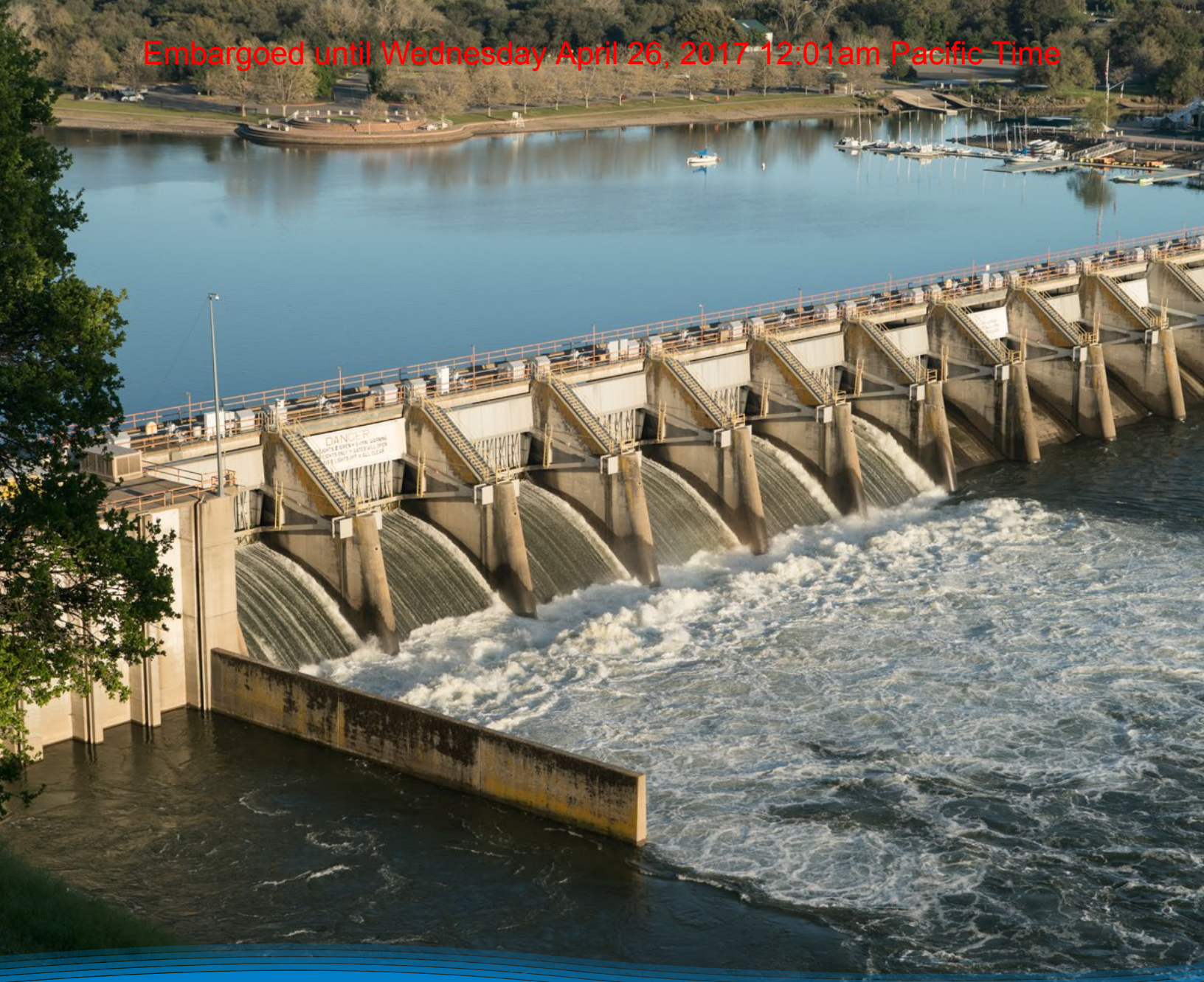


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Impacts of California's Five-Year (2012-2016) Drought on Hydroelectricity Generation

Peter Gleick



April 2017

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The Pacific Institute envisions a world in which society, the economy, and the environment have the water they need to thrive now and in the future. In pursuit of this vision, the Institute creates and advances solutions to the world's most pressing water challenges, such as unsustainable water management and use; climate change; environmental degradation; food, fiber, and energy production for a growing population; and basic lack of access to fresh water and sanitation. Since 1987, the Pacific Institute has cut across traditional areas of study and actively collaborated with a diverse set of stakeholders, including policymakers, scientists, corporate leaders, international organizations such as the United Nations, advocacy groups, and local communities. This interdisciplinary and nonpartisan approach helps bring diverse interests together to forge effective real-world solutions. More information about the Institute and our staff, directors, funders, and programs can be found at www.pacinst.org.

ABOUT THE AUTHOR

PETER GLEICK

Dr. Peter Gleick is a world-renowned expert, innovator, and communicator on water and climate issues. In 1987 he cofounded the Pacific Institute, which he led as president until mid-2016, when he became president emeritus. He developed one of the first analyses of climate change impacts on water resources, the earliest comprehensive work on water and conflict, and defined the basic human need and right to water—work that has been used by the United Nations and in human rights court cases. Dr. Gleick has pioneered and advanced the concepts of the “soft path for water” and “peak water.” A recipient of the prestigious MacArthur “Genius” Fellowship, Dr. Gleick was elected to the U.S. National Academy of Sciences and currently serves on the boards of numerous scientific journals and organizations. He is also the author or coauthor of many scientific papers and 11 books. Dr. Gleick holds a B.S. from Yale University, and an M.S. and Ph.D. from the University of California, Berkeley.

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INTRODUCTION

The severe hydrological drought afflicting California between 2012 and 2016 has ended, with an extremely wet winter beginning in October 2016. That five-year period was the driest and hottest in the instrumental record going back to the late 1800s. Impacts on communities, ecosystems, farmers, and the economy were widespread but have been unevenly distributed. The Pacific Institute has regularly analyzed the consequences of California droughts, beginning with comprehensive assessments of the 1987-1992 drought ([Gleick and Nash 1991](#), [Nash 1993](#)), the 2007-2009 drought ([Christian-Smith et al. 2011](#)), and this most recent drought ([Cooley et al. 2015](#), [Gleick 2015](#), [Cooley et al. 2016](#), [Feinstein et al. 2017](#)).

This analysis is the third assessment of the impacts of the drought on hydropower production and greenhouse gas emissions from California's energy sector ([Gleick 2015](#), [Gleick 2016](#)). This analysis finds that during the five years ending September 30, 2016 (the end of the 2016 "water year"), hydropower generation was substantially below average, and the associated economic cost

to California ratepayers was approximately \$2.45 billion dollars.¹ The additional combustion of fossil fuels for electricity generation also led to a 10 percent increase in carbon dioxide emissions from California's in-state power plants ([CARB 2015](#)) along with increased emissions of other pollutants.

BACKGROUND: CALIFORNIA'S ELECTRICITY GENERATING SYSTEM

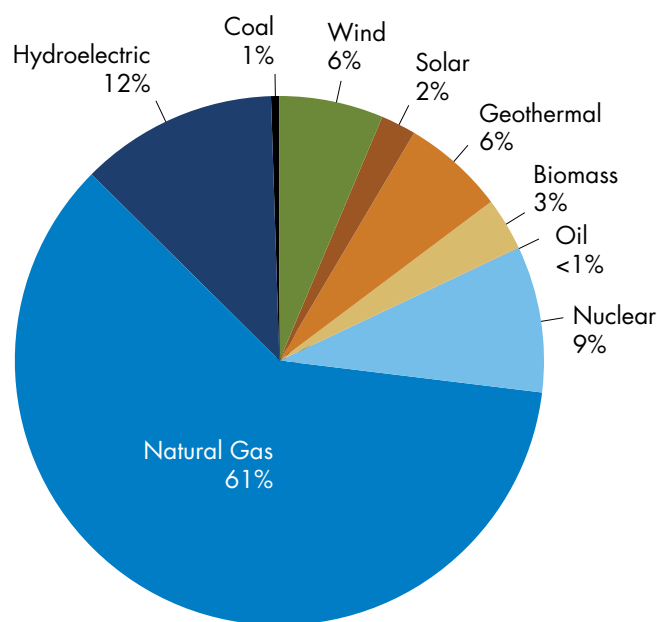
The links between water use and energy production—sometimes referred to as the water-energy nexus—have been well documented.² Water is used to cool thermal power plants (typically coal, oil, natural gas, nuclear, central solar, and geothermal) and to drive hydroelectric turbines. Electricity generated at the hundreds of major hydropower stations in California is relatively inexpensive compared to almost every other form of electricity generated. Hydropower produces

1 All cost estimates have been adjusted for inflation and are reported in 2016 dollars unless otherwise stated.

2 For more detail and references on this issue, see "Water-Energy Nexus," <http://pacinst.org/issues/water-energy-nexus/>.

few or no greenhouse gases,³ and is extremely valuable for satisfying peak energy demands, which are often the most difficult and costly forms of electricity to provide. In 2013, as the drought was taking hold, hydropower accounted for 12 percent of in-state electricity generation (Figure 1), down from the long-term average of around 18 percent, while more than 60 percent of in-state electricity came from fossil fuels, largely natural gas. Other non- or low- fossil carbon emitting sources, such as solar, wind, biomass, geothermal, and nuclear made up 26 percent of the state's electricity in 2013.

Figure 1.
California In-State Electricity Generation by Source, 2013 🔍



Note: This graph shows only in-state generation by source. Additional electricity is generated in other states and sent to California.

Source: [CEC \(2015\)](#).

Hydroelectricity generation is a function of water flows in California's rivers, water stored in reservoirs, and the way those reservoirs are operated, and is subject to seasonal and inter-annual variation. As shown in Figures 2 and 3, production typically rises in winter and spring months with increased runoff and drops during late summer, fall, and early winter when runoff is low. In wet years, hydroelectricity generation increases; during dry years, and especially during droughts, total hydroelectricity generation drops (Figure 3). Moreover, a linear trend fitted to the data shows that hydropower generation has been declining over the past 15 years, largely due to drought conditions. Note the modest recovery in 2016: California received close to an average amount of precipitation, though runoff remained well below normal due to depleted reservoir and soil moisture levels. For this analysis, all data are analyzed for the California "water year"—defined as October 1 to September 30 (see Box 1).

Figure 4 shows total hydroelectricity generation in California from 1983 to 2014, plotted against the unimpaired natural water flows in the Sacramento and San Joaquin Rivers by water year (October 1 to September 30).⁴ The correlation between the two curves is strong: when runoff falls, hydroelectricity production falls, and when runoff is high, hydroelectricity production increases.

While it is increasingly difficult to find a "normal" water year in California, in-state electricity generation (excluding power imported from outside the state) from hydropower facilities averaged 18 percent from 1983 to 2013. In 2011, a wet year, hydropower accounted for 21 percent

³ There is growing interest and concern about possible methane emissions from artificial reservoirs (see, for example, [Deemer et al., 2016](#)). We have not included any estimate of those emissions here, or (most relevant for this analysis) a possible change in such emissions due to the drought.

⁴ Unimpaired runoff refers to the amount of runoff that would be available in a system without human consumptive uses. Because almost all hydroelectricity production occurs in upstream reaches of the Sacramento/San Joaquin rivers, before withdrawals for cities and farms, this is an appropriate dataset to apply.

Figure 2.
Monthly Electricity Generation in California by Source (thousand megawatt-hours per month), 2001-2016

- Natural Gas
- Hydroelectricity
- Wind, Solar
- Nuclear

Source: [US Energy Information Administration \(2017\)](#).

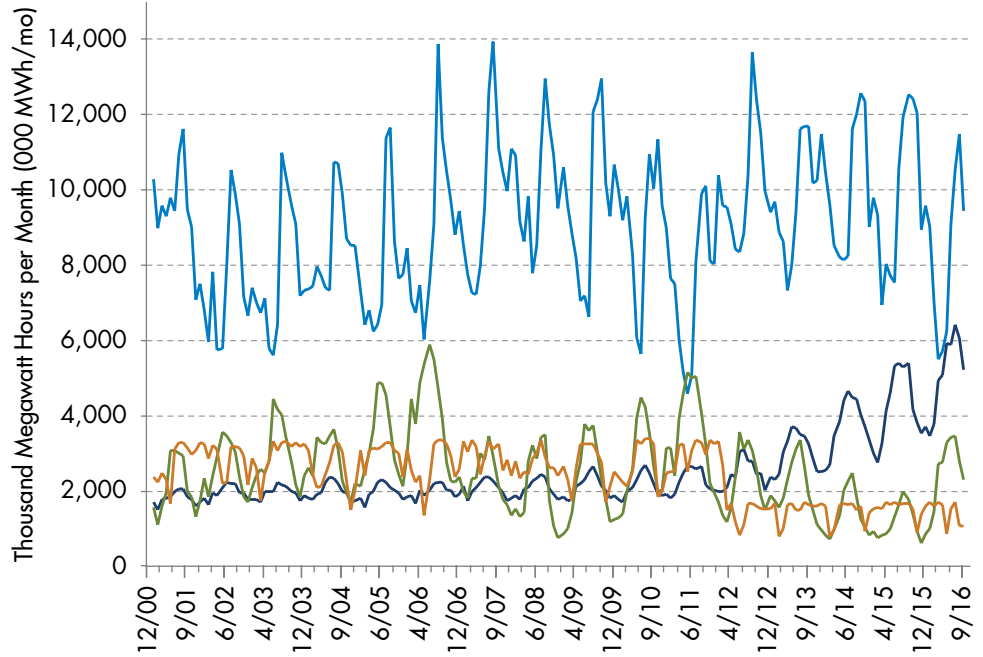
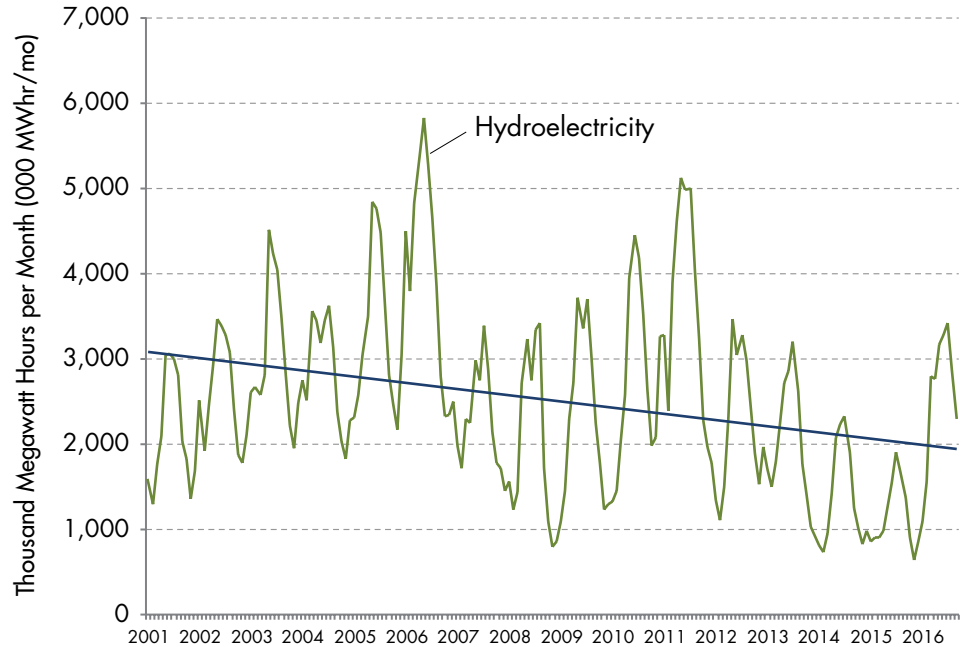


Figure 3.
Total In-State Hydroelectricity Generation in California (thousand megawatt-hours per month), Water Years 2001-2016

Note: A linear trend is plotted over the period 2001-2016.

Source: [EIA 2017](#).



Box 1.

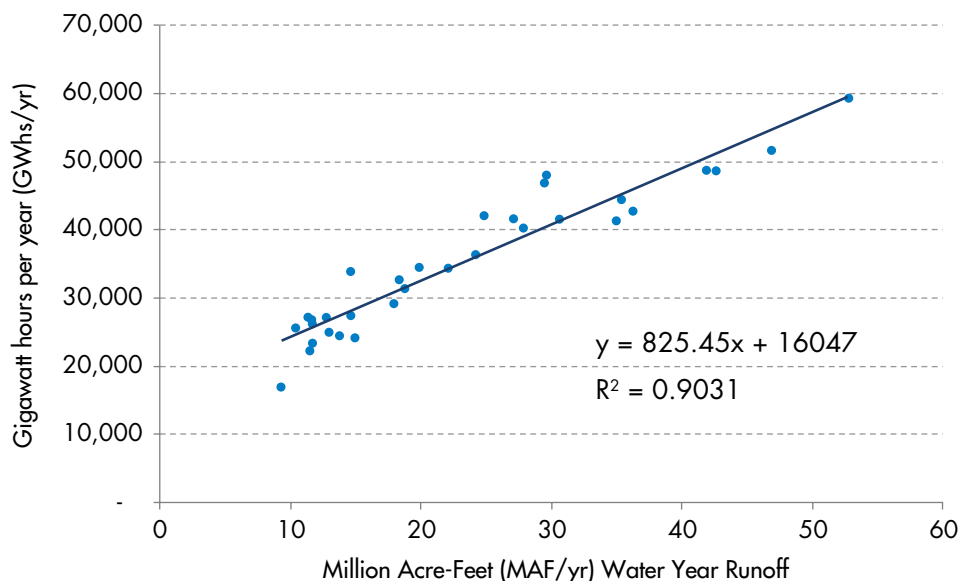
The Water Year versus the Calendar Year

While the calendar year runs January 1 to December 31, the “water year” in California runs from October 1 to September 30 of the following year. Water managers and hydrologists evaluate moisture records over the water year rather than the traditional calendar year. The water year is defined this way because California has a Mediterranean-type climate with a distinct wet and dry season. The wet season begins October 1 and ends in spring, around mid-April, followed by a period with very limited precipitation from April through September.

The water year is designated by the calendar year in which it ends, thus the period October 1, 2013 to September 30, 2014 is called the 2014 water year. Unless otherwise explicitly mentioned, the results presented here for the five drought years of 2012 through 2016 are from October 1, 2011 through September 30, 2016. The U.S. Geological Survey uses the same water year definition.

Figure 4.
California Hydroelectricity Generation (gigawatt-hours per year) versus Water-Year Runoff in the Sacramento/San Joaquin Rivers (million acre-feet per year), Water Years 1983-2014

Source: Hydroelectricity production from the US Energy Information Agency; data for unimpaired runoff from the Department of Water Resources. (EIA 2014, CDWR 2014).



of in-state electricity generation (CEC 2017a). The energy share from hydroelectricity has diminished as demand for electricity has continued to grow in California. This is because total installed hydroelectricity capacity has remained relatively constant at around 14,000 megawatts (MW), increasing by less than 3 percent between 2001 and

2015 (Figure 5). The small number of undammed rivers and growing environmental, economic, and political constraints limit any potential expansion California’s hydroelectric capacity. A small number of new dams have been proposed for California, but they would add very little or no additional hydroelectric capacity.

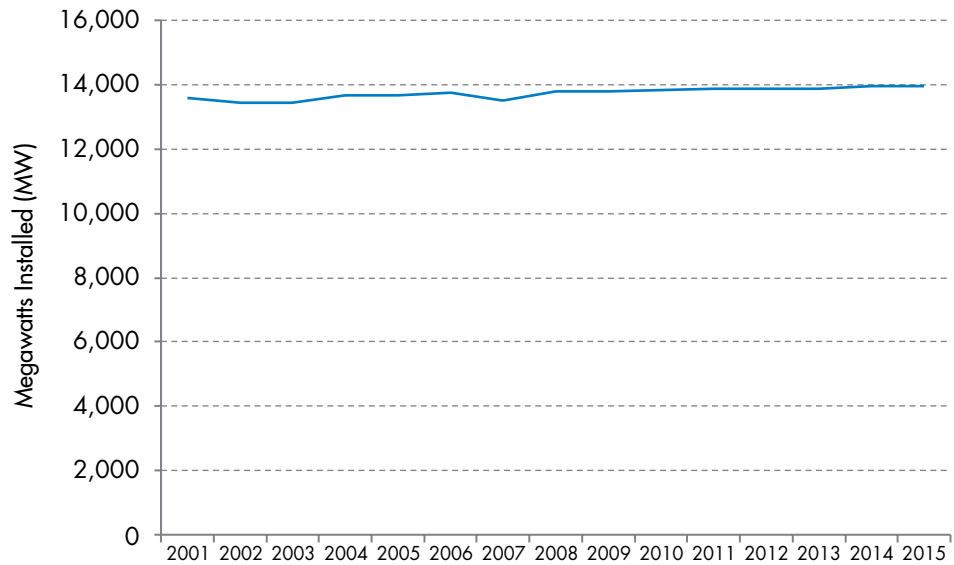
Figure 5.

Total Installed Capacity of California Hydroelectricity (megawatts), 2001-2015



Note: No significant additions have occurred since 200.

Source: [CEC \(2017b\)](#).



THE EFFECTS OF DROUGHT ON CALIFORNIA HYDROELECTRICITY GENERATION

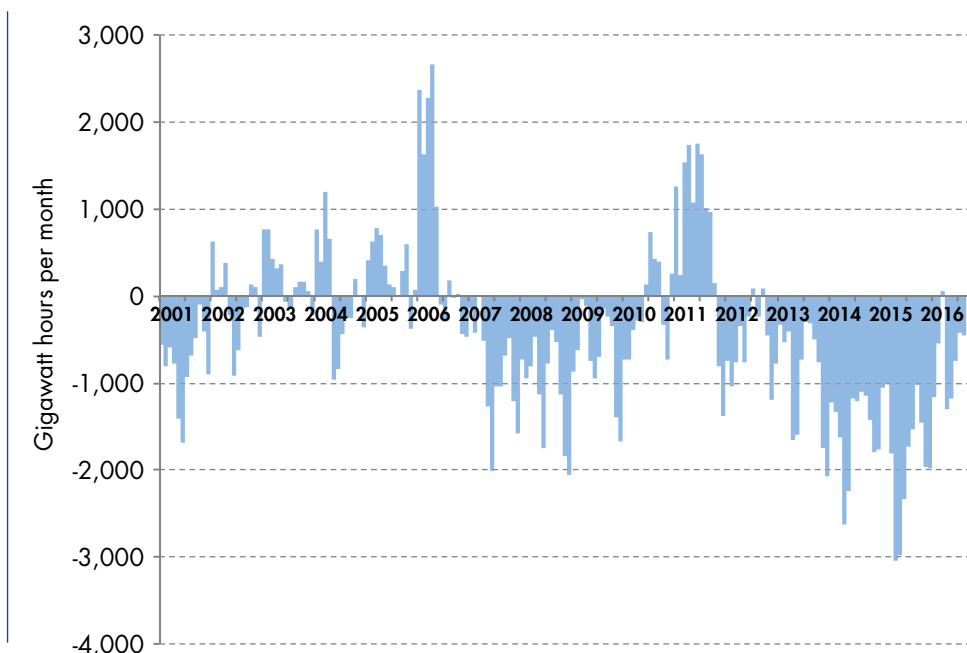
As noted above, when less water is available in rivers or stored in reservoirs, less hydroelectricity is generated. During the 2007-2009 drought in California, hydroelectricity production accounted for around 13 percent of the state's overall electricity generation ([Christian-Smith et al. 2011](#)), down from an average of 18 percent. The recent five-year drought was more severe, and hydropower generation was even lower, around 10.5 percent of total electricity generation. In 2015, the driest year of the drought, hydropower provided less than seven percent of total electricity generated in-state; in 2016, an increase in precipitation increased hydropower generation to around 12 percent. Figure 6 shows the decline from average monthly generation levels. In these periods, reductions in hydropower were made up primarily by burning more natural gas, increasing purchases from out-of-state sources, and expanding wind and solar generation.

ECONOMIC COST OF REDUCED HYDROELECTRICITY

Hydropower, accounting for both fixed and variable costs, is considerably less expensive than most other forms of electricity, and its marginal cost (the cost of producing one more unit of electricity and a function of both fixed and variable costs) is especially lower than that of natural gas. As a result, the drought has led to a direct increase in the cost of generating electricity. Using estimates of hydroelectricity generation from the California Energy Commission and the U.S. Energy Information Administration (EIA), we estimate that, during the five-year period from 2012 to 2016, hydroelectricity generation was reduced by approximately 65,600 gigawatt-hours (GWh) compared to the long-term average and replaced by a mix of energy sources. During that period, the average monthly marginal cost of California's electricity system varied between two and just over six cents per kilowatt-hour (\$0.02 to 0.06/kWh), with a long-term average of around \$0.035/kWh ([CAISO 2015, 2016](#); personal communications, Eric

Figure 6.
Reductions in Hydroelectricity Generation Due to California Drought (gigawatt-hours (GWh)/month), 2001 through September 2016 🔍

Source: Computed here from [EIA \(2017\)](#) electricity data to the end of September 2016 compared to generation during average hydrologic years.



Cutter 2014, 2015, 2016; [Klein 2010](#)).⁵ To calculate the impact on electricity costs, the average of the hourly marginal cost data over each month from 2012 to 2016 was used to compute an average monthly marginal electricity cost. Applying these costs to the monthly hydropower anomalies in Figure 6, the total reductions in hydropower generation during the 2012-2016 period increased statewide electricity costs by approximately \$2.45 billion (2016 dollars).⁶

There is growing concern that the current drought may be part of a longer trend toward more extreme weather ([Swain et al. 2014](#), [Mann and Gleick 2015](#)). Indeed, an observation of the past 16 years (Figure 6) shows an apparent shortfall in hydroelectricity, including the three-year drought period beginning in 2007, with a brief respite of average or slightly above average generation during 2010 and 2011. When these longer-term water shortfalls over the past decade are taken into account, California's electricity is becoming more expensive.

5 Computed from the Locational Marginal Price (LMP) for Day Ahead energy for the NP15 APNode (NP15_GEN-APND) (for 2012-2016) <http://oasis.caiso.com/>. Personal communications, Eric Cutter 2015, 2016, 2017; [Klein 2010](#). This represents the price per MWh of electricity for delivery on a specified date, stated in U.S. dollars, published by the California ISO.

6 Hourly marginal costs of electricity in California from 2012 through 2016 were provided by E. Cutter from the hourly "Day Ahead CAISO price data for NP15" (Personal communications, E. Cutter, 2015, 2016, 2017). [Klein 2010](#) includes detailed and careful descriptions of the advantages and limitations of using single-point leveled costs. For the purposes of this assessment, we use the monthly marginal costs of electricity over the drought period calculated as the average of the hourly data for a given month.

On average, under stable climate conditions ("hydrologic stationarity"), decreases in hydropower generation in dry years should be balanced with increases in generation during wet years. As shown in Figures 3 and 5, however, there appears to be a downward trend in hydroelectric generation unrelated to changes in installed generation capacity. This raises the question of the role of climate change in affecting the state's long-term hydrologic conditions—a question beyond the scope of this analysis, but one that researchers are actively pursuing (see [Vine 2012](#), [Madani et al. 2014](#), [Diffenbaugh et al. 2015](#), [Mann and Gleick 2015](#)).

GREENHOUSE GAS EMISSIONS ASSOCIATED WITH REDUCED HYDROELECTRICITY GENERATION

In addition to the direct economic costs of replacing hydroelectricity generation, there are environmental costs associated with the additional combustion of natural gas, including increased air pollution in the form of nitrous oxides (NO_x), volatile organic compounds (VOCs), sulfur oxides (SO_x), particulates (PM_{2.5}), carbon monoxide (CO), and carbon dioxide (CO₂)—the principal greenhouse gas responsible for climatic change. Using standard emissions factors from the California Air Resources Board and the California Energy Commission for combined-cycle natural gas systems (Table 1), the 2012-2016 drought led to substantial increases in pollutant emissions (Table 2). These emissions included more than 24 million metric tons (26.5 million tons) of additional CO₂, or about a 10-percent increase from California (in-state) power plants over the same five-year period (CARB 2015). Many of these pollutants are known contributors to the formation of smog and triggers

for asthma. No estimates of the health impacts or the economic costs of these increased emissions are included here. This analysis also excludes unintentional emissions of greenhouse gases that may occur throughout the natural gas fuel cycle, such as the massive methane emissions associated with the Porter Ranch natural gas storage facility leak (Walton and Myers 2016).

These emissions estimates are somewhat uncertain, assuming all additional natural-gas combustion came from efficient combined-cycle systems rather than conventional or advanced simple-cycle natural gas systems, where emissions are higher due to lower efficiencies of combustion. They also assume that natural gas made up the entire shortfall in hydroelectricity, though recent rapid expansion of renewables makes it difficult to precisely identify which energy sources displace lost hydroelectricity on an hour-to-hour basis.⁷

⁷ With only rare exceptions, 100 percent of electricity from renewables is fed into the grid, while natural gas generation is the marginal source.

Table 1.

Criteria Air Pollutant Emissions Factors for Conventional Combined Cycle Natural Gas Generation (pounds per MWh)

NO _x	VOCs	CO	SO _x	PM _{2.5}	CO ₂
0.07	0.21	0.1	0.01	0.03	810

Sources: California Energy Commission, Loyer and Alvarado, 2012; Christian-Smith et al. 2011. Criteria air emissions factors from stationary source natural gas power plants.

Table 2.

Total Additional Emissions from Natural Gas Use During the 2012-2016 Drought (tons)

NO _x	VOCs	CO	SO _x	PM _{2.5}	CO ₂
2,300	6,900	3,300	330	980	26,600,000

Sources: Rounded to two or three significant figures, as appropriate. NO_x stands for nitrous oxides, VOCs for volatile organic compounds, CO for carbon monoxide, SO_x for sulfur oxides, PM_{2.5} for particulate matter (with a diameter of 2.5 micrometers), and CO₂ for carbon dioxide. Several of these pollutants are also greenhouse gases that contribute to climate change or have negative health effects.

SUMMARY

California's severe drought from 2012 to 2016 had a wide range of economic, social, and environmental impacts, including reductions in river flows and associated declines in hydroelectricity generation, which must be replaced by other energy sources. Hydropower is less expensive and, in most cases, less polluting than other conventional electricity sources. In California, the marginal source of electricity is typically natural gas, which is both more expensive (based on real-time purchase prices from the grid) and more polluting than hydroelectricity. For the five years from October 2011 through the end of the 2016 water year, California experienced a reduction of around 66,000 GWh of hydroelectricity compared to

average water years, at a cost of approximately \$2.45 billion. In addition, the combustion of replacement natural gas led to a 10 percent increase in carbon dioxide emissions, as well as other pollutants from California's in-state power plants. As of March 2017, the hydrologic drought has likely ended. Indeed, the state has swung to the other hydrologic extreme: severe and intense precipitation and flooding. Reservoir levels have been restored; precipitation and snowpack are well above normal, especially in the Sierra Nevada range. Hydropower generation is expected to be far above normal over the next year, with associated reductions in the cost of electricity and pollution from fossil fuels.

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