Characterizing the uncertainties of future extreme heat on electricity peak demand

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Objective

Long-term electric resource planning is confronted with various levels of deep uncertainties, including the impact of climate change on both demand and supply. California has set ambitious climate goals to slow down the impact of climate change such as achieving a carbon-free electricity supply by 2045 (Senate Bill 100). Meeting California's climate goals requires a massive deployment of intermittent renewable energy resources including building almost six times the amount of solar energy capacity than what is currently available (CEC 2021[1]). However, without considering the uncertainties associated with climate change, this deployment can potentially leave the state without power, particularly during the evening hours when solar is not generating power, and the current resources may be inadequate to meet the surge in demand. Numerous studies have demonstrated that already vulnerable populations are at an increased risk during extreme weather events when power outages occur.

This paper aims to characterize the impact of climate-driven extreme heat on electricity demand in LA County through literature reviews and by replicating the analysis using more recent data. The study simulates various assumptions, including different emissions projections, and explores the recent climate adaptation policy proposed by LA County, which could potentially accelerate AC adoption and impact peak demand in the short term. The paper also discusses how these uncertainties can impact the reliability of the power system and suggests steps to include in the resource planning process for future study.

Research Questions

1. How do various climate models project extreme heat in LA County, and what are the differences in projections across different timeframes?
2. What is the relationship between temperature and peak electricity demand in LA County, and how is it expected to change in the future?
3. How would the proposed ordinance on accelerating AC adoption impact peak demand in the near term?
4. How can climate change and climate adaptation be accounted for in long-term electric resource planning to meet California's climate goals?

[1] California Energy Commission. "SB 100 Joint Agency Report," 2021. https://www.energy.ca.gov/sb100

Background

Extreme heat has been a primary driver of electricity demand and reliability needs in California for decades. However, with climate change, we expect more frequent and severe heat waves in the future. In 2023, the world experienced the hottest summer on record (Copernicus 2023[2]), September 2023 was also the warmest September on record globally, following the warmest two months on record, July and August 2023. California has experienced three straight years of energy reliability challenges, including rotating outages during a multi-day extreme heat event in August 2020, heat waves in June 2021, and a 10-day extreme heat event in August- September 2022. The prolonged heat wave in September 2022 set a record high for power demand in California and exacerbated the already tight supply that has been experienced during extreme heat events in recent years. Moving to a carbon-free grid requires heavy penetration of non-dispatchable resources that are affected by environmental factors such as cloud cover, temperature, humidity, wind speed, and precipitation. While the availability of such resources varies and is uncertain, demand is also dependent on weather, especially on temperature. Therefore, the effect of climate change on both supply and demand is deeply uncertain.

California has continued to take a leadership role in addressing climate change and has set several ambitious climate goals over the years. Since 2018, California has had a goal of achieving 100% carbon-free electricity and economy-wide carbon neutrality by 2045 (SB 100). Most recently, Governor Newsom set accelerated new targets for renewable energy, clean buildings, carbon removal, and clean fuels in the transportation sector. However, resource and infrastructure investment decisions entail long-term implications for cost, reliability, resilience, and equity, and achieving such goals poses major concerns.

To help address this challenge, resource planning should take into account that flexible resources, as well as a greater amount of battery build-out, are coming online currently and over the next five years (CARB 2022[3]). The state's electricity grid is expected to be stressed further in the coming years by heat waves, drought, wildfires, and the growing intermittent power supply from renewables.

The literature on temperature-dependent electrical loads (Burlio et al., 2019[4] and Burillo et al., 2017[5]) suggests that in the short run, people tend to use more AC during hot weather, while in the long run, there is a compounding impact as people who don’t already have AC will adopt and use it more frequently.

Los Angeles County is exploring the implementation of a policy to establish a maximum temperature for rental units to safeguard vulnerable renters from extreme heat during summer months. This policy could

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[2] Copernicus. “Surface Air Temperature for September 2023,” n.d. https://climate.copernicus.eu/surface-air-temperature-september-2023.

[3] “2022 Scoping Plan Documents | California Air Resources Board,” 2022 https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022-scoping-plan-documents.

[4] Burillo, Daniel, Mikhail Chester, Stéphanie Pincetl, and Janet Reyna. “Forecasting Peak Electricity Demand for Los Angeles Considering Higher Air Temperatures Due to Climate Change.” Applied Energy 236 (February 1, 2019): 1–9. https://doi.org/10.1016/j.apenergy.2018.11.039.

[5] Burillo, Daniel, Mikhail Chester, Benjamin L. Ruddell, and Nathan G. Johnson. “Electricity Demand Planning Forecasts Should Consider Climate Non-stationarity to Maintain Reserve Margins During Heat Waves.” *Applied Energy* 206 (November 1, 2017): 267–77. https://doi.org/10.1016/j.apenergy.2017.08.141.

potentially accelerate the adoption of air conditioning (AC) and show an immediate impact on electric demand.

Method

This study aimed to estimate peak demand during extreme heat events using a structural equation model found in the literature (Burillo et al., 2017) which is based on the relevant infrastructure and their thermal and electrical performance characteristics. The literature challenges the widely adopted linear relationship (Sathaye et al., 2013)[6] between peak demand and temperature, which is inaccurate when the maximum temperature goes beyond what was considered normal historically. Instead, the study argues that an S-curve is a more accurate representation of the relationship between outdoor thermal forces, ambient dry-bulb air temperature, and individual AC loads. As daily maximum temperature (Tmax) increases, the expected number of ACs simultaneously active in a region during the peak period increases up to a theoretical limit of 100%.

The mathematical form of the structural equation model is expressed as follows:

$$D_{peak}\ (GW) = D_{base} + n \cdot AC_L \cdot 10^{-6} \text{ ....(1)}$$

$$n = \frac{1}{Q_{AC}^{-1} + e^{-AC_{CR} \times T_{max}}} \text{ ....(2)}$$

$$AC_L = AC_{NL} \times [(1 + AC_{LF})^{(T_{max} - T_{NL})}] \text{..............................(3)}$$

Table 1 Structure Equation Model nomenclature (Burillo et al., 2017)

Symbol	Units	Description
Dependent/response variable		
D_{peak}	GW	Daily peak demand in region
Structurally interdependent variables		
n	# ACs	Number of Acs coincidently active during peak demand
AC_L	kW	Average load of one AC unit while in active mode
Independent predictor variables		
T_{max}	°C	Daily maximum ambient air temperature (dry bulb temperature)
D_{base}	GW	Base daily peak demand in region, equal to the average demand between T_{max} = 22-24°C (72-75 °F)
Q_{AC}	# ACs	Quantity of Acs in region
Constants		
AC_{LF}	%/°C	AC load increase factor (= 1.33% kW/1°C)
T_{NL}	°C	Nominal load temperature, T_{max} Value for AC_{NL} (=29°C, 85°F)

[6] Sathaye, Jayant A., Larry L. Dale, Peter H. Larsen, Gary A. Fitts, Kevin Koy, Sarah M. Lewis, and André Frossard Pereira de Lucena. "Estimating impacts of warming temperatures on California's electricity system." Global Environmental Change 23, no. 2 (2013): 499-511.

e	-	Euler's number

The literature used the current AC penetration in LA County as 6.7e5 (48% for both residential and commercial). The supplemental document included sensitivity analysis using the 1.1e6 for the high AC penetration (80% for residential and 90% for commercial). I used these two values to simulate changes in peak load dependent on future extreme heat projections.

Description of scenarios

For daily maximum temperature data, I used Localized Constructed Analogs (LOCA) derived products from the Cal-Adapt website. LOCA is a statistical downscaling technique that uses historical observed data to add improved fine-scale detail to global climate models. I have used LOCA downscaled CMIP5 climate projections (Thomas et al., 2018[7]) from 32 global climate models for LA County. The historical period is 1950-2005, and there are two future scenarios available: RCP 4.5 (Medium Emissions Scenario) and RCP 8.5 (Medium Emissions Scenario) over the period 2006-2098. These three datasets are downloaded from the CalAdapt website:

1. LOCA daily maximum temperature 32 model ensemble maximum modeled historical 1950-2005
2. LOCA daily maximum temperature 32 model ensemble maximum RCP 4.5 2006-2098
3. LOCA daily maximum temperature 32 model ensemble maximum RCP 8.5 2006-2098

Figure 1. Daily maximum temperature scenarios included in this study

Historical (1950-2013)	The ensemble average for each RCP model historical run were included. This data is provided for the years 1950-2005.
Medium Emissions Scenario (RCP 4.5)	This scenario is characterized as having medium greenhouse gas concentration levels and assumes a stabilization will occur shortly after 2100.
High Emissions Scenario (RCP 8.5)	This scenario is characterized by increasing GHG emissions over time, and factors in the highest GHG concentration levels of all the scenarios by 2100.

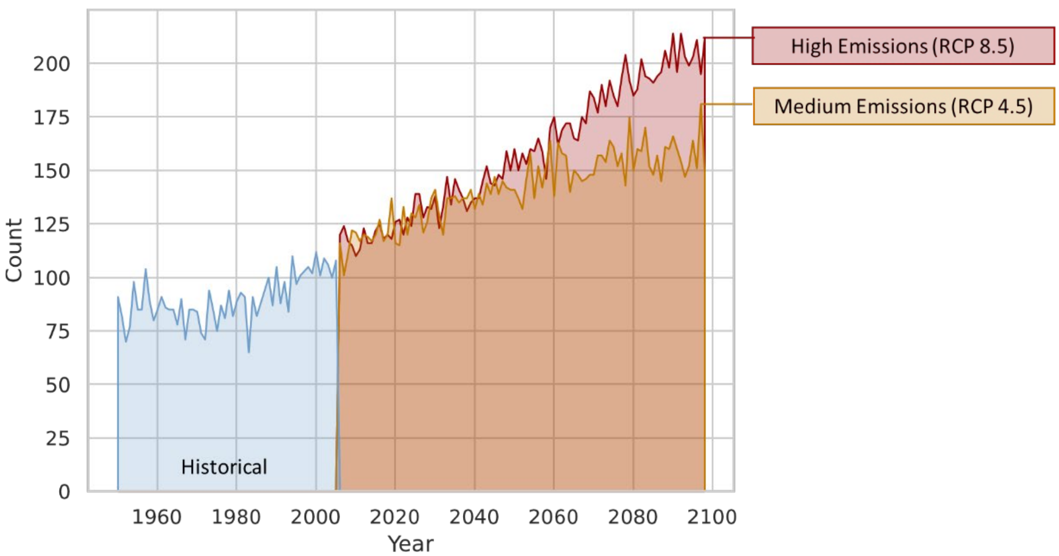
Exploring daily maximum temperature data

According to climate models from Cal-Adapt, many areas in the state are projected to experience a significant increase in the number of days with extreme heat. In this study, I examined how the frequency and timing of extreme heat days are expected to change under different emission scenarios for LA County. I calculated the number of extreme heat days per year when the daily maximum temperature exceeds 94.4 °F (98th percentile).

[7] Thomas, N., Mukhtyar, S., Galey, B., Kelly, M. (University of California Berkeley). 2018. Cal-Adapt: Linking Climate Science with Energy Sector Resilience and Practitioner Need. California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC-2018-015

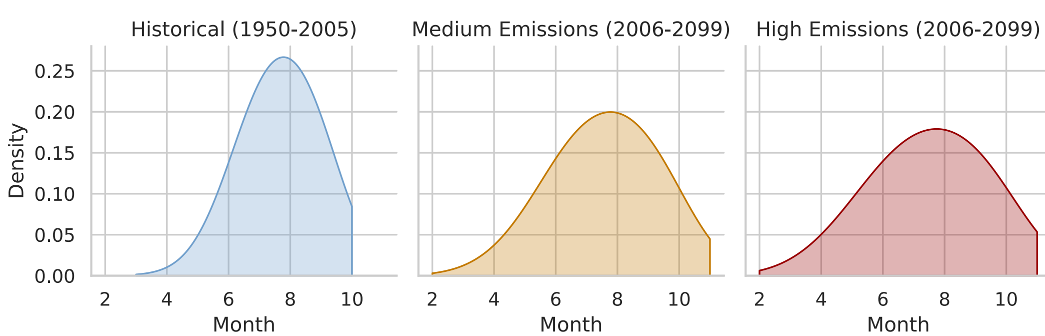
The findings for the frequency of extreme heat days are presented in Figure 1 which shows that the annual number of extremely hot days is expected to increase for all future scenarios. Under the high emissions scenario, the number of extreme heat days is projected to almost double by the end of the century. The rate of increase for the medium emissions scenario is expected to temper down around mid-century, but it is still projected to be 50% higher than the current level.

Figure 2 Number of Extreme Heat Days per Year for historical versus future projections



To further understand the impacts of extreme heat, I explored the timing of extreme heat days by different months and presented the results as density plots for different scenarios in Figure 2. The findings reveal that extreme heat days used to be clustered around the summer months, from June to September. However, under future scenarios, extreme heat days are projected to start earlier and last longer throughout the year.

Figure 3 The timing of extreme heat days by months for historical versus future emissions scenarios



The shift in the timing of extreme heat days throughout the year will have significant implications for clean energy resource planning, particularly for solar energy supply. As the sun sets earlier during Spring and Fall, the availability of solar energy will be limited during these months. This highlights the need to address the hourly timing of extreme heat during the day and to ensure an adequate supply of clean energy during heatwaves.

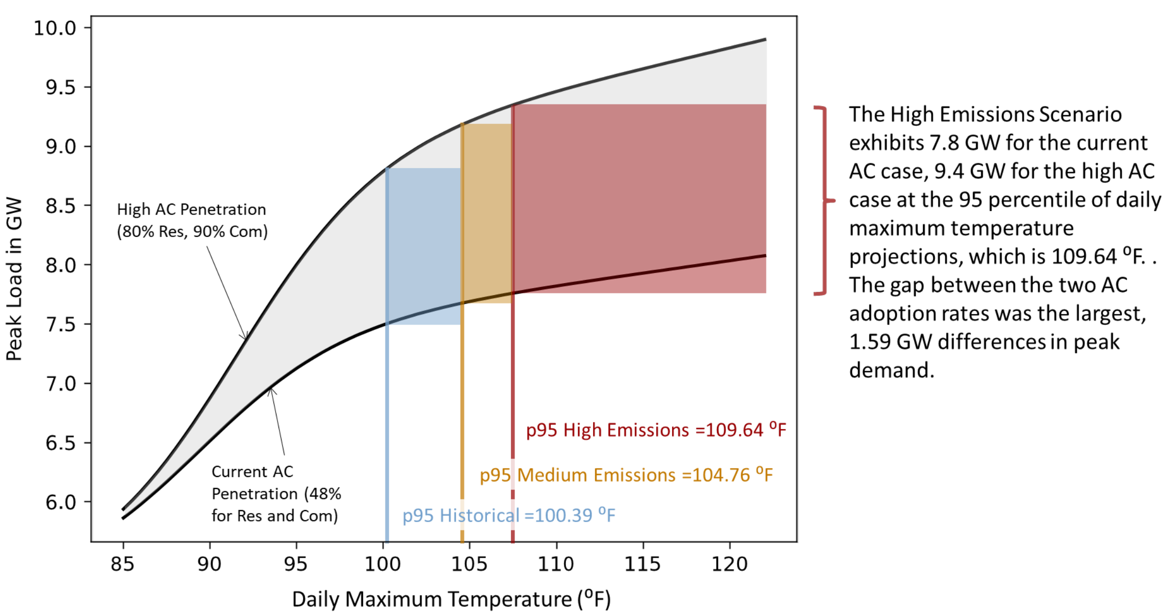
However, it is important to note that currently, Cal-Adapt does not provide hourly temperature data, which could limit the accuracy of long-term period analysis. Additionally, using an hourly time step for long-term period analysis could be computationally demanding.

Results

In this study, I utilized a structure equation model to estimate the peak load using daily maximum temperatures ranging from 85 to 122.5 ^{o}F for two AC penetration cases, as shown in Figure 3. The high AC adoption case represents the adoption of the maximum temperature ordinance in LA County. The findings demonstrate that the high AC adoption case leads to a much more rapid increase in peak load compared to the current AC adoption case, which is consistent with the literature. Furthermore, as the maximum temperature increases, the magnitude of the increase in peak load from the current AC adoption to high AC adoption also increases.

I evaluated different climate scenarios, including a historical case, by taking the 95th percentile of daily maximum temperature for each scenario and calculating the expected peak load. I chose the 95th percentile to understand the worst-case scenario and to gain insights into the backend extreme case. The results indicate that the differences between the two AC adoption rates are 1.32, 1.52, and 1.59 GW, respectively. The high emissions case exhibits the largest gap in peak loads and the highest peak load, highlighting the need to continue efforts to decarbonize the energy system to avoid extreme stress to the grid system.

Figure 4 Changes in Peak Load for different AC penetration and Future emissions scenarios



To understand how much intermittent clean resources are needed to cover the 1 GW peak load, a complex analysis is required. However, using a simple assumption from the most recent planning, we can estimate that 14 GW of solar resources is equivalent to 1 GW (7% ELCC factor[8]). With energy storage, the capacity can be significantly reduced to 1.7 GW of battery and 2.7 GW of solar resources using the same assumptions.

It is important to note that the estimates presented in this study are specific to LA County and are based on the impacts of climate-induced extreme heat and accelerated AC adoption alone. The capacity needed for the entire state could be much larger, particularly when considering the additional renewable energy needed to meet clean energy goals and the increasing power demand from electric vehicles (EVs).

Discussions and future research

As the state continues to transition towards a cleaner and more sustainable energy system, the demand for renewable energy resources and energy storage will continue to increase.

This study examined the peak electricity demand changes in LA County due to extreme heat for different climate projections and the impact of accelerating AC adoption on peak demand in the near term. The findings provide valuable insights into the complex relationship between extreme heat and energy supply, which can inform infrastructure planning and management to ensure the reliability of the power supply during extreme heat events.

The study highlights several important aspects that require attention,

1. the need for proactive measures to reduce greenhouse gas emissions to mitigate the impacts of extreme heat.
2. the need for developing more accurate and efficient methods for analyzing the hourly timing of extreme heat and its impacts on clean energy resource planning.
3. the need for evaluating climate adaptation strategies and local policies that can affect electricity demand.

By utilizing these findings, we can better inform infrastructure planning and management at both the local and state levels to ensure a reliable and sustainable energy system for the future. However, further research is needed to better inform decision-making and ensure the reliability of the power system during heatwaves.

[8] https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/20230210_irp_e3_astrape_updated_incremental_elcc_study.pdf