

# The Grid Under Extremes

## Pandemic Impacts on California Electricity Consumption

WHEN CONFRONTED WITH CRISES AND OTHER extreme events, the core responsibility of the grid does not change: to meet society's demand for electricity in a safe and reliable manner. However, these extreme events are now interacting with a transitioning grid system that is constantly evolving and adapting to meet new societal needs. This change includes the decarbonization of energy systems while also ensuring equity in its reliability, accessibility, and affordability of energy for all. In this article, we examine a single extreme event with unprecedented impacts on the energy system: the COVID-19 pandemic. Using California as an example, we explore in detail the pandemic-related impacts on electricity consumption and make recommendations for improving planning, forecasting, and other operations in response to extremes.

### Living With Extremes

In the United States and across the world, there have been stark examples of how unprecedented events can rapidly shape the trajectory of the energy sector. These events range from global impacts from the COVID-19 pandemic to regional extreme weather events. In the United States,



these extreme weather events are typified by the abnormally cold weather in Texas in 2021 that resulted in wide-ranging impacts on the energy system. This event not only resulted in power outages, but also disruptions in natural gas for heating and even access to clean water. Such events may

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become even more severe, frequent, and perhaps even more unpredictable in the future due to climate change. Therefore, now is the time to begin planning for such high-impact, low-probability extreme events in a systematic, data-driven way that can be generalized to energy systems across the United States and the world.

Understanding how extreme events impact the power system requires analyzing how they affect both the supply side (e.g., generation and transmission/distribution networks) and the demand side (e.g., residential, commercial, industrial consumption patterns). On the supply side, extreme weather

ransomware attack in the United States resulted in a multiday shutdown of service and an emergency declaration in 17 states.

Extreme events can also significantly impact the demand for electricity. The COVID-19 pandemic and the resulting restrictions in movement of people and changes in economic activity led to substantial global decreases in electricity use that persisted for months. Albeit not at the magnitude of the COVID-19 pandemic, economic recessions, such as those related to the 2008 global financial crisis, can also lead to notable decreases in electricity demand.

Other extreme event types may impact demand in a different direction entirely. For example, during heat waves there can be substantial increases in electricity demand to cool buildings. This demand increase can be so large and interact with other grid factors related to hot weather, to the point that rolling blackouts are required to maintain the integrity of supply. Such a situation was observed in California during the summer of 2021.

Given these extreme events and a growing record of their impacts, an urgent need exists to not only plan for the recurrence of such event types, but also plan for events that have not yet happened. This is all occurring under the backdrop of climate change and society's response to mitigating climate change through the transition to a decarbonized energy system.

Three critical areas can help address future extreme events in a transitioning grid:

- 1) the creation of new metrics for characterizing the impacts of historical events that can facilitate comparisons across event types, locations, and exposed populations
- 2) the development of methods for simulating historical events and events that could happen in the future
- 3) the deployment of energy system modeling and decision support tools to rapidly enable event response when an event occurs.

In this article, we use the example of the COVID-19 pandemic and related responses in California to demonstrate the extent of impacts that extreme events can have on the energy system and how these impacts can be measured. The article assesses impacts on forecasting and planning operations to provide a window into the future of the grid under extremes.

## The Grid and the Pandemic

During the initial stages of the COVID-19 pandemic, many regions around the globe implemented policies that restricted movement and interactions of populations, sometimes referred to as *stay-at-home* or *shelter-in-place* (SIP) orders. These lockdowns had dramatic effects on society, affecting individuals and entire economic sectors including education, industry, transportation, and commercial enterprises large and small. Many of these sectors struggled to adjust to rapidly shifting consumer behaviors and protective policies. Electric utility companies have the responsibility to



events, such as extreme cold, hurricanes, flooding, and so on, can impact vulnerable power infrastructure, such as nonwinterized generators. Wildfire and high wildfire risk conditions can result in shutoffs of power for public safety purposes. These de-energization scenarios are a protective measure increasingly deployed in California and soon in other areas of the Western United States, often coinciding with extreme heat and drought conditions. Disruptions in energy supplies, such as those experienced in Western Europe related to conflict in Ukraine, can have downstream impacts on energy availability and prices globally. There are also new and emerging extreme threats to the grid related to cyberattacks. For example, the 2021 Colonial Pipeline

provide reliable service to their customers, regardless of the unprecedented nature of societal responses toward combating the spread of COVID-19.

Demand for electricity is traditionally one of the most consistent consumer behavior patterns. Monday through Friday, people go to work, and the demand for electricity moves with them into areas dense with commercial and industrial buildings. At night, when individuals return home, electric demand shifts back to residential areas. COVID-19 lockdowns affected both the location of demand as well as the scale, as many businesses shut down and many consumers changed their regular daily routines. With nearly all employees deemed nonessential being asked to remain in their homes and no longer commuting to work, changes in both residential and commercial consumption were anticipated. The expected magnitude of this change was not yet clear, confounding efforts to generate accurate forecasts of electricity demand.

The ability to effectively supply electricity to consumers relies on an accurate forecast of demand. Given these pandemic-driven changes in the location and scale of demand, new challenges emerged for utilities, independent power producers, load balancing authorities, and others who participate in electricity markets. How should they go about forecasting demand under COVID-19 restrictions with little, if any, historical data to use as a guide? A variety of early news media and industry reported that during the initial stages of the pandemic (March–July 2020) there were significant shifts in overall electric demand of large areas in the United States. However, an understanding of the drivers of demand changes and methods for improving demand forecasts under such conditions remained elusive.

### **California and Electricity Demand During the Pandemic**

To demonstrate the extent of changes that extreme events like the COVID-19 pandemic can have on electricity systems, we focus on California in the early months of the pandemic. The California Bay Area was one of the first regions in the United States to have experienced the early effects of the COVID-19 pandemic. Early in March several major Silicon Valley companies started either encouraging or requiring employees to work from home. On March 17, an SIP order was issued in six Bay Area counties (Alameda, Contra Costa, Marin, San Francisco, San Mateo, and Santa Clara). Two days later, on March 19, a SIP order was issued for the entire state of California.

As a result of California's early investment in smart meters, the changes in electric demand can be investigated at a very granular level and reveal contrasting patterns of change in demand between different consumer sectors. In the analysis that follows, we make use of recent electric consumption data in the service territory of Pacific Gas and Electric. This analysis recognizes the privacy of utility customer usage information and adheres to the California Public Utility Commission's aggregation rules that protect this privacy.

To illustrate the dramatic changes in electric consumption starting in March 2020, we analyze a few key counties of interest (Figure 1). Across these selected counties there is substantial variation. San Francisco experienced some of the largest declines in consumption matched to comparable days (matching International Organization for Standardization week of the year, and day of the week) in 2016–2019. Other counties, such as Marin, experienced much smaller decreases. This variation suggests that certain county-level characteristics, such as the proportion of residential versus nonresidential consumption, could be affecting the overall change in consumption.

### **Electricity Consumption Change Using Counterfactuals**

To accurately estimate how much consumption change was related to the pandemic, accounting for changes that may be related to other confounding factors, such as weather patterns, is important. We help account for such factors by developing a counterfactual model, an approach that is often used to understand what could have happened under different historical circumstances. In this application, a counterfactual model allows us to examine what electricity consumption would have been in the absence of the pandemic, accounting for actual weather patterns and other variables. We compare this counterfactual estimate to actual electricity consumption data to quantify the change in consumption related to only the pandemic. To analyze the differences in the impacts on residential and nonresidential consumption patterns, we develop counterfactual models for both classes of customers. The data are aggregated over a number of Bay Area counties (San Francisco, San Mateo, Santa Clara, Marin, and Alameda) using five years of electricity consumption data (1 January 2016 to 31 December 2020).

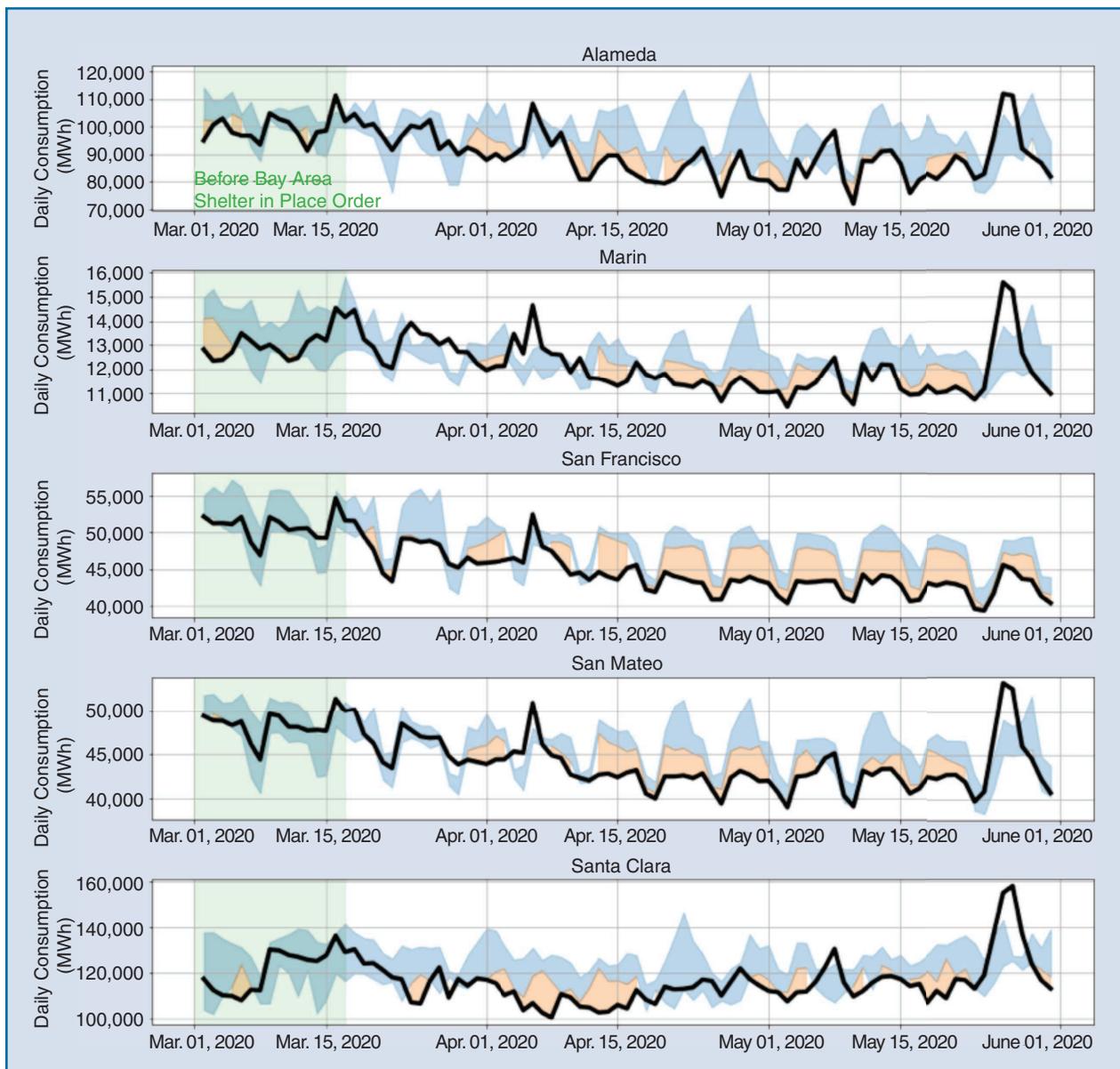
We train two counterfactual models—one for residential energy consumed in a day and one for nonresidential energy consumed in a day aggregated in the five San Francisco Bay Area counties listed previously. We train linear regression models using Lasso, a method that performs both regularization and variable selection to improve prediction accuracy and prevent overfitting. The regression model features incorporate both weather and holiday data. We use categorical indicators for each specific holiday, a variable for generic holidays, variables for each day of the week, month, as well as for whether a given day is a weekend day or not. In addition, in the model we account for day of the week, month, year, and whether a day is a weekday or not. We also account for weather patterns by using daily heating and cooling degree days and include additional squared and cubed terms to account for any nonlinearity in the temperature dependency.

The electricity consumption data from 2020 is reserved to compare with the counterfactual. The remaining four years of data (2016–2019) are used to train models whose prediction for consumption during 2020 is taken as the counterfactual estimate. For the purpose of evaluating predictive power of models, we use all of the data of 2019 as a test data set and all of the previous data for training.

The counterfactual model results show significant differences in the magnitude and direction of consumption changes between the residential and nonresidential sectors, as shown in Figure 2. Since the beginning of the pandemic, residential consumption was consistently at or above the counterfactual level, while nonresidential consumption was significantly lower. In both cases, demand shifts occurred after the SIP order. These results highlight the need to account for differences in sectoral composition and other intrinsic attributes of electricity systems when estimating demand-side impacts of such events in different locations.

### Comparing Daily Patterns of Electricity Consumption Before and During the Pandemic

During the pandemic, system operators not only experienced unprecedented changes in the magnitude of daily electricity consumption but also changes to patterns in loads across different times of day. To analyze these patterns, we first calculate the hourly consumption of an average week during the pandemic. We then compare this to an average historical week using data from 2016 to 2019 (Figure 3) for several Bay Area counties (San Francisco, San Mateo, Santa Clara, Marin, and



**figure 1.** The daily consumption in 2020 versus comparable days in 2016–2019 for selected counties in California’s Bay Area. The bold black line depicts electric consumption in 2020. The blue shaded region depicts the range (min to max) of electric consumption during the equivalent days of the year in 2016–2019. The orange shaded region depicts the gap between the minimum consumption seen in the 2016–2019 period and the actual consumption seen in 2020, where 2020 consumption is below the 2016–2019 minimum.

Alameda). The averages are calculated by taking every hourly electric consumption data point in the time range (each year), grouping by hour of the week, and taking the mean value. In this manner, we effectively average over weather conditions.

For the nonresidential sector, the largest drop in consumption occurred during working hours, but the general load shape remained relatively the same. However, the load shape for residential consumption changed significantly, from a prepandemic dual peak load shape with peaks in the morning and evening, to a shape that is much flatter during the middle of the day. Additionally, we see that the typical weekends in the period before the pandemic have a shape that more closely aligns with weekdays during the pandemic. In other words, weekdays during the pandemic more closely resemble weekends before the pandemic. This characteristic is a representation of how much change occurred in the electricity system and the corresponding changes in human behaviors and economic activity that occurred as well in response to COVID-19.

### Forecasting Performance in the Aftermath of the Pandemic

To maintain reliable grid operations, grid operators need to be able to predict how demand may change during extreme

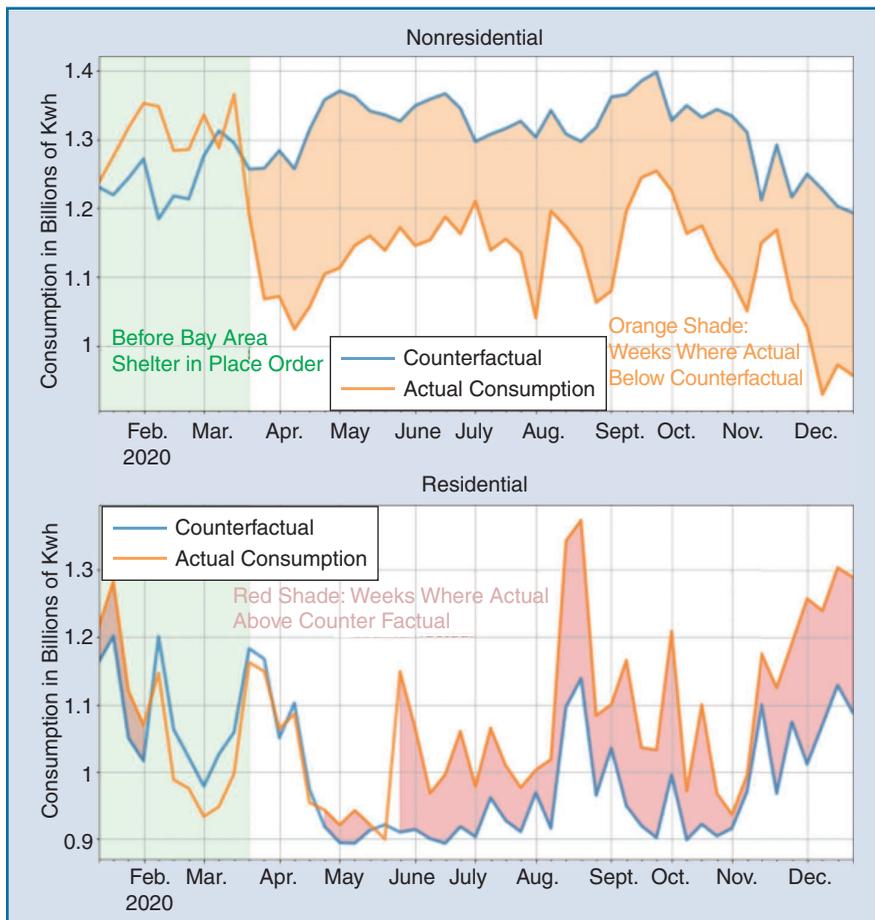
events. To see how quickly system operators were able to adjust to the changing load patterns of the pandemic, we analyze the performance of electricity demand forecasts during the first few months of the pandemic. While the day-ahead forecasts are easier to adjust daily according to information from most recent days, week-ahead forecasts can indicate if actual electricity demand is deviating from what the operators predicted a week ago. Therefore, we assess the performance of week-ahead forecasts by comparing the actual demand to the demand that was forecasted by the system operator. If forecasted demand was statistically higher than actual demand, this is an overprediction. If forecasted demand was statistically lower than actual demand, this is an underprediction. If the forecasted and actual demand were similar, there is no bias in the forecast.

We first examine the performance of week-ahead daily forecasts of electricity demand at the state level. Figure 4 shows whether the daily forecast for the next week was an overprediction or underprediction using statistical methods. Before California's SIP order, forecasts typically were either an underprediction or neutral prediction with no bias. Starting from the week of SIP, there were five consecutive weeks of overprediction, which demonstrates the extent

of the unexpected drop in electricity demand during the SIP order. After these five weeks, the forecast performance recovered.

Based on these results, we further analyze which times of the day the forecast was biased. Figure 5 shows a more detailed look into hourly forecast results for each week starting from the first week of 2020. For the weeks of overprediction identified in Figure 4 (in red), which is from March 16 to April 19 in Figure 5, the majority of overprediction hours are between 5 a.m. and 5 p.m. This shows that the drop in electricity consumption mainly happened during working hours, consistent with the closure of many worksites during this time.

At a more granular geographical level, we examined the forecast performance for three utilities in California (Pacific Gas and Electric, Southern California Edison, and San Diego Gas & Electric). Figure 6 shows the forecasting performance (represented by the distribution of forecast errors) for the weeks immediately before and after the SIP order for each utility.



**figure 2.** The weekly actual versus counterfactual estimates for residential and nonresidential consumption aggregated from selected counties in the California Bay Area.

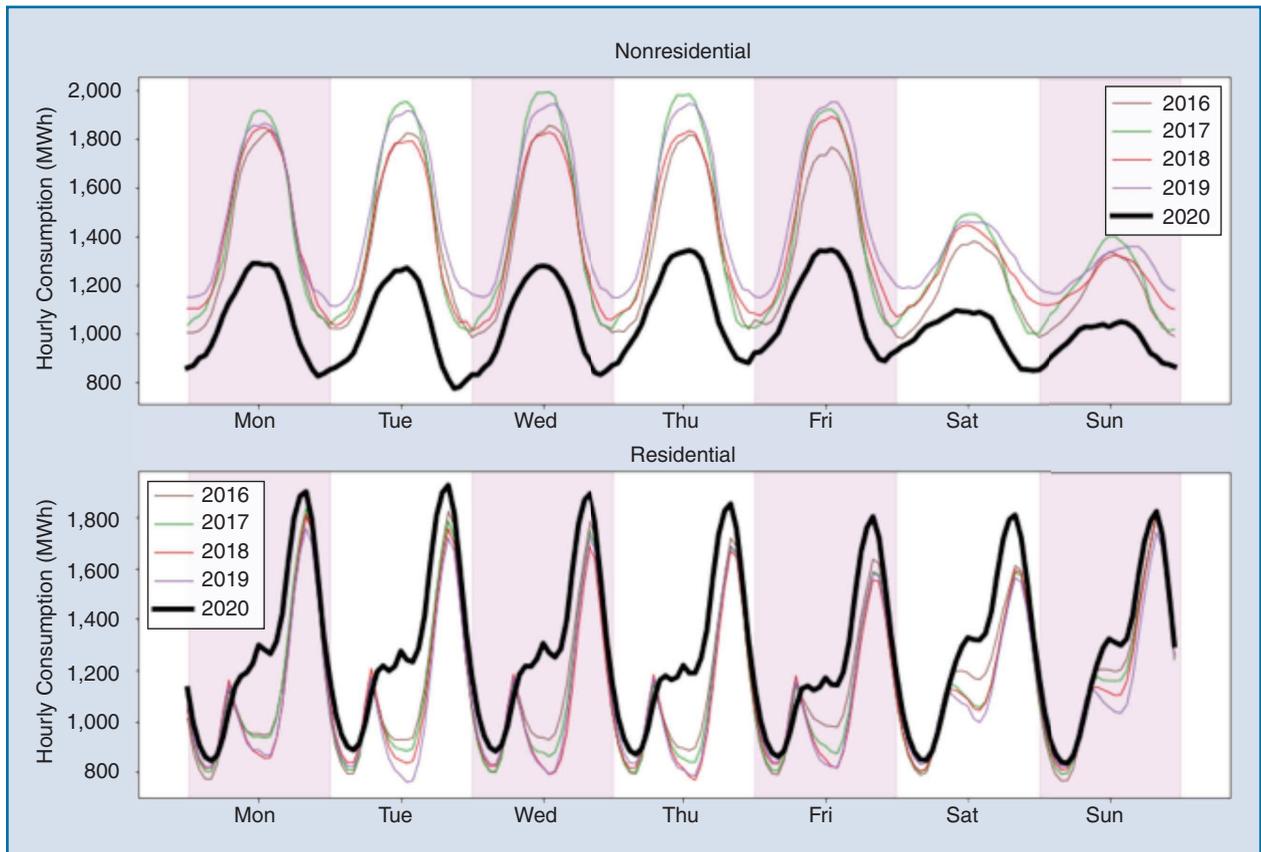
A shift in the forecast error distribution can be observed between the two time periods, consistently toward the direction of overpredicting consumption after the SIP order.

As an extension beyond the California case, the week-ahead electricity demand forecast is also investigated for several European countries including Italy, Spain, France, and Germany. As shown in Figure 7, compared to California there are similar overprediction periods observed after the breakout of the pandemic in these examined countries. However, the duration of timing of the overprediction period differs across countries.

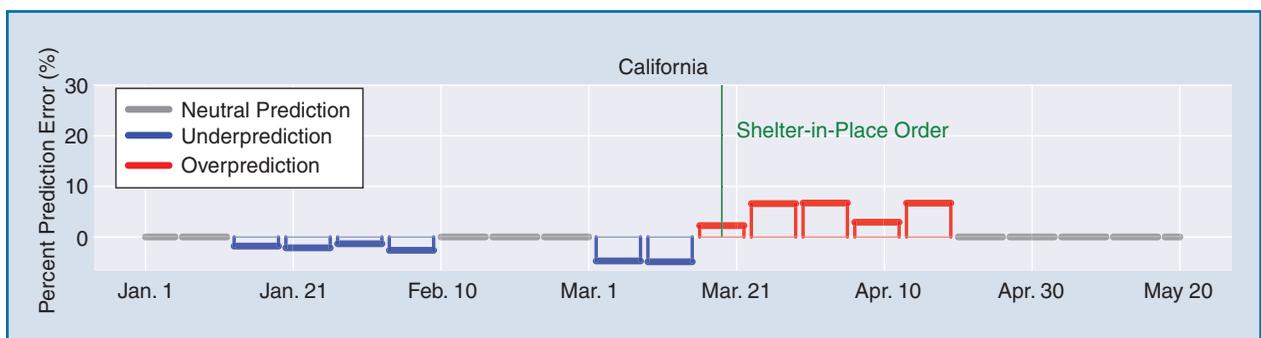
This difference likely reflects a multitude of factors including variations in COVID-19 infection rates and COVID-19-related government policies intended to protect human health.

### Discussion

In this article, we applied energy data to understand changes brought about by extreme events, focusing specifically on the COVID-19 pandemic. In doing so, some important insights emerged with direct implications for electricity system planning and forecasting. One of the key findings is that



**figure 3.** The hourly consumption over an average week during the pandemic (2020), versus before the pandemic (2016–2019) for residential and nonresidential customers, in select San Francisco Bay Area counties. Nonresidential consumption was reduced. In contrast, residential consumption increased especially during midday.



**figure 4.** The performance of week-ahead electricity demand forecasts for California. Each colored bar represents a week, with the deviation from the neutral representing the extent of over and under prediction.

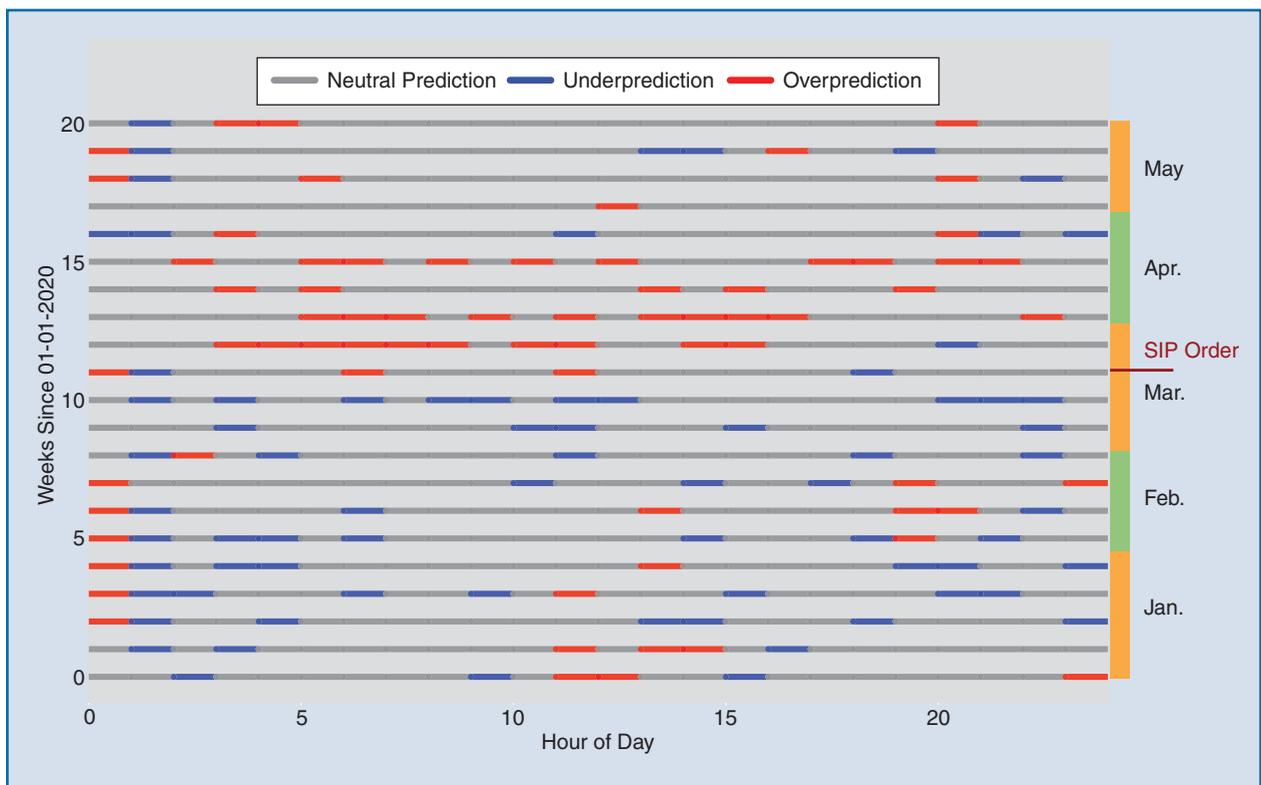
COVID-19-related restrictions had customer-sector impacts that went in divergent directions. In the San Francisco Bay area, during the first two months of COVID-19 restrictions, there is approximately a 14% increase in electricity consumption for residential users and a 26% decrease in electricity consumption for nonresidential users. The total electricity demand increased by approximately 9%, but this change in demand was varied across sectors.

This change suggests that, given different mixes of electricity consumption for residential and nonresidential users in different locations, there could be nonuniform changes in electricity consumption dependent on contextual characteristics. This situation is likely not only observed for California, but in other areas across the U.S. and world. Such conclusions emphasize the need to understand factors influencing this heterogeneity, ranging from the stringency of SIP restrictions to sociodemographic characteristics to multiple or concurring events, such as extreme weather.

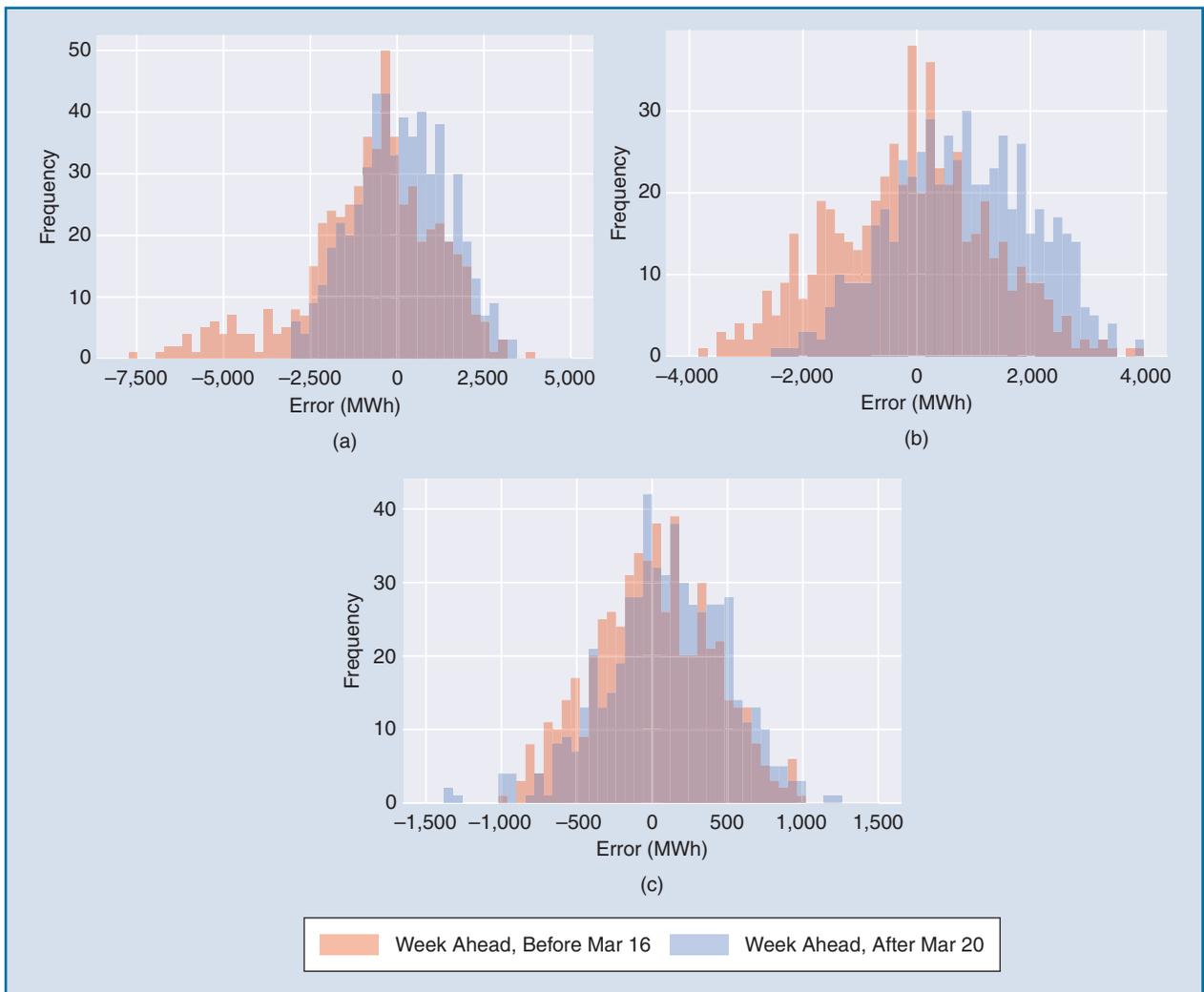
We also observed that these changes in electricity use patterns also manifest at different times of day, as shown by the load shape analysis, where weekdays during the COVID-19 SIP period were more similar in appearance to weekends before the pandemic. These changes in demand had substantial impacts on planning and forecasting activities of utilities. During weeks at the beginning of California's SIP restrictions, the week-ahead hourly forecast errors were abnormally high, with the utility slow to adjust.

Given these unprecedented changes in electricity demand related to the pandemic, and the difficulty of utilities to forecast and appropriately plan for those extreme events, we discuss ways to address the three critical areas described in the introduction. These approaches are designed to more broadly cover extreme events and other crises that could potentially impact the power sector and extend beyond insights that are limited to the pandemic:

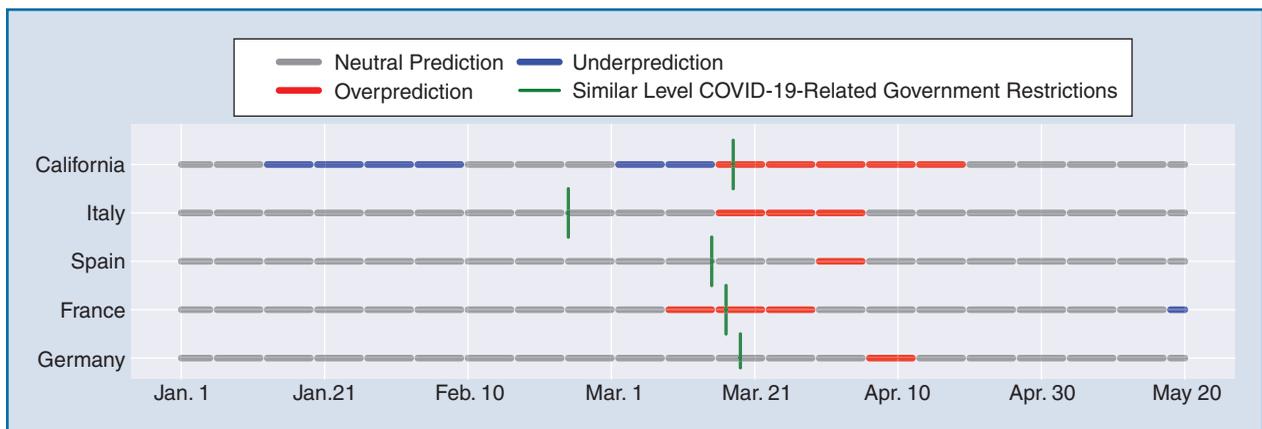
- 1) Create new metrics for characterizing the impacts of historical events that can facilitate comparisons across event types, locations, and exposed populations. The application of counterfactual modeling not only develops meaningful comparisons to past events, but also helps to concretely quantify the magnitude and duration of these events. The approach brings understanding to when, where, and how long the largest impacts from the events occurred, as well as when the system returns to normal. While counterfactual modeling was applied to daily data for different sectors in this analysis, it could be applied to even higher resolution data. Additionally, linking energy data to other sources of information, such as sociodemographic characteristics, sector information, and features of electricity systems, could be essential for understanding the impacts of extreme events. Utilities and other entities engaged in the energy system could expand the use of counterfactual modeling as a crucial component for



**figure 5.** The week-ahead hourly forecast status for California in weeks starting from 1 January 2020 (first week), to starting from 18 May 2020 (the 21st week).



**figure 6.** The week-ahead hourly forecast error frequency before and after SIP for three utilities in California. The error is calculated by taking the difference of the week-ahead hourly forecast from the actual hourly values. Negative error values represent an underprediction, and positive values represent an overprediction. If the error distribution is centered around zero, the forecast is unbiased. (a) PG&E, week-ahead hourly forecast error before/after SIP. (b) SCE, week-ahead hourly forecast error before/after SIP. (c) SDG&E, week-ahead hourly forecast error before/after SIP.



**figure 7.** The performance of week-ahead electricity demand forecasts for California and selected European countries. Similar levels of COVID-19-related government restrictions were generated by using a stringency index value of 50 or higher from the Oxford Covid-19 Government Response Tracker (OxCFRT).

understanding impacts from extreme events to better prepare for them in the future.

- 2) Develop methods for simulating historical events and events that could happen in the future. An extreme event, such as the pandemic, can have major impacts on the operation of the energy system. Such impacts may be mitigated if the grid becomes more prepared for such events. Although the COVID-19 pandemic was an unprecedented event that took even the most seasoned energy analysts and forecasters by surprise, the frequency and severity of system impacts caused by other extreme events, such as weather extremes can be projected in a way that incorporates simulations of weather extreme scenarios in the future. Such scenario development can also be used to project other extreme events not related to the weather, such as a financial crisis, a public health emergency, or an expected disruption in energy supply. Awareness of the possibility of potential impacts from extreme events through simulation and scenario development can serve to improve the preparation of energy systems to be resilient to such extreme events.
- 3) Deploy energy system modeling and decision support tools to rapidly enable event response when an event occurs. As demonstrated during the pandemic, updating the demand forecasting models took approximately five weeks to account for COVID-19-related restrictions and changes in consumer behavior. These model updates could potentially be done much sooner. For forecasting models to have better performance under such circumstances, they will need to be flexible and adaptable to new data sources. They cannot be limited to a fixed set of data inputs. Perhaps most importantly, forecasters need confidence in the model outputs for practical use in real-world situations. Probabilistic forecasts, which include some form of uncertainty quantification, could help grid operators and others understand how confident they should be in forecasts. This is particularly important during extremes events where forecast uncertainty could be quite high.

## Conclusions

Using the example of COVID-19-related impacts on the California energy system in the early stages of the pandemic, we show just how dramatically a single extreme event can change electricity consumption. The situation not only altered how much electricity is consumed, but when and where. Using insights from this unprecedented event, three observations are described for how to 1) improve the ability to measure impacts from extreme events, 2) plan for future extreme events, and 3) be responsive to extreme events as they are occurring. These observations may be helpful considerations for designing systems that can be deployed in real-world applications.

Partnerships between utility practitioners in system operations and planning with investigators in the research community are needed to produce systems that can plan for and respond to the next series of extreme events. This is particularly important as the future of energy systems involves balancing a decarbonization transition while building resilience to extreme events. This situation will present new challenges and opportunities for energy equity, access, affordability, and sustainability.

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## For Further Reading

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