrastructure and Identification of Adaptation Measures

California is experiencing climate change impacts. These impacts include, among others, sea level rise, increasing temperatures, shifting precipitation trends, extreme weather events, increasing size and duration of wildfires, and earlier melting of The Sierra Nevada snowpack. All of these impacts affect energy supply and demand and virtually all aspects of related energy infrastructure including electricity, natural gas and fuels (conventional and renewable), transport, conversion, delivery, and use of energy. This paper describes what is known about many of the impacts today and what is projected to 2100. Potential solutions or strategies are also offered on how to best adapt to these changes.

This paper first presents a brief discussion about potential impacts to California's energy infrastructure and concludes with the identification of adaptation or coping strategies that the State could implement in the near future. Identifying optimal greenhouse gas reduction options as an adaptation strategy will require delicate balancing of air, water, energy, and other objectives. The interplay and linkages of how these objectives are met and their implications for energy supply are beyond the scope of this paper.

Potential Impacts of Climate Change on California's Energy Infrastructure

Projections of changes in climate in California for the 21st century have been developed at fine enough temporal (daily) and geographical (grids about 7 by 7 miles) resolutions for meaningful studies of impacts and adaptation, some of which are mentioned in this document.[1] In addition, the Scripps Institution of Oceanography has estimated hourly sea level scenarios that not only take into account long-term changes in sea level but also fluctuations in sea levels due to tides and storms. The impacts identified in this section are based mostly on these climatic and sea level scenarios.[2]

This section first discusses impacts due to sea level rise and then focuses on impacts due to changes in temperature and precipitation levels.

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[1] Cayan, D., et al., Climate Change Scenarios and Sea Level Rise Estimates for California 2008 Climate Change Scenario Assessment. Draft PIER Report. 2008

[2] It is important to note that the scenarios are based on statistical models that translate the outputs from global climate models to California. Work is underway to develop more sophisticated scenarios using dynamic regional climate models.

Sea Level Rise

During the past century, sea levels along California's coast have risen about seven inches. From 1961 to 2003, global average sea level rose at a rate of 0.07 inches per year and at an accelerated average rate of about 0.12 inches annually during the last decade of that period.[3] Sea-level rise is expected to accelerate and proceed at significantly higher rates than previously thought. Recent estimates indicate that sea-level rise over the 21st century could increase over its historical rate by a considerable amount. By 2050, sea-level rise could range from 30 to 45 cm (11 to 18 inches) higher than 2000, and by 2100, sea-level estimates could be 60 to 140 cm (23 to 55 inches) higher than 2000. As sea level rises, there will be an increased rate of extremely high sea-level events, which can occur when high tides coincide with winter storms and their associated high wind wave and beach run-up conditions. These high sea-level events can be exacerbated by El Niño occurrences.[4]

California open coastal areas rated as having "very high" and "high" vulnerability to sea-level rise according to the U.S. Geological Survey's Coastal Vulnerability Index are in Humboldt Bay between the cities of Arcata and Eureka, along San Francisco and Marin Counties' coast, in Monterey Bay from Santa Cruz to Monterey, and along most of the coast from San Luis Obispo to the southern border with Mexico.[5] Other parts of California's coast, alternatively, is at "low" to "moderate" risk. The San Francisco Bay can also be heavily impacted by sea level rise as demonstrated by an ongoing study being performed by the Pacific Institute.[6]

Sea Level Rise, Storm Surges and Electricity Infrastructure

Climate change could potentially impact coastal power plants either through sea level rise, which could inundate low-lying facilities, or through increased storm frequency or intensity, which could affect offshore water intake and discharge pipes. Intakes and outfalls in shallower water would likely be affected more by storm surge and debris than those located further offshore in deeper waters. The vulnerability of a facility would depend on its elevation, the neighboring area, and the extent to which it faces heavy wave action.[7]

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[3] California Energy Commission. *The Future is Now- An Update on Climate Change Science, Impacts, and Response Options for California*. September 2008. CEC-500-2008-077, 4-5.

[4] Climate Action Team Report draft Chapter 2.

[5] Hanak, Ellen and Lund, Jay. *Adapting California's Water Management to Climate Change*. Public Policy Institute of California. November 2008, 4.

[6] Heberger, M., H. Cooley, P. Herrera, and P. Gleick. The Cost of Adapting to Sea Level Rise Along the California Coast and in the San Francisco Bay. Draft Report. 2008 Climate Change Assessment.

[7] California Energy Commission, *Potential Changes in Hydropower Production from Global Climate Change in California and the Western United States,* Consultant Report prepared by Aspen Environmental Group and M Cubed, June 2005, CEC-700-2005-010, 48.

Notwithstanding the potential impacts on power plants associated with sea level rise, however, a preliminary analysis has concluded that neither issue appears to be particularly threatening in California: "It appears that very few existing coastal plants are at risk."[8] A similar conclusion was reached by a California Energy Commission contractor report, which stated that "…coastal climate change effects appear to only impact the Diablo Canyon Power Plant."[9] New analysis indicates that sea level rise impacts may be greater than previously projected. Potentially other coastal power plants may be affected by sea level rise, but more information is needed.

The Diablo Canyon Power Plant is located on a coastal terrace well above sea level. Cooling water is pumped from an intake pipe located in a rocky intertidal zone that takes the full brunt of northern swells from Pacific storms. The facility has had to curtail power during storm events on average twice per storm season. Both generating units are cut back to 20 percent power as a preventative measure to avoid shutting down (or tripping) the units if intake flow is impeded by debris buildup on the intake screens. The units can be down anywhere from 18 to 24 hours to several days. The more frequent the storms, or the greater the intensity, the more likely that the facility would have to cut power from debris generated from the storms.[10]

The Ormond Beach and Mandalay Generating Stations were reviewed, given their location on the Oxnard Plain. Cooling water intake locations differ for the two plants: The Ormond Beach facility takes water through an intake pipe located 2,500 feet offshore, and the Mandalay facility takes water through a canal. For the latter, the canal is susceptible to shoaling and debris and trash accumulation during storm events. However, no plant shutdowns have occurred at either facility due to storms. Climate change has not been raised as an issue for these coastal power plants.[11]

Sea level rise and the increased winter inflows into the Sacramento/San Joaquin Delta will also increase the potential for levee failures. There are substantial energy infrastructures, such as underground natural gas storage facilities and electrical transmission lines, in the Delta that would be affected by these events.

Even stringent emissions reductions and resulting lower temperature increases cannot prevent substantial sea-level rise because ocean waters store heat effectively and will expand volumetrically for centuries, long after air temperatures have been stabilized. Adaptation is the

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[8] Vine, Edward, *Adaptation of California's Electricity Sector to Climate Change,* Public Policy Institute of California, November 2008, 8.

[9] California Energy Commission. *Potential Changes in Hydropower Production from Global Climate Change in California and the Western United States*. Consultant Report prepared by Aspen Environmental Group and M Cubed. June 2005. CEC-700-2005-010, 47.

[10] Ibid., 48.

[11] Ibid., 49.

only way to deal with the long-lasting threat of sea-level rise to coastal bay and delta areas.[12] Existing facilities that use once-through ocean cooling will have a limited life as State Water Board policies are enacted, but other impacts should also be taken into account. Siting policies ensuring that new power facilities are not constructed in vulnerable areas are thus necessary. There are no major coastal transmission facilities located in areas that would be significantly impacted by sea level increases; thus, sea level rise would have little or no impact on the reliability of the transmission system. At the same time, higher sea levels and increased wave height could benefit generation from emerging ocean technologies, however, more research is necessary.

Sea Level Rise and Storm Surges on Petroleum and Transportation Fuels-Related Infrastructure

The upper range of potential sea level rise of 1.4 meters (55 inches) for California by 2100 would pose several challenges for the state and its associated petroleum infrastructure. The ability to cope with and reduce the impacts of such a change is directly related to the scope of the necessary modifications and the time frame to complete the anticipated work. It is likely that the long lead time is a benefit in terms of planning for and implementing any petroleum infrastructure improvements, but scientists do not rule out the possibility of more abrupt changes in climate.

The petroleum- and transportation fuels-related infrastructure in California normally involves movement of raw and finished transportation fuel products via waterborne vessels and use of a network of pipelines that connect wharves to refineries, storage tank farms, distribution terminals, and associated appurtenances. The wharf structures used to unload and load marine vessels are designed to accommodate a wide range of tidal variation on a daily and annual basis. An increase in the mean average sea level of nearly 4.6 feet will significantly raise the maximum high tide levels such that the existing wharf system used for movement of petroleum products and other waterborne commerce will need to be elevated.

The majority of petroleum infrastructure wharves will be modified over the next couple of years as part of industry's compliance with the Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS). It is reasonable to assume new regulations or standards could be developed before 2100 that will require further modifications to wharves. At a minimum, wharves will probably be replaced or renovated over the next 90 years due to finite lifetimes for piles, decking, dockside structures, and associated equipment. These natural upgrade or replacement cycles will create an opportunity to respond to rising sea levels, which could minimize the economic impacts of such changes.

[12] California Energy Commission. *The Future is Now — An Update on Climate Change Science, Impacts, and Response Options for California*. September 2008. CEC-500-2008-077, 7.

In addition, other potential issues that may also require some degree of modifications include:

- Marine vessel clearance under bridges, referred to as air draft.
- Gravity assisted outfalls for wastewater discharges.
- Increased coastal erosion impacts on petroleum infrastructure assets with ocean exposure.
- Offshore petroleum production facilities.

Marine Vessel Overhead Clearance Impacts

Marine vessels used to transport crude oil and other transportation-related products sometimes traverse inland waterway routes that necessitate crossing under bridges or other types of overhead structures. The Golden Gate Bridge is one such example. If the marine vessel is of sufficient size (height of vessel and running draft), there may be limited periods when crossing under a bridge would be possible (usually at low or lower tide conditions) because of air draft restrictions. It is possible that a 4- to 5-foot increase in sea levels would preclude or impose new movement limitations on certain marine vessels. There are over 24,000 bridge structures in California, but no more than 20 bridges meet the criteria of a crossing on a navigable waterway utilized by marine vessels transporting petroleum products.[13] No study has been undertaken as of this time to quantify the percentage and types of marine vessels that could be impacted by decreased air drafts.

Gravity-Assisted Outfalls for Wastewater Discharge Impacts

Refiners and other petroleum-related businesses usually discharge treated wastewater and storm water runoff to collection and conveyance systems that at some point rely on gravity to maintain adequate flows. Interruption of these wastewater discharges could pose an operational problem for refiners that have discharges in port areas of the state that are currently gravity-assisted.

Coastal Erosion Impacts

Nearly all of California's refineries are located in estuarine, protected harbor, or inland locations. Therefore, increased coastal erosion anticipated with higher sea levels should not pose a direct impact on their operations. But there is one California refinery that has exposure to the ocean, Chevron's El Segundo facility in Southern California. It is possible that increased coastal erosion at this location could necessitate fortifications to the coastal property adjacent to

[13] United States Department of Transportation, Federal Highway Administration, bridge statistics as of December 31, 2007. Actual count for California was 24,182 bridge structures. A link to the file is as follows: http://www.fhwa.dot.gov/BRIDGE/strtyp07.xls.

the refinery to prevent damage or saltwater intrusion into the facility property. In addition, there may be heightened operational concerns associated with the mooring buoy equipment used to receive and export petroleum-related products via marine vessels. The gradual pace of sea level rise should provide adequate lead time to make sufficient modifications, but potential costs are unknown at this time.

Offshore Petroleum Production Facility Impacts

California has a number of offshore facilities operating in state and federal waters that produce crude oil and natural gas. Over the next 10 to 20 years, drilling along the California coast could expand. Some of the existing offshore facilities could be decommissioned long before the rise in sea level begins to manifest any significant operational impacts. New facilities erected over the next several decades will likely incorporate new engineering standards and technological innovations to better withstand potentially greater storm intensities and heightened wave action. The incremental project costs directly associated with higher sea levels is unknown, but may be somewhat modest relative to the overall cost of typical offshore production platforms and pipelines to the mainland.

Projected Ambient Temperature and Precipitation Levels

In general, the climate projections for California have suggested the following: 1) Warming will be more pronounced in the summer than in the winter season; 2) Inland areas will see a more pronounced warming as compared with coastal regions; 3) Heat waves will go up with an increasing tendency for multiple hot days in succession; 4) The spatial footprint of heat waves will be more likely to encompass multiple population centers in California; 5) Increases in temperatures in the next few decades will be mainly a function of past emissions, so that the temperature projections for the next 30 to 40 years are already “in the pipeline”; and 6) Temperature projections by the end of this century are a strong function of the total level of emissions from now through the rest of this century.

With respect to precipitation, the current climate scenarios suggest that California will continue to enjoy a Mediterranean climate with relatively cool and wet winters and hot dry summers. Precipitation levels, however, will change, but the nature of this change varies depending on the global climate model considered. Most of the global climate models considered suggest decreased precipitation levels by the end of the century but there are significant uncertainties in these projections.

Potential Impacts of Temperature and Precipitation on Power Generation and Hydroelectric Generation in Particular

From basic thermodynamic considerations, the efficiency of conventional power plants burning fossil fuels should go down with increased ambient temperatures. This potential problem may become more pronounced in power plants using dry cooling. The efficiency of transmission and distribution lines is also affected by high ambient temperatures. It is prudent to consider the potential effect of climate change on fossil fuel-based power plants and transmission and distribution lines.

Depending on the amount of rainfall in an average year, in-state hydroelectric generation accounts for about 12-20 percent of California's total electricity production. A dry, high warming climate could result in a 19 percent reduction in hydroelectric generation compared to a 1984-1998 baseline, whereas a wet, high warming climate could increase generation by 5 percent.[14]

Climate change is expected to increase the amount of water flowing into California's rivers in the winter and reduce water flows in late spring and summer. Rising temperatures increase the amount of winter precipitation falling as rain rather than snow, decreasing the extent of, and causing earlier melting of, the Sierra snowpack.[15] Over the past 100 years, the fraction of the annual runoff that occurs during April–July has decreased by 23 percent for the Sacramento basin and 19 percent for the San Joaquin basin.[16] By mid-century, the amount of water stored as snow on April 1 is projected to decrease by 12 to 42 percent at all elevations. By the end of the century, the average decrease could be as much as 32 to 79 percent. The largest reductions are projected at lower elevations and will particularly affect snowpack in the wetter, northern half of the state.[17]

Most of the state's hydropower is concentrated in the north. Large hydro is a significant portion of total generation for both Pacific Gas and Electric Company (PG&E) and the Sacramento Municipal Utility District (SMUD). SMUD is particularly vulnerable, as hydropower accounted for 50 percent of its generation in 2006. Hydroelectric facilities most likely to be affected by climate change are in the Sacramento, Feather, San Joaquin, and American River systems, which

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[14] Madani, Kaveh, Josue Medellin-Azuara, Christina Connell, and Jay Lund. "Statewide Impacts of Climate Change on Hydroelectric Generation and Revenues in California." Presentation at the Fifth Annual California Climate Change Research Conference, Sacramento, California, September 8-10, 2008.

[15] Kahrl, Fredrich and Roland-Holst, David, *California Climate Risk and Response,* Research Paper No. 08102801, Department of Agricultural and Resource Economics, University of California, Berkeley, November 2008, 31.

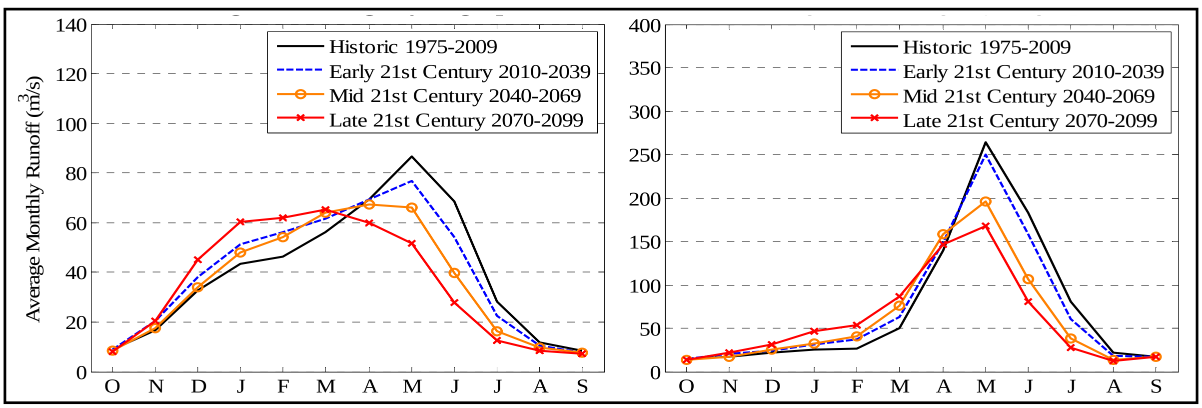
[16] California Energy Commission, *The Future is Now- An Update on Climate Change Science, Impacts, and Response Options for California,* September 2008, CEC-500-2008-077, 3.

[17] Bedsworth, Louise and Hanak, Ellen, *Preparing California for a Changing Climate*, Public Policy Institute of California, 2008, 7.

have large hydropower to storage capacity ratios and changes in projected runoff are large relative to current storage capacity.[18]

In a recent study, Vicuna et. al[19] estimates the impacts of climate change on two high-elevation hydropower systems in California: The Upper American River Project, operated by Sacramento Municipal Utility District in Northern California, and the Big Creek system, operated by Southern California Edison in Southern California. The operations of these two high-elevation systems were simulated using historic and climate change scenarios. Hydrologic scenarios under climate change imply an average reduction in runoff for both systems (with a greater reduction for the Big Creek systems) and a change in the hydrograph toward earlier timing of runoff (see Figure 1). The change in the hydrograph is greater for the Upper American River Project system because of the lower elevation of the basins where the system is located. The simulation results show that, associated with the reduction in runoff, there is a reduction in energy generation in both systems. However, due to the greater change in the hydrologic conditions for the Upper American River Project system, spills are greater in that system, and hence the reduction in energy generation (and associated revenues) is greater as well. In both systems the ability to meet peak historic power demands in the summer months would remain basically unaltered. However, an increase in the occurrence of heat waves especially later in the summer period (September) would increase peak power demand at times when these systems might not be at peak power capacity unless operating strategies are modified.

Figure 1: Average Changes in Monthly Hydrologic Conditions in the Upper American River Project (left) and Big Creek Systems (right) in the San Joaquin River



Source: Vicuna et al. 2008

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[18] California Energy Commission, *Potential Changes in Hydropower Production from Global Climate Change in California and the Western United States*, Consultant Report prepared by Aspen Environmental Group and M Cubed, June 2005, CEC-700-2005-010, 35.

[19] Vicuna, Sebastian; Dracup, John A.; Dale, Larry. "Climate Change Impacts on the Operation of Two High-Elevation Hydropower Systems in California" (draft). PIER California Climate Change Center. November 2008.

In the Pacific Northwest, average annual hydropower generation (which supplied about 5 percent of California's electricity in 2007) could decrease as much as 15 percent by 2020 and 30 percent by 2050, compared to baseline hydropower production.[20]

Much of California's (as well as the Pacific Northwest's) hydropower system is part of a broader multi-use system, including water supply, flood control, and recreation. Future changes in broader water policies may jeopardize hydropower production in some areas. For example, earlier snowmelts, particularly if coupled with heavy stream flows, could result in releasing water from reservoirs and diverting it from hydropower facilities to avoid flooding and damage to dams.[21] To accommodate seasonal shifts in inflows to the winter months, water storage may shift to aquifers by drawing down reservoirs in the summer and fall and recharging groundwater basins, making more surface space available to store upcoming winter and spring rains. The value of such a strategy will increase as warming shifts more precipitation from snow to rainfall.

Power generation by the Central Valley Project (CVP) is expected to decrease by 3 percent at mid-century and by 6 percent by the end of the century, and power use by the CVP is expected to decrease by 1 percent by mid-century and 3 percent by the end of the century. The power generation by the State Water Project (SWP) is equally expected to decrease by 3 percent by mid-century and by 6 percent by the end of the century, and the power used by the SWP is expected to decrease by 6 percent by mid-century and 10 percent by the end of the century. Both CVP and SWP include low-elevation hydropower units associated with the major reservoirs belonging to these two systems.[22]

In a three-year project, the Energy Commission and the National Oceanic Atmospheric Administration (NOAA) funded the Hydrologic Research Center to develop and implement an integrated management system (INFORM) for reservoir operation at the Folsom, Oroville, Shasta, and Trinity reservoirs. Through the Hydrologic Research Center, researchers will demonstrate and quantify the improved efficiency of water management for hydropower production, water supply, and flood control in California.[23] The Hydrologic Research Center is also using the same system with climate scenarios for periods far into the future to investigate how the INFORM system would could assist water managers cope with climate change. A

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[20] Markoff, M. and A. Cullen, "Impact of Climate Change on Pacific Northwest Hydropower," *Climatic Change* Vol. 87, pp. 451-469, 2007.

[21] Vine, Edward, *Adaptation of California's Electricity Sector to Climate Change,* Public Policy Institute of California, November 2008, 5.

[22] Chung, F. and J. Anderson. 2008. "Using Future Climate Projections to Support Water Decision Making in California." Draft DWR Paper. 2008 Assessment Report.

[23] HRC-GWRI. 2007. *Integrated Forecast and Reservoir Management (INFORM) for Northern California: System Development and Initial Demonstration*. California Energy Commission, PIER Energy-Related Environmental Research. CEC-500-2006-109.

similar system for the Folsom reservoir suggested that modern decision support systems such as INFORM could significantly reduce climate change impacts.[24]

Southern California Edison (SCE) currently conducts cloud seeding programs in the state, which on average seem to increase precipitation in the Sierra Nevada by 5 percent. It is also participating with the Energy Commission to study how precipitation processes change as temperature increases and how those altered processes could affect the SCE's cloud-seeding program.

Some researchers also suggest that aerosols from urban areas and other sources[25] may be inhibiting precipitation in the Sierra Nevada, resulting in reductions in precipitation on the order of 12 percent.[26] The same researchers indicate that these aerosols also may be interfering with cloud seeding operations in the Sierra Nevada.[27] NOAA and the Energy Commission's Public Interest Energy Research (PIER) Program hope to conduct a large field campaign in the winter of 2009/2010 to better evaluate (or assess) the nature of this problem and potential solutions.

As indicated before, most global climate models are suggesting now that climate change may result in reductions of precipitation levels in California. If this is the case, reducing the negative effect of aerosols on rain and snow levels in the Sierra Nevada may become a highly desirable climate change adaptation option for increasing water availability and hydropower generation. However, scientific understanding about the specific aerosols causing this effect is poor so the identification of specific adaptation measures would be premature without further studies.

Impact of Temperature and Precipitation on Natural Gas Infrastructure

California consumes approximately 2,200 billion cubic feet (Bcf) a year of natural gas. In-state production makes up about 13 percent of the state's total gas supply. California natural gas production is expected to remain fairly constant at around 330 Bcf per year through 2010. Since no new sources of natural gas have been discovered in the state at this time, annual production is expected to decline to about 300 Bcf by 2015, as mature fields are depleted. The balance of natural gas supplies that the state consumes is imported from out-of-state through five major pipelines.

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[24] Yao, H, and A. P. Georgakakos, 2001: "Assessment of Folsom Lake Response to Historical and Potential Future Climate Scenarios." *Journal of Hydrology* 249: 176–196.

[25] Atmospheric aerosols are complex mixture of solid and liquid particles originating directly from different sources such as combustion or formed in the air from chemical reactions involving precursor pollutants such as oxides of nitrogen and volatile organic compounds.

[26] Rosenfeld, D., et al., (2008). *Aircraft Measurement of the Impacts of Pollution Aerosols on Clouds and Precipitation Over the Sierra Nevada*. CEC-500-2008-015.

[27] The aerosols that result in reduced precipitation levels are in the nanometer size, while the aerosols using for cloud seeding are relatively large.

Climate change appears to have little impact on natural gas availability since most of the supply comes from basins located in Alberta, the Rockies, and the Southwestern United States. As supply of conventional natural gas declines in some regions, production from shale formations is expected to gradually increase. These sources of shale gas are also located in regions that cannot be affected by rising sea levels.

There are several liquefied natural gas (LNG) facilities currently proposed along the coast, but the need for those facilities has diminished as more natural gas pipelines are planned to tap natural gas supplies from the Rockies. LNG facilities, if they are constructed, must take into account the potential effects of rising sea levels along the coast.

Natural gas supply tends to be relatively stable. However, consumption of the fuel does fluctuate significantly throughout the day and seasonally. The fuel demand fluctuations are the result of changes in temperature that affects the need for space heating or natural gas-fired electricity generation for air conditioning. Natural gas-fired electricity generation will also fluctuate depending on seasonal precipitation and snow pack levels that affect hydroelectric production.[28]

Currently, natural gas storage facilities in the state provide consumers and suppliers the operational flexibility to balance supply and demand on a seasonal, weekly, and daily basis. The value of gas storage has been in its ability to match production, which is generally at steady rates, with consumption. A major change in the natural gas demand will affect the general pattern of natural gas withdrawal from storage facilities.[29] As the demand for natural gas increases for electricity generation due to higher temperatures, natural gas utilities might not be able to keep up with traditional natural gas storage levels. This might raise the cost of natural gas to the state utilities and consumers.

Natural gas utilities might be able to adapt to changing patterns of natural gas consumption. Most natural gas pipelines (except for the Kern River pipeline) have room to accommodate additional supplies of natural gas heading west to California. The pipeline proposals from the Rockies, such as the Ruby pipeline, will provide additional flexibility to the natural gas supplies into California in the future.

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[28] Results of the First 10 Weather Cases For The West Coast/ California Storage Modeling Effort. Prepared for the California Energy Commission (PIER) by ICF International, June 2008

[29] Fugitive volatile organic compound (VOC) emissions would go up with higher temperatures, but current VOC emissions are relatively low and should go down even further given the fact that fugitive methane emissions from the natural gas system will be further controlled as suggested in the ARB scoping plan.

Impact of Temperature and Precipitation on Renewable Generation

Renewable generation is especially sensitive to climate change because of its inherent dependency on ambient natural resources including hydrological resources, wind patterns and intensity, and solar radiation. The U.S. Climate Change Science Program has identified several impacts on the country's renewable energy, including changes in availability of water, biomass, and incoming solar radiation as well as significant changes in established wind patterns.

Additional potential impacts include decreased efficiency in geothermal generation by increasing the ambient temperature at which heat is discharged. According to the recent assessment by the U.S. Climate Change Science Program, "For a typical air-cooled binary cycle geothermal plant with a 330°F resource, power output will decrease about 1% for each 1°F rise in air temperature" (Bull et al. 2007). Due to the state's diverse landscape, California theoretically could be vulnerable to all of these potential scenarios. More research is necessary on each of the topics. Climate change impacts identified for traditional energy production methods — power plant cooling and water availability[30] — also would apply to certain renewable technologies such as biomass, geothermal, and solar thermal.

Biomass generation sources include the wastes and byproducts of forestry, agricultural, and municipal activities. Unless significant changes occur within these sectors, the significance of their effect on biomass energy production will be limited. One study shows that climate change-induced events, such as tree or forest die-offs, could present a short-term opportunity or a long-term loss for California.[31] Additionally, according to the Energy Commission's *Update on Climate Change Science Impacts and Response Options for California* report, warmer temperatures are predicted to have negative impacts on fruit, nut, avocado, and cotton production. However, high-quality wine grapes have thrived with warmer temperatures and a longer growing season.[32] Variation in crop yield poses risk to the viability of existing and future biomass facilities for production of electricity and transportation fuels. Potential reductions in the availability of water could have a significant impact on the supply of biomass for electricity generation. More research is needed to determine the direct effects that climate change will have on biomass supplies and the influence that this would have on the optimal siting of a biomass facility.

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[30] Bull, S. R., D. E. Bilello, J, Ekmann, M. J. Sale, and D. K. Schmalzer, 2007: *Effects of Climate Change on Energy Production and Distribution in the United States in Effects of Climate Change on Energy Production and Use in the United States. A Report by the U.S. Climate Change Science Program and the subcommittee on Global Change Research*. Washington, DC.

[31] Edwards, A., 1991: *Global Warming From an Energy Perspective, Global Climate Change And California*, Berkeley, CA: University of California Press: Chapter 8.

[32] Moser, S. 2008. *The Future Is Now: An Update on Climate Change Science, Impacts, and Response Options for California.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2008-077.

Wind generation will most likely be affected on a regional basis rather than uniformly throughout California. Analysis conducted by Breslow and Sailor suggest that average wind speeds in the United States will decrease by 1.0 to 3.2 percent in the next 50 years and will eventually decrease 1.4 to 4.5 percent over the next 100 years.[33] Further research is needed to understand the location and scale of changes in California's wind patterns, especially in areas targeted for extensive wind energy development.

Research must be conducted on California-specific impacts sustained by photovoltaics, particularly because of California's aggressive policies targeting rooftop systems. Photovoltaic generation is dependent on both the amount of incoming solar radiation and changes in temperature. Case studies conducted outside of California have shown that a 2 percent decrease in solar radiation was accompanied by a 6 percent decrease in electricity output of solar cells.[34]

The Energy Commission's PIER Program is developing detailed climate scenarios using dynamic regional climate models. This research will provide estimates of wind fields and ground-level solar radiation that can be used to estimate impacts to wind and solar resources.

With growing reliance on intermittent renewables for lower carbon electricity, increasing portfolio diversity among renewable resources as well as advanced technologies for energy storage would be the best adaptation strategy to climate change. Continued portfolio analysis with additional risk variables such as climate change impacts and the cost of greenhouse gas emissions are recommended when creating long-term procurement plans that will most likely be heavily weighted with renewable technology.

Impacts of Temperature and Precipitation to the Electricity Transmission System

While increasing temperatures and other climate-related changes are unlikely to impact the transmission of electricity in California, the forecasted increase in wildfires resulting from global climate change could affect the electricity imports and the transmission of electricity from remote regions. The transmission network is designed to withstand high-temperature conditions under adverse circumstances, and continuing these design practices would insure that the forecasted temperature increases would not significantly reduce the reliability of the transmission network. California currently imports 30 percent to 35 percent of its electricity from the Pacific Northwest and the Southwest, and current energy policies are expected to increase the transmission of electricity generated in remote regions in Northern and

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[33] Breslow P. and Sailor J. *Vulnerability of Wind Power Resources to Climate Change in the Continental United States*, Tulane University, April 2001.

[34] Fidje A. and T. Martinsen, 2006: *Effects of Climate Change on the Utilization of Solar Cells in the Nordic Region*. Extended abstract for European Conference on Impacts of Climate Change on Renewable Energy Sources. Reykjavik, Iceland, June 5-9, 2006.

Southeastern California to coastal load centers through fire-prone regions.[35] Increased reliance on remote generation, coupled with the increased likelihood of wildfires, could create a significant vulnerability in California's transmission system.

Creating a transmission system that uses redundant facilities to deliver remotely generated power can reduce California's vulnerability to likely increases in wildfires. Redundancy essentially creates more than one delivery pathway for remote generation so that if any single transmission line is out of service due to fires, then there is an alternate means to deliver the power to load centers. Looped transmission networks with the various pathways separated such that they would not be vulnerable to the same wildfire event further reduce California's vulnerability.

Temperature and Electricity Demand in California[36]

Electricity demand per capita has remained nearly flat in California over the last few decades, partly due to energy efficiency incentives. However, aggregate energy demand is growing rapidly, spurred by rapid population growth, especially in the warm Central Valley, and an overall increase in air conditioner use.

Over the twenty-first century, the frequency of extreme heat events for major cities in heavily air-conditioned California is projected to increase rapidly and, with it, peak electricity demand for air conditioning. In 2004, for example, 30 percent of California peak electricity demand was attributable to residential and commercial air conditioning use alone. During the 1990s and much of the next decade, an increasing number of homes were built in warm, arid regions such as the Central Valley, western Riverside County, and some parts of the Mojave Desert such as Victorville and the Lancaster/Palmdale areas. Homes in these areas were less expensive than those in the cooler, coastal regions. The upward trend in aggregate peak demand in California is expected to approach or exceed 67 gigawatts (GW) in 2016, which is a 1.35 percent per year increase since 2000. The anticipated population growth underlying these forecasts over the same period is 1.30 percent, indicating that demand growth is expected to very slightly outpace population growth. During summertime extreme heat days in California, the use of air conditioning and other cooling appliances increases electricity load nearly linearly with higher temperatures.

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[35] Current state policies increasing reliance on renewable electric generation are expected to result in a significant increase in solar and wind generation in remote regions in Northern and especially Southern California. The aging of the existing fleet of generators near load centers, coupled with the lack of air emissions offset credits for replacements in or near those same load centers, increases the likely reliance on transmission lines bringing power into load centers.

[36] From California Energy Commission, *Climate Change, Extreme Heat, and Electricity Demand in California*, PIER Project Report, August 2007, CEC-500-2007-023.

Overall, projected increases in extreme heat under the higher Intergovernmental Panel for Climate Change's temperature scenarios by 2070– 2099 tend to be 20–30 percent higher than those projected under lower scenarios. Increases range from approximately double the historical number of days for inland California cities (such as Sacramento and Fresno) and up to four times present-day levels for previously temperate coastal cities (such as Los Angeles and San Diego). This implies that current-day "heat wave" conditions may dominate summer months — and patterns of electricity demand — in the future. When the projected extreme heat and observed relationships between high temperature and electricity demand for California are mapped onto current electricity availability, maintaining technology and population constant for demand-side calculations, researchers have found a potential for electricity deficits as high as 17 percent during peak electricity demand periods.

Calculations of electricity demand under a range of human comfort levels also highlight the potential for adaptation to play a major role, reducing projected increases in electricity demand by roughly one third for inland cities, and by as much as 95 percent for cooler coastal cities.

Auffhammer and Aroonruengsawat [37] combined four years of residential billing data for California's three largest utilities with daily temperature and pricing information to estimate temperature consumption response functions by climate zone as defined for the California Energy Commission's building standards. They found increases in demand in the coastal regions to be relatively modest due to the lower increase in coastal temperatures, while increases inland, especially in the Central Valley, were found to be substantial. Demand in the next 40 years was generally insensitive to the global emissions scenarios considered, while demand at the end of this century was heavily dependent on global emissions pathways in this century. On average, the authors forecasted that statewide electricity demand in the residential sector would go up by about 7 percent in the next few decades beyond what is expected from population growth alone. By the end of this century, demand is forecasted to increase by 20 percent to 50 percent.

Increasing supplies is one response to increased levels of demand. To the extent that combustion-based supplies are considered, worsening air quality due to hotter climatic conditions may make obtaining air quality permits more difficult and more costly. Additionally, efficiencies of combustion alternatives tend to decrease with increasing temperatures, so increasing amounts of additions may need to be considered if such additions are combustion-based. Alternative technologies such as solar photovoltaic and thermal electricity generation represent an important future technology for this region, with electricity production being proportional to solar radiation. In addition to increasing supply, peak demand can be reduced through a variety of energy reduction measures, including load management, and new meters

[37] Auffhammer, M. and A. Aroonruengsawat, 2008. "Impacts of Climate Change on Residential Electricity Consumption: Evidence from Billing Data." Draft PIER Paper. 2008 Assessment Report.

showing end use consumption data, high efficiency air conditioners, use of thermal mass, natural cooling, increased insulation, planting shade trees, and use of reflective surfaces.

Potential Temperature and Precipitation Impacts on Petroleum and Transportation Fuels

- *Interruption of Electricity Service*
  Climate change is expected to increase average temperatures and alter precipitation patterns for California. One consequence of these anticipated changing conditions is that electricity service could experience intermittent outages as loads exceed demand. Loss of electrical service can impact the production and distribution of transportation fuels.

  Most refineries in California have cogeneration units that supply most or their entire electrical load during peak demand periods and are therefore somewhat isolated from electricity interruptions for their primary operations, but not all refineries have this capability to become independent from the electrical grid. As such, a loss of electrical service can result in a refinery undergoing an emergency shutdown of process units. Once the emergency shutdown sequence is initiated, refinery operations will usually be curtailed for a minimum of three days. Reduced refinery operations decrease production and can lead to temporary spikes in wholesale and retail fuel prices, increasing costs to consumers by millions of dollars per day statewide.[38]

  Loss of electrical service can also disrupt the ability of refiners to dispense the fuel they produce. The majority of the gasoline and diesel fuel produced by refineries in California is distributed to more than 50 terminals connected to a network of petroleum product pipelines. Many of these distribution networks employ electrical pumps that would cease operations during an electricity outage. The distribution terminals also require electricity to operate the pumps and valves associated with the truck-loading racks.

- *Refineries*

  Refineries in California use a great deal of water to create steam used in their industrial processes. In many cases, refiners use treated wastewater to meet a portion of their total water demand. Climate change could alter the average quantity and seasonal deposition of snowfall in the Sierra Nevada watershed, significantly reducing the volume of

[38] California businesses and consumers purchase more than 18 billion gallons per year or nearly 50 million gallons per day of gasoline and diesel fuel. Temporary loss of refinery output due to emergency shut-downs caused by a loss of electrical service have normally precipitated price spikes of between 10 and 20 cents per gallon that can persist for several days to a couple of weeks. Under these circumstances, the economic cost to consumers would range between $10 and $20 million per day for the state.

seasonal run-off and water availability. Decreased water supplies will limit availability for all uses. To the extent that potable water sources are no longer available for use by industry (including refineries), other potential sources would have to be pursued along with strategies and technologies aimed at reducing water intensity at refineries.

Adaptation strategies to consider include use of additional wastewater treatment sources or employment of desalination technologies to maintain adequate water availability for California refineries. These approaches would likely be available for most of the state's refiners, but those facilities located in the San Joaquin Valley may face additional challenges due to fewer alternative water source options available to them.

- *Bio-refineries*

  Reduced water supplies to the state could impact agricultural intensity and activity. California currently uses a smaller portion of alternative fuels (less than 6 percent) in all transportation fuels, but the average concentration is expected to continue rising over the next several years. Over the longer term, it is likely that alternative and renewable fuels use could account for a large percentage of transportation fuel use. As such, decreased water availability for agricultural use could impact the cost and availability of alternative and renewable fuels using California-source/derived feedstocks or energy crops. It is unknown how extensive or severe these water-reduction impacts could be for California agriculture and the production of alternative and renewable fuels and the operation of bio-refineries.

- *Petroleum Pipelines*

  California refineries produce transportation fuels for use in California and outside the state. Exports of gasoline, diesel, and jet fuels are transported in petroleum product pipelines that originate at California refineries and terminate at distribution terminals located in Nevada and Arizona. Periodically, these pipeline operations are interrupted by damage caused by flash flooding. Altering patterns of precipitation that increase these types of events could result in a greater number of pipeline service disruptions and associated temporary price spikes.

Coping and Adaptation Strategies for Energy-Related Climate Impacts

Of the multiple coping and adaptation strategies for these scenarios that have been identified, some of them could be implemented almost immediately because the science is clear and existing laws and regulations provide the necessary legal framework for action. In other cases, however, it is prudent to wait for additional scientific results before committing to a particular strategy or set of strategies, either because of the high level of uncertainty in the type or levels of impacts these strategies may engender or because the current legal framework does not allow the implementation of the identified adaptation strategies.

The following are adaptation strategies that are ready for implementation:

a) Energy Efficiency Standards

- The Energy Commission will continue to pursue energy efficiency standards including those standards that also result in lower levels of water consumption.
- The Energy Commission will use the cost of greenhouse gas emissions when considering the cost and benefits of new energy efficiency standards. The Energy Commission will determine the appropriate cost of greenhouse gas emissions after consultations with experts using a public process.

b) Siting and Relicensing of New Energy Facilities

- The Energy Commission will assess greenhouse gas impacts for power plant siting cases through our Order Instituting Informational Proceeding (OII) on GHG emissions and in individual siting cases, and consider the potential impact of sea level rise for coastal facilities.
- The Energy Commission's PIER climate change program should continue foundational regional climate modeling and related studies needed to assess the potential impacts of climate change on energy infrastructure from sea level rise and other impacts. The Commission will use these findings to decide what additional actions are required including modifications to its siting and planning programs. Work has begun on a scoping study.

c) Energy Management and Planning

- The Energy Commission and the Department of Water Resources shall continue supporting the enhancements and demonstration of modern decision support systems for the management of existing major water reservoirs in California to adapt to current levels of climate variability and increase our resilience to increases levels of climate variability and change in the future. Work is funded and underway.
- The Energy Commission's PIER Program will continue research on factors that may affect hydropower generation due to climate change, such as increased water temperature in rivers and streams requiring additional release of water from upstream reservoirs for environmental purposes.

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