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A retrospective study of the 2012-2016 California drought and its impacts on the power sector

TITLE: A Retrospective Study of the 2012-2016 California Drought and its Impacts on the Power Sector

AUTHORS: Jordan D. Kern, PhD[1*]; Yufei Su[2]; Joy Hill[2]

**Corresponding Author*

1. Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, United States, jkern@ncsu.edu

2. Department of Environmental Science and Engineering, University of North Carolina-Chapel Hill, Chapel Hill, NC 27516, United States

Abstract

Over the period 2012-2016, the state of California in the United States (U.S.) experienced a drought considered to be one of the worst in state history. Drought's direct impacts on California's electric power sector are understood. Extremely low streamflow manifests as reduced hydropower availability, and if drought is also marked by elevated temperatures, these can increase building electricity demands for cooling. Collectively, these impacts force system operators to increase reliance on natural gas power plants, increasing market prices and emissions. However, previous investigations have relied mostly on ex post analysis of observational data to develop estimates of increases in costs and carbon dioxide (CO_2) emissions due to the 2012-2016 drought. This has made it difficult to control for confounding variables (e.g. growing renewable energy capacity, volatile natural gas prices) in assessing the drought's impacts. In this study, we use a power system simulation model to isolate the direct impacts of several hydrometeorological phenomena observed during the 2012-2016 drought on system wide CO_2 emissions and wholesale electricity prices in the California market. We find that the impacts of drought conditions on wholesale electricity prices were modest (annual prices increased by $0-3/MWh, although much larger within-year increases are also observed). Instead, it was an increase in natural gas prices, punctuated by the 2014 polar vortex event that affected much of the Eastern U.S., which caused wholesale electricity prices to increase during the drought. Costs from the drought were much different for the state's three investor owned utilities. Overall, we find that increased cooling demands (electricity demand) during the drought may have represented a larger economic cost ($3.8 billion) than lost hydropower generation ($1.9 billion). We also find the potential for renewable energy to mitigate drought-cased increases in CO_2 emissions to be negligible, standing in contrast to some previous studies.

Key Words

Drought, electricity markets, prices, greenhouse gases, renewable energy

1. Introduction

There is growing interest in understanding the effects of hydrometeorological variability, and especially drought, on the economic and environmental performance of bulk power systems and electricity markets (van Vliet et al., 2012; Van Vliet et al., 2016; Voisin et al., 2016). In the United States (U.S.), California is particularly vulnerable to drought due to its reliance on in-state and imported hydropower (California Energy Commission, 2017a). Over the period 2012-2016, California experienced a drought considered to be one of the worst in state history (Belmecheri et al., 2016; Griffin and Anchukaitis, 2014; Lund et al., 2018). During this time, hydrometeorological impacts included extremely low precipitation, snowpack, and streamflow, along with elevated temperatures (AghaKouchak et al., 2014; Mote et al., 2016). The drought is estimated to have caused 10 billion dollars in economic damages across the state (Lund et al., 2018).

The lone estimate of the drought's negative economic impact on California's electric power grid is $2.45 billion (Gleick, 2017), a number that reflects the estimated market value of hydropower that was "lost" over the years 2012-2016. On average, California relies on in-state hydropower to provide 13% of its electricity needs, with most of this generation coming from dams located in the Sierra Nevada Mountains. In the worst year of the drought (2015), in-state hydropower generation decreased to 41% of average (California Energy Commission, 2017b), helping to meet only 6% of California's electricity needs (California Energy Commission, 2017a).

This estimated $2.45 billion in lost hydropower revenues was reported widely (Fracassa, 2017; Kasler, 2017), but it likely does not represent the full cost of the drought to electric utilities and their customers. Drought can also impact electricity demand. For example, if drought is associated with elevated air temperatures that increase residential and commercial cooling needs, it can increase the amount of electricity utilities need to purchase on the wholesale market or produce from self-owned resources. Overall, electricity demand in California appears to have increased mostly along a linear growth trajectory over the years 2010-2018, including during the drought (California Energy Commission, 2019). However, the effects of the drought on demand varied across sectors, and across end-uses within sectors. For example, in the residential and agricultural sectors (the second and fourth largest consumers of electricity in California, respectively (California Energy Commission, 2019)), many utilities reported decreased electricity consumption during the drought years, even as elevated air temperatures increased cooling demands and irrigation (pumping) requirements on a per crop basis. This has been attributed to reduced water consumption during the drought, which in turn reduced energy requirements for water treatment and distribution (Spang et al., 2018).

An addition mechanism for drought to impact costs for utilities is by altering the wholesale price of electricity. In particular, the combination of reduced hydropower availability (supply) and increased cooling requirements (demand) that can occur during drought in California may increase wholesale prices by forcing the market to rely on higher marginal cost generators (i.e. more expensive natural gas power plants) (Boogert and Dupont, 2005; Gutierrez et al., 2014). If the 2012-2016 drought caused wholesale electricity prices in California to increase, it would have mitigated some financial pain for hydropower-owning utilities; hydropower production, although greatly reduced, would have been more valuable. At the same time, however, higher market prices could have made it more expensive for utilities to meet demand via purchases from the wholesale market. Wholesale electricity prices in California did increase during the middle of the drought, reaching an apex in 2014 (Figure 1). However, there has been no attempt to understand how supply and demand effects from the drought might have contributed to this increase (especially compared to other factors known to affect market prices, like natural gas prices); nor has there been an attempt to quantify how increased prices influenced the cost of the drought for California utilities.

Another open question from the 2012-2016 drought has to do with the role of the state's growing reliance on variable renewable energy (wind and solar) in mitigating the environmental impacts of drought. In particular, the substitution of natural gas generation for hydropower during drought is known to increase carbon dioxide (CO_2) emissions in California (Fulton and Cooley, 2015; Hardin et al., 2017; Herrera-Estrada et al., 2018). Previous studies have pointed to the state's growing fleet of wind and solar capacity as a counterbalancing force that was able to mitigate increases in CO_2 emissions that would have occurred during the 2012-2016 drought due to a loss of hydropower (Hardin et al., 2017; He et al., 2019; Zohrabian and Sanders, 2018). In fact, carbon dioxide (CO_2) emissions from California's electric power sector actually decreased over the years 2012-2016 (California Air Resources Board, 2018).

On the surface, these data seem to support the idea that wind and solar power can help reduce the drought-vulnerability of power systems– an idea that has gained more attention in recent years (He et al., 2019; van Vliet et al., 2016). However, the role wind and solar play in reducing drought-caused increases in emissions deserves further examination. Previous studies have relied exclusively on historical data from 2012-2016 to evaluate the California grid's response to drought without accounting for the confounding effects of year-to-year changes in the generation mix. From 2012 to 2016, installed capacity of wind and solar in the state more than doubled, and generation from those resources partially offset losses in hydropower generation, in turn reducing the amount of "replacement" generation needed from natural gas plants. This may (falsely) give the impression that future grid configurations with greater installed wind and solar capacity will be better equipped to replace lost hydropower during a drought, and thus avoid associated increases in carbon emissions. Here, we develop a more nuanced understanding of the role that renewable energy in California plays in mitigating CO_2 increases caused by drought.

In this study, we use newly developed grid simulation software to perform a series of controlled computational experiments that identify the direct influence of drought (and its hydrometeorological constituents) on CO_2 emissions, wholesale electricity prices, and costs for utilities in California. We test different underlying generation mixes, varying the penetration of variable renewable energy, in order to better understand how the presence of renewable energy affects the magnitude of drought-caused increases in CO_2 emissions. Our results provide new insights and important context regarding the economic and environmental impacts of the 2012-2016 drought, its effect on the California grid, and the vulnerability of California's power system to drought in the future under alternative grid configurations.

2. Methods

Modeling Approach

We make use of the California and West Coast Power system (CAPOW) model (Su et al., 2020), an open source stochastic simulation tool designed specifically for evaluating hydrometeorological risks in the U.S. West Coast bulk power system. The model accurately reproduces historical daily price dynamics in California's wholesale market (Figure 1), although it sometimes fails to capture the highest observed peak prices due to its use of publically available natural gas "hub" price data. These data are averages of contracted gas prices experienced by market participants. It is likely that during high demand periods, certain power plants experience gas prices much higher than the hub price, causing spikes in the wholesale electricity price that our model does not capture.

The model's geographical scope covers most of the states of Washington, Oregon and California and the operations of the region's two wholesale electricity markets, the Mid-Columbia (Mid-C) market in the Pacific Northwest and the California Independent System Operator (CAISO) in California. Within the CAISO market, we focus on the service areas of the state's three main investor owned utilities, Pacific Gas & Electric (PG&E), Southern California Edison (SCE), and San Diego Gas & Electric (SDG&E).

CAPOW simulates power system operations using a multi-zone unit commitment and economic dispatch (UC/ED) model formulated as a mixed integer linear program. The model's objective function is to minimize the cost of meeting demand for electricity and operating reserves in the two major markets represented, subject to constraints on individual generators, the capacity of transmission pathways linking zones, and others. CAPOW takes as inputs time series of air temperatures and wind speeds at 17 major airports from the NOAA Global Historical Climatological Network (National Oceanic and Atmospheric Administration, 2019); solar irradiance at 7 different National Solar Resource Database sites (Sengupta et al., 2018); and streamflow at 105 different gauges throughout the West Coast ((BPA) Bonneville Power Administration, 2019; CDEC, 2019). Air temperatures and wind speeds are used to simulate daily peak electricity demand via multivariate regression; hourly values are conditionally resampled from the historical record. It is important to note that in this paper we do not directly account for the effects of reduced water consumption during drought on electricity demand. There is limited data available that would allow for parameterization of a tight model coupling among hydrologic triggers, water conservation policies, and electricity demand.

We use daily wind speeds to simulate aggregate zonal wind power production, and daily solar irradiance to simulate zonal solar power production (both via multivariate regression), before conditionally resampling down to an hourly time step. Time series of daily streamflow are forced through hydrologic mass balance models of major hydroelectric dams in the Federal Columbia River Power System (Pacific Northwest), Willamette River basin (Oregon), Sacramento, San Joaquin and Tulare Lake basins (California). Hydropower availability is calculated on a daily basis across every zone in the model, then dispatched optimally on an hourly basis by the UC/ED model. Model outputs include the least cost generation schedule identified down to the individual generator level, hourly zonal electricity prices ($/MWh), and plant level emissions of CO_2 (tons).

For this study, we collected historical daily temperature, solar irradiance, and streamflow data over the period 1970-2017, and wind data over 1998-2017. Missing wind data (1970-1998) at each site were filled by bootstrapping from the historical record, conditioned on daily temperatures. For the purposes of placing the 2012-2016 drought within the larger context of stationary hydrometeorological uncertainty, we also make use of a 1000-year stochastic dataset of air temperatures, wind speeds, solar irradiance and streamflow created by the authors and described in a separate paper (Su et al., 2020).

Figure 2 compares drought hydrometeorology (2012-2016) with the full 1970-2017 observed record (black) and the 1000-year synthetic dataset (gray). Data shown are averages across all weather and streamflow monitoring stations. The drought years experienced historically low stream flows and elevated temperatures, relative to the recent observed record and the synthetic dataset, while wind speeds and solar irradiance were relatively normal. Even compared alongside the expanded, 1000-year synthetic dataset, modeled hydropower availability and electricity demand for 2012-2016 (and especially 2014-2015) indicate extraordinary conditions (Figure 3).

Note again that demand data shown are modeled purely as a function of hydrometeorological data being passed through statistical models. These estimates thus represent scenarios in which reductions in energy consumption by the water sector do not occur.

3. Results and Discussion

Effects of Drought on Market Prices and Emissions

First, using the 1000-year synthetic dataset, we calculate an average, 365-day profile for every streamflow gauge, wind/temperature station, and solar irradiance site used in the CAPOW model. We pass these average profiles through the CAPOW model, which first translates them into to corresponding time series of available hydropower, wind and solar power production, as well as electricity demand. Then the UC/ED component of the CAPOW model simulates the operation of much of the West Coast grid, including the CAISO market. Representing "non-drought" hydrometeorological conditions in this manner is unrealistic, in that the 365-day profile does not exhibit any within-year extremes (which do occur even in non-drought years). However, it does allow for easy assessment of within year anomalies caused by the drought, as well as comparison of the timing of these anomalies with the timing of extreme prices.

Figure 4 compares daily CAISO prices calculated using the 365-day average hydrometeorological profile (turquoise) alongside prices modeled using observed weather and streamflow data from the 2012-2016 drought (magenta). Comparing these two series within a given panel (year), we see significant differences in daily price dynamics, especially in late spring/summer during the worst years of the drought (2013-2015), when prices in the drought simulations are as much as \$10/MWh greater than "average" conditions. Underlying these higher prices in the drought simulations are a lack of snowmelt (hydropower) and elevated temperatures (increased demand), which cause scarcity in the CAISO market.

Nonetheless, compared to price differences observed between "average" and drought conditions within a given year, the differences are much greater *across years* (e.g. 2013 vs. 2014). This suggests that within year electricity price dynamics, as well as differences in prices across years, are driven more by fluctuations in the price of natural gas than by weather and streamflow conditions. Natural gas prices varied continuously over the period 2012-2016, increasing sharply during 2014, especially at the beginning of the year, when a polar vortex event drastically increased heating demands in the Eastern U.S., causing natural gas shortages and a spike in the price of fuel across the entire country (U.S. Energy Information Administration, 2014). Note that during this period, there is close agreement between estimated prices in "average" and drought conditions. This strongly suggests that this *other* hydrometerological extreme – extreme cold weather occurring thousands of miles away in the Eastern U.S. – was the primary cause of the very high wholesale electricity prices experienced in early 2014 at the height of the drought. This is particularly interesting given evidence (Wang et al., 2014) that both dry conditions in California during 2014 and the occurrence of the polar vortex in the Eastern U.S. were caused by the synoptic climate event-- a jet stream pattern that created a persistent high pressure "ridge" over the Western U.S. If these atmospheric conditions become more frequent and/or severe as a result of climate change (Swain et al., 2014), it could add a significant, new dimension to the vulnerability of California's grid in the future.

We can also isolate the effects of the individual hydrometeorological constituents of droughts on both prices and emissions (Figure 5). In the top panel, yellow bars show daily CAISO prices under a 365-day average hydrometeorological profile calculated from the 1000-year synthetic dataset. One-by-one, we then add in constituents of the 2012-2016 drought, beginning with historically low streamflow in California, then observed streamflow in the Pacific Northwest (which typically exports a significant amount of hydropower down into California), elevated air temperatures, and finally wind speeds and solar irradiance. The time series labeled "Historical" represent results from the full historic 2012-2016 weather and streamflow dataset.

Power sector CO_2 emissions (bottom panel) appear more sensitive to drought conditions than prices (top panel). Comparing emissions under average hydrometeorology with emissions under 2012-2016 conditions, we see large increases, particularly during the two hottest and driest years, 2014-2015. There are clear differences in the strength of the effect across individual drought constituents. In most years, the two largest contributors to increased emissions are very low streamflow in California (i.e. reduced in-state hydropower production) and high air temperatures (i.e. increased electricity demands for cooling).

Note as well that the bar graphs in Figure 5 indicate standard errors associated with each price and emissions estimate. For each hydrometeorological scenario (e.g., average conditions + historical CA streamflow), identical weather and streamflow inputs are used in multivariate regression models to create five separate records of power system inputs (time series of wind power, solar power, etc). For a given scenario (bar) shown in Figure 5, the standard errors measure the (limited) influence of randomness in regression residuals on the results.

The Cost of Drought to Electric Utilities

A first step in measuring the cost of the 2012-2016 drought for electric utilities in Calfironia is to quantify impacts on market prices in CAISO. In Figure 6 (top panel), we compare the electricity price in CAISO under average hydrometeorology (solid bars) and historical 2012-2016 hydrometeorology (white bars). We also compare electricity prices resulting from two different model choices regarding the price of natural gas: 1) a static, average natural gas price of \$3.5/MMBtu (orange bars); and 2) the historical 2012-2016 natural gas price regime (pink bars). The price impacts from drought are equal to the delta of each solid/white bar pair; these results are then plotted in the bottom panel of Figure 6.

We find that the drought likely caused average market prices in CAISO to increase between \$0-3/MWh, depending on the year, although within-year price differences could be much greater (see Figure 4). Figure 6 also indicates that natural gas prices influence how the market experiences the effects of drought. For example, in the bottom panel, if a constant, average price of natural gas is assumed for each year (orange bars), the most significant impacts from drought occur in 2015. This is consistent with our findings that, in terms of lost hydropower generation and increased cooling demands, 2015 was the "worst" year during the 2012-2016 drought (see Figure 3). In reality, the combination of extreme drought conditions in 2014, coupled with high natural gas prices (including those caused by the 2014 polar vortex) actually made 2014 the worst drought year, in terms of increased wholesale prices.

Table 1 further explores the potential costs of drought in the service areas of the three main investor owned utilities in California (PG&E, SCE and SDG&E). The first economic cost to grid participants that we consider is the "net" value of lost hydropower. In Table 1, we estimate this as the difference between summed daily hydropower revenues (production in MWh multiplied by market price in \$/MWh) under average hydrometeorological conditions and each drought year. This allows us to capture losses from reduced hydropower production, as well as the benefits to hydropower producers from experiencing higher market prices during the drought. In general, we find that increased prices do relatively little to make up for a loss in hydropower production. Across the three utility service areas considered, the net value of lost hydropower over 2012-2016 is approximately $1.9 billion. The only previous estimate of the value of lost hydropower generation during the drought is $2.45 billion (Gleick, 2017). Our estimate is likely lower due to a few different factors. First, we only assess hydropower that directly participates within the CAISO market. A smaller, but still significant amount of hydropower capacity is operated by other utilities (e.g. Los Angeles Department of Water and Power, Sacramento Municipal Utility District, San Francisco Public Utility Commission, PacifiCorp). Lost hydropower in those areas is not considered. We also directly account for the economic benefits to hydropower producers from increased market prices, which helps offsets lost production somewhat.

Next, we determine the costs associated with higher electricity demand due to elevated air temperatures during the drought. In Table 1, we estimate these additional costs as the difference between summed daily electricity costs (electricity demand in MWh multiplied by the market price in $/MWh) under average hydrometeorological conditions and each drought year. We find that, in the absence of secondary economic/policy feedbacks (e.g., water conservation efforts in urban areas), increased electricity demand driven by higher air temperatures could have increased costs for utilities by more than $3.8 billion – representing a significantly greater cost than the loss of hydropower.

We also find major differences in how the three investor-owned utilities likely faired during the drought. For example, in the case of PG&E, which is the largest private owner of hydropower capacity in the U.S., the value of lost hydropower represents a greater cost than increased consumption. The opposite is true for SCE, which owns less hydropower capacity and has electricity demands are more sensitive to temperature extremes.

Renewable energy and drought-caused emissions increases

The second major objective of this paper is to evaluate the potential for variable renewable energy to mitigate increases in CO_2 emissions caused by drought. To answer this question, we measure the response of two different versions of the CAISO grid to drought. In one version we assume 2012 levels of installed wind and solar capacity, and in another we assume 2015 levels of installed wind and solar capacity (more than double 2012 levels). Figure 7 compares the performance of these two versions of the model when simulated under 2015 hydrometeorological conditions (arguably the most extreme year of the drought). Panel A tracks daily differences in fossil fuel generation over the entire year, confirming that a version of the grid with greater (2015) levels of installed wind and solar power relies on less generation from fossil fuels to meet demand. Nonetheless, having increased wind and solar power capacity in place does not prevent the drought conditions from causing an uptick in the use of fossil fuels.

In panel B, we track daily differences in fossil fuel generation caused by drought conditions in 2015 (i.e. relative to average hydrometeorology) under two different levels of installed wind and solar capacity, 2012 (black) and 2015 (orange). Drought conditions in 2015 appear to cause nearly identical responses (increases) in fossil fuel generation under the two different capacity mixes, despite the fact that double the amount of renewable energy capacity is installed in 2015. This is confirmed by panel C, which plots the difference of the two series shown in panel B. The result approximates a stationary noise process, suggesting that differences between the two renewable energy scenarios is due primarily to stochastic model residuals created by CAPOW when translating hydrometeorological time series into corresponding records of wind and solar power production, electricity demand, etc. (see error bars in Figure 5).

Figure 8 confirms that the presence of more renewable energy does very little to prevent increased CO_2 emissions during drought. We track total CO_2 equivalents emitted by power plants in CAISO under historical drought conditions (open bars) and an "average" hydrometeorological year (solid bars). We also control for installed renewable capacity. Black bars represent CO_2 emissions in a version of the model that assumes 2012 renewable energy levels. Green bars assume historical capacity levels, which gradually increase over the 5-year period (purple dotted line).

As installed renewable energy capacity increases from 2012-2016 (open bars), emissions are mostly steady before declining in the last year of the drought; they would have decreased faster under average hydrometeorological conditions (solid bars). However, the deltas in emissions between average and historical hydrometeorology look very similar for the two different renewable energy scenarios. The bottom panel confirms this; in fact, we see that drought-caused increases in CO_2 emissions are actually lower in most years if we assume static 2012 installed renewable energy capacity. This could be a sign that the model is relying more on higher emission natural gas combustion turbine units (as opposed to slightly less flexible combined cycle units) when there is more renewable energy installed. If the latter proves to be true, in the short term it raises the possibility that increased renewable energy capacity in CAISO could in fact lead to more severe (larger) emissions responses during drought.

4. Conclusion

In this paper, we closely examine the impacts of the 2012-2016 drought on California's electricity grid. For the first time, we isolate the drought's hydrometeorological constituents and perform a series of controlled experiments in order to understand how weather, streamflow, fuel prices, and renewable energy individually and collectively affected grid outcomes. We first explore the impacts of the drought on wholesale prices for electricity, finding that the drought increased prices on average by between $0-3/MWh, with the biggest underlying causes being a decrease in streamflow (hydropower generation) and elevated temperatures (modeled electricity demand). While an important impact, our results also make clear that natural gas prices were the dominant driver of higher electricity prices experienced during the drought, especially during early 2014 when natural gas prices spiked nationwide due to extremely cold weather in the Eastern U.S. These high gas prices caused a spike in wholesale electricity prices at the height of the drought. Interestingly, the incidence of extreme cold in the Eastern U.S. and extreme drought in California were driven by the same synoptic climate event – a persistent high pressure ridge over the U.S. West Coast.

Our estimates of the cost of the drought in the CAISO system are on the same order of magnitude as the lone previous estimate. However, we find that the cost of the drought in the electric power sector could have been much higher than previously reported, with utilities experiencing significantly increased demand due to higher air temperatures and cooling demands. A limitation of this work, however, is our failure to account for feedbacks from policies aimed and reducing water consumption, which actually reduced electricity demand in some sectors. Improving understanding in this area remains an outstanding challenge. We find essentially no evidence supporting the idea that the presence of greater variable renewable energy capacity *before a drought begins* will help mitigate associated increases in CO_2 emissions caused by water scarcity and higher temperatures. The results of our controlled experiments show that even when renewable energy capacity more than doubles from 2012 to 2015 levels, the CAISO grid experiences the same increase in fossil fuel generation and CO_2 emissions during drought years. In fact, there is some evidence that drought-caused emissions increases may be more severe under higher installed renewable energy capacity. This could be caused by increased reliance on flexible but inefficient natural gas combustion turbines to help integrate renewables.

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6. Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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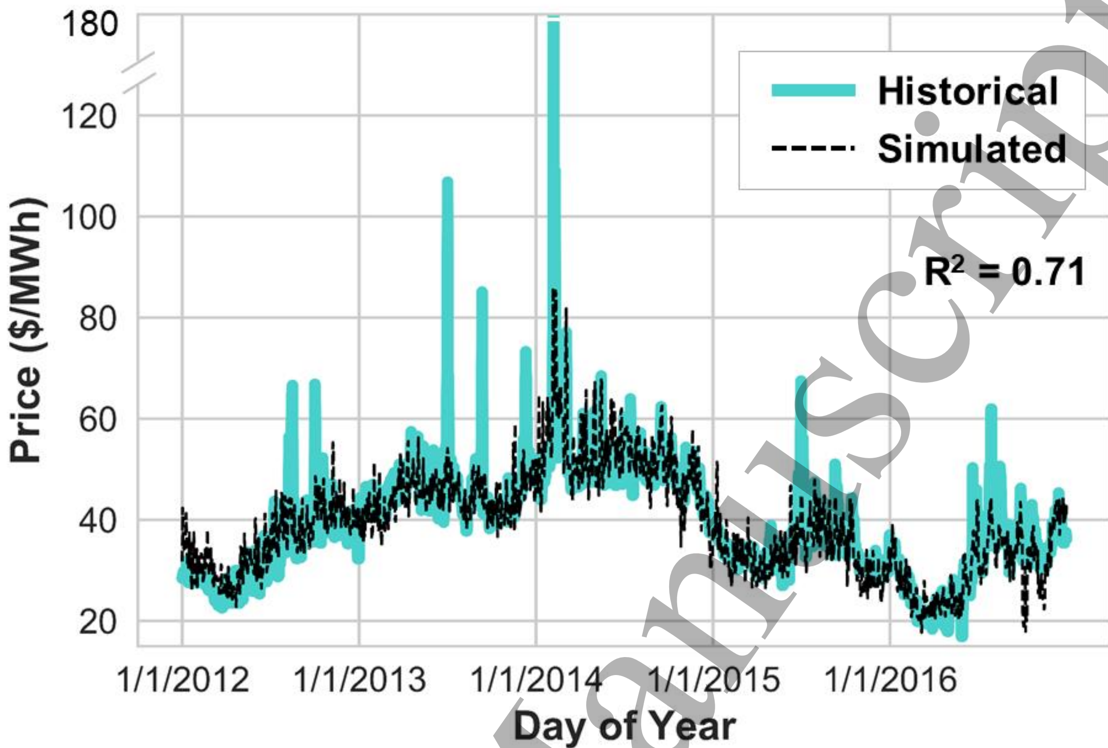

Figure 1. Comparison of historical daily electricity prices in the CAISO market during the 2012-2016 drought (green) alongside prices simulated by the CAPOW model (black). The model is able to capture a significant portion of the variation in daily prices, but struggles in some instances to capture very large price spikes. Note that prices generally increased during the first half of the drought, reaching an apex in 2014, before declining during the last two years.

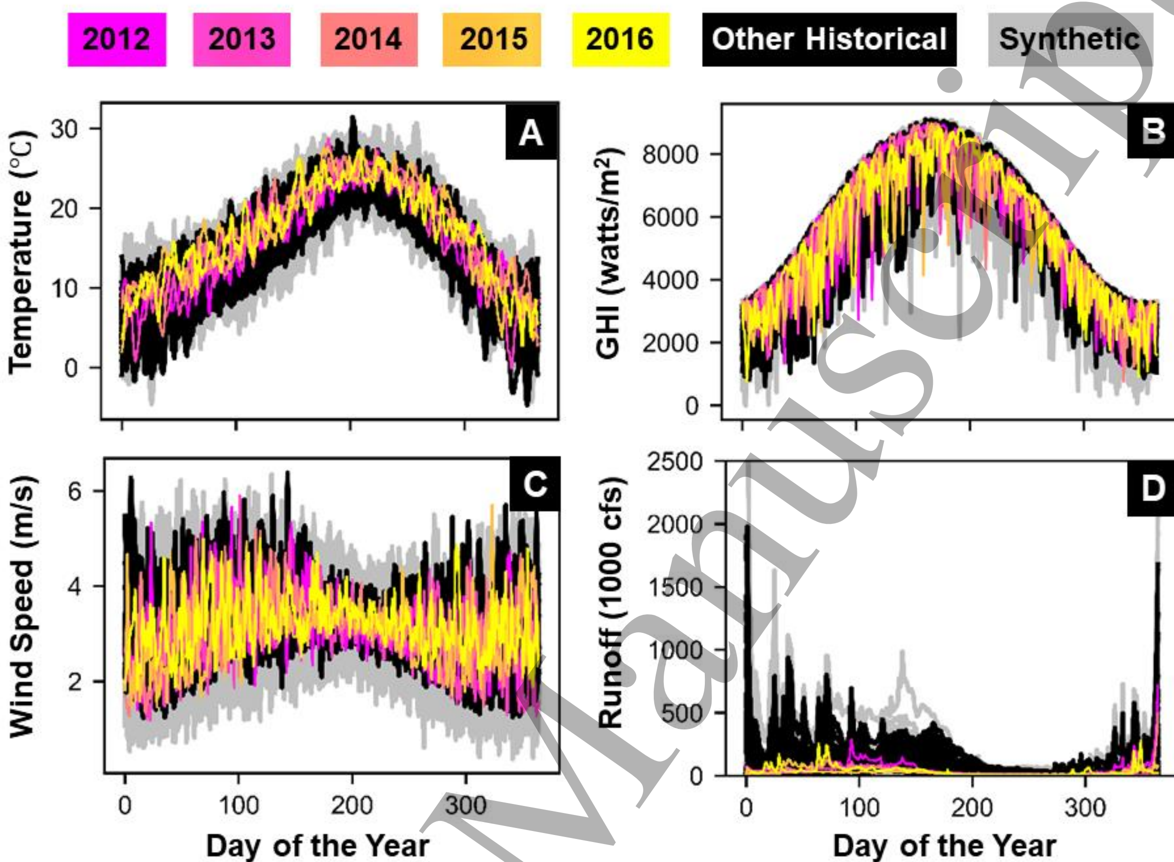

Figure 2. Comparison of historical drought year hydrometeorology (2012-2016) with the longer observed record (1970-2017) (black) and the 1000-year synthetic dataset (gray). While stream flows reached historical lows (panel D) and temperatures were elevated (panel A), the 2012-2016 drought experienced relatively normal wind speeds (panel C) and irradiance (panel D).

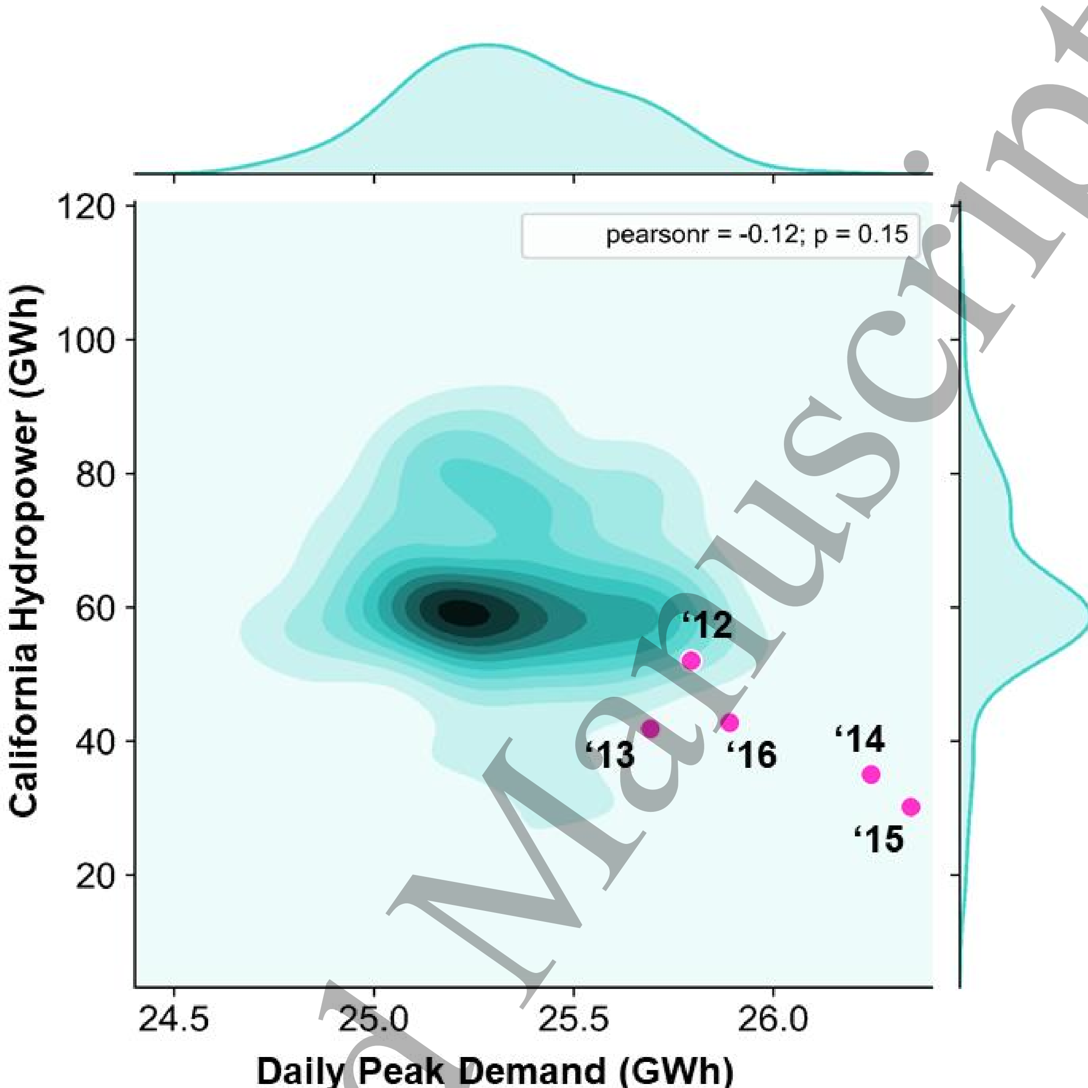

Figure 3. Joint density function of total CAISO hydropower production and average CAISO peak demand for the 1000-year synthetic dataset (green) and the 2012-2016 drought years (pink). Historical data shown is purely a function of observed hydrometeorological data passed through statistical estimation of electricity demand and reservoir operations models. No policy feedbacks (reduced water use) are considered when predicting electricity demand.

Figure 4. Daily wholesale electricity price dynamics in the CAISO market, 2012-2016. Different colors represent different hydrometeorological scenarios. Natural gas price fluctuations are responsible for most observed within year price dynamics and year-to-year differences. The large price spike in early 2014, at the height of the drought, was not caused by drought conditions in the California. Instead, this was caused by extreme cold conditions in the Eastern U.S. that increased the price of natural gas across the entire U.S.

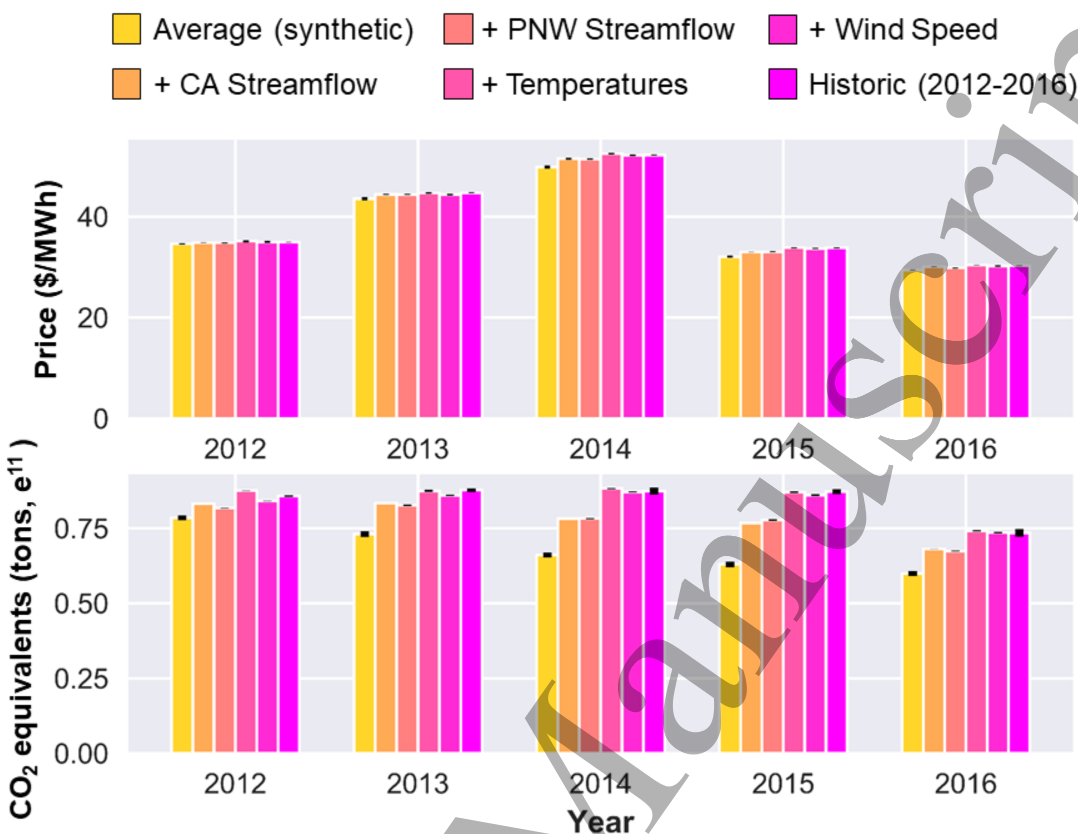

Figure 5. Additive effects of individual hydrometeorological constituents of drought on average electricity prices in the CAISO market (top panel) and CO_2 emissions (bottom panel). Results confirm that year-to-year changes in the price of natural gas (i.e. comparing across years) leads to much more significant changes in price than weather and streamflow conditions (i.e. comparing across scenarios within a single year). In the bottom panel, we see that low streamflow and high temperatures in California result in the largest relative increases in power sector CO_2 emissions.

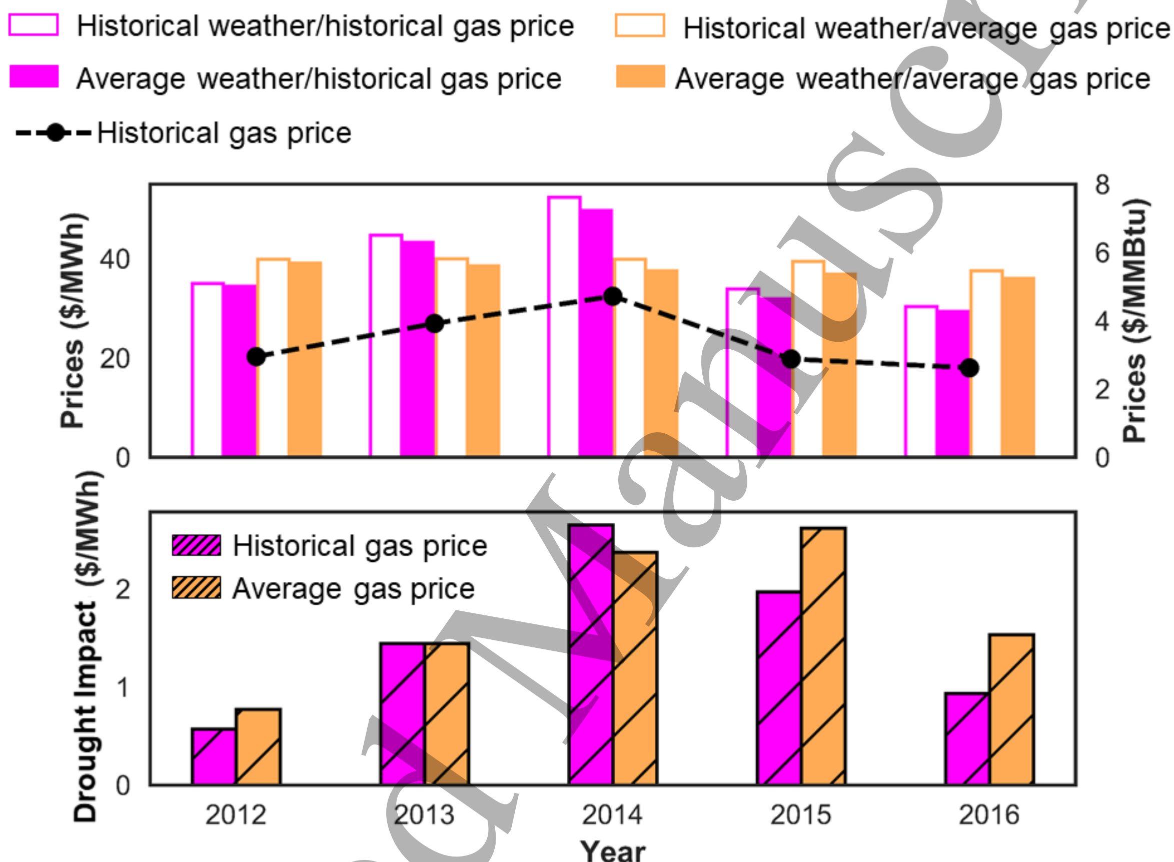

Figure 6. Top panel: Comparison of CAISO electricity prices under historical meteorology (white bars) and average conditions (solid bars), and under historical natural gas prices (pink bars) and average natural gas prices (orange bars). Bottom panel: The drought likely caused wholesale prices to increase between $0-3/MWh, depending on the year. We also find that the co-occurrence of high natural gas prices (brought about by the polar vortex in the Eastern U.S.) and drought conditions in California caused the biggest price impacts in 2014, even though 2015 experienced the lowest hydropower and highest cooling demands.

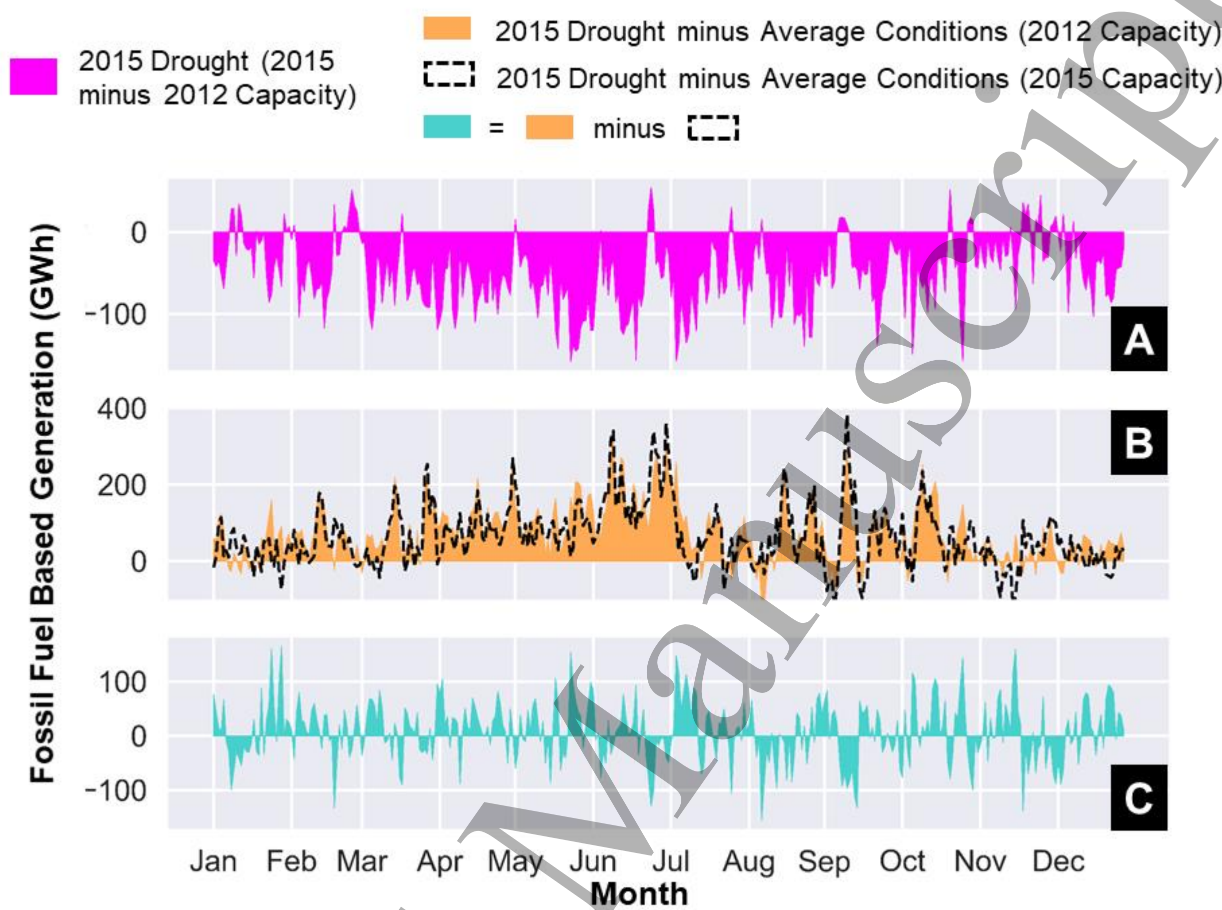

Figure 7. Panel A: Changes in fossil fuel generation during 2015 attributable to more than doubling installed wind and solar capacity. Panel B: Crought caused changes in emissions for the two renewable energy scenarios (2012 (orange) and 2015 (black dotted line)). Differences between these two series are appear to mostly be due to random model errors (panel C). The presence of more renewable energy does very little to prevent increased reliance on fossil fuel generation during drought.

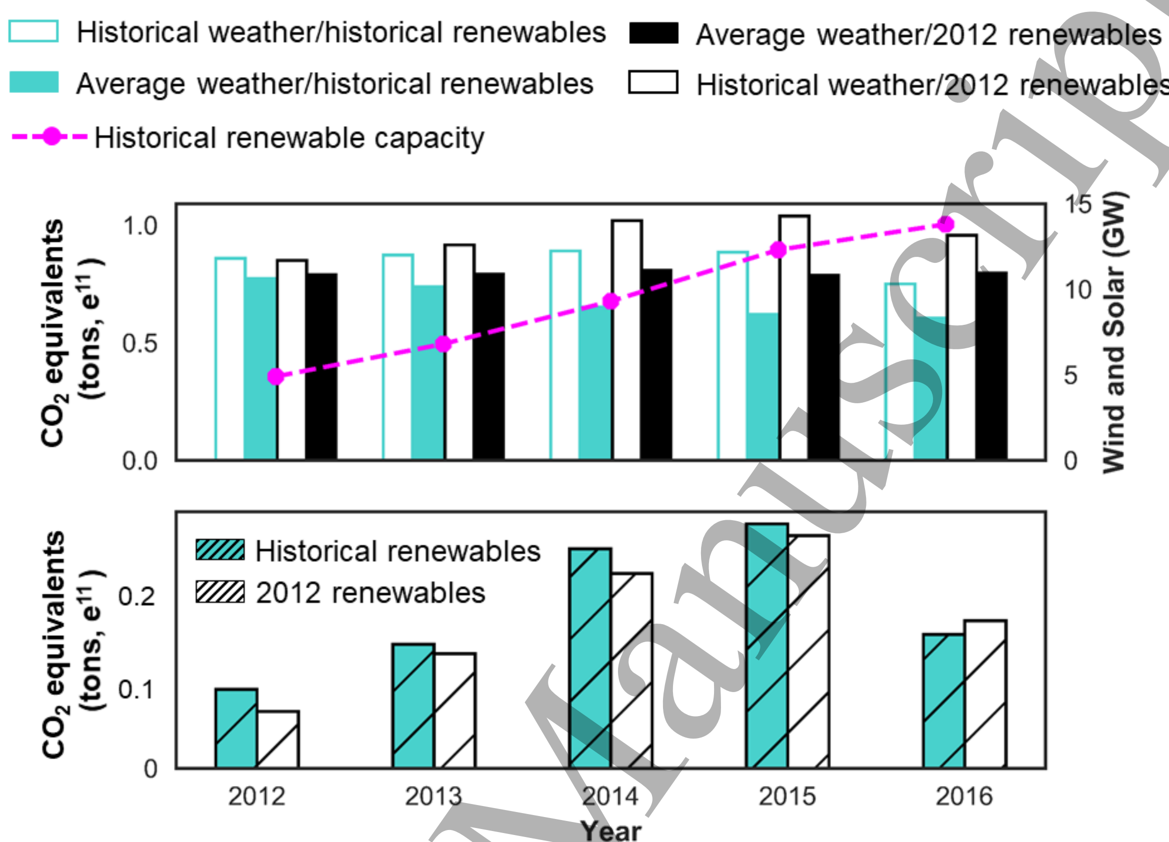

Figure 8. Top panel: CO_2 emissions under historical 2012-2016 hydrometeorology (open bars), average hydrometeorology (solid bars), 2012 renewable energy capacity (black bars) and historical 2012-2016 renewable capacity (green bars), which gradually increase over the 5-year period. Bottom panel: CO_2 emissions increases during the 2012-2016 drought are actually slightly lower under 2012 renewable energy capacity. This is likely due to greater reliance on higher emission natural gas combustion turbine units when there is more renewable energy installed.

Table 1. Evaluation of the costs of drought in the CAISO market. Higher temperatures increased modeled electricity demand while low streamflows reduce hydropower. The combined effects are an increase in market prices. PG&E and SCE are shown to be the most strongly affected, with PG&E impacted more by a loss of hydropower, and SCE affected more by a modeled increase in demand.

		Average Hydrometeorological Conditions			Drought Impacts			Hydropower Revenues			Demand Costs			
		Demand (GWh)	Hydro (GWh)	Price ($/MWh)	Demand Increase (GWh)	Lost Hydro (GWh)	Price Increase ($/MWh)	Average Conditions ($M)	Drought Year ($M)	Lost Hydro Value ($M)	Average Conditions ($M)	Drought Conditions ($M)	Increased Demand Costs ($M)	Net Drought Impact ($M)
PG&E	2012	117653	24082	34.70	2411	4882	0.16	784	657	127	4109	4218	108	235
	2013	117623	24082	43.33	3173	8887	1.57	1037	685	352	5115	5451	336	688
	2014	117838	24082	49.71	3913	11228	2.39	1207	671	536	5887	6383	495	1031
	2015	118331	24082	32.30	2028	12926	1.58	759	375	384	3862	4133	272	656
	2016	118250	24082	29.35	2378	8438	1.03	659	466	194	3512	3721	208	402
SCE	2012	119994	4268	34.70	4890	988	0.16	139	106	32	4215	4421	207	239
	2013	118270	4268	43.33	6107	1498	1.57	185	127	58	5152	5621	469	528
	2014	119294	4268	49.71	7954	2290	2.39	213	105	108	5969	6694	725	832
	2015	121210	4268	32.30	4723	2598	1.58	137	55	81	3974	4350	376	457
	2016	120521	4268	29.35	3715	1550	1.03	118	77	41	3606	3858	252	293
SDG&E	2012	25318	0	34.70	635	0	0.16	0	0	0	885	916	31	31
	2013	24901	0	43.33	773	0	1.57	0	0	0	1082	1157	75	75
	2014	25180	0	49.71	1269	0	2.39	0	0	0	1258	1389	130	130
	2015	25315	0	32.30	1055	0	1.58	0	0	0	825	906	81	81
	2016	25370	0	29.35	568	0	1.03	0	0	0	753	801	48	48
							Total ($M)	5238	3325	1913	50206	54019	3814	5726