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Assessing Overheating Risk and Energy Impacts in California's Residential Buildings

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ABSTRACT

On average, extreme heat causes more weather-related deaths in the United States than any other natural hazard. These events are projected to become more frequent, intense, and prolonged, making it increasingly important to maintain safe thermal conditions in residential buildings while limiting excessive cooling energy use. Given that the median age of Californian homes is 45 years and almost 40% lack mechanical cooling systems, most of the state's current housing stock is insufficient to withstand the effects of a warming planet. This deficiency undermines one of the most essential goals of housing: to shelter people from outdoor weather. We aim to quantify the overheating risk in the housing sector to support the development of public policies related to maximum safe indoor thermal limits and building energy use. We used ResStock, a residential building stock energy modeling framework developed by NREL, to assess the heat resilience of homes. We generated 52,218 building models to represent California's residential housing stock, considering key characteristics such as floor area, housing type, construction, insulation, HVAC type, and building year. We first assessed the overheating risk based on simulated indoor air temperatures and a range of possible thresholds developed from a comprehensive literature review. Then, we identified dwelling units vulnerable to overheating and estimated the additional energy impacts associated with installing mechanical cooling systems. We analyzed the building stock's peak demand load profiles and total cooling energy consumption. Our findings suggest that while there is a noticeable risk of overheating in southern counties compared to their northern counterparts, the most significant disparity exists between counties in the Shasta Cascade/Central Valley regions and their neighboring areas. Under baseline conditions, coastal counties are generally the least prone to overheating, even without air conditioning, due to their proximity to the Pacific Ocean and other large bodies of water. Inland counties, like those in the Sierra Nevada region, are also less vulnerable to overheating due to the cooler temperatures at higher altitudes. After scaling the results, we estimated that approximately 1.6 million dwelling units across California must install cooling systems to supplement overheating risk. If these retrofits include only compressor-based air-conditioning (AC), we should expect an increase in peak electricity demand from the grid by approximately 2%. To balance cooling demand and environmental sustainability, we aim to analyze the effectiveness of low-energy or passive cooling systems using our modeling framework in the future. Our sensitivity analysis showed that increasing the threshold temperature reduces the number of homes subject to overheating risk while overshadowing the effects of changing the threshold hours and days on overheating risk. These results significantly impact the electricity grid, emphasizing the need to consider passive cooling options like shading and cool roofs or energy-efficient cooling options like fans and evaporative coolers.

INTRODUCTION

The average global temperature on Earth has increased by approximately 1 °C (1.8 °F) above pre-industrial levels in 2017, and it is likely growing at a rate of 0.2 °C (0.36 °F) per decade (Intergovernmental Panel on Climate Change 2022). While natural variability plays a role, overwhelming evidence indicates that human activities—particularly those that generate and release greenhouse gasses (GHGs) into the atmosphere—are primarily responsible for global warming (Gillett et al. 2021).

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Air conditioning (AC) equipment contributes significantly to these GHG emissions, accounting for approximately 3.9% today from operational energy use, embodied emissions, and refrigerant leakage (Woods et al. 2022). Yet, AC is necessary in many circumstances for maintaining comfortable indoor temperatures, leading to a self-perpetuating cycle of AC usage contributing to global warming, which causes greater reliance on AC usage. The prevalence of AC usage in homes in the United States (U.S.) is among the highest in the world. The percentage of homes with installed AC units has increased from 77% in 2001 to 88% in 2020 (Energy Information Administration 2022).

Consequently, the residential sector accounted for about 16% of the total primary energy consumption in 2022, surpassing the commercial industry by 3% (Energy Information Administration 2024). Various factors, including climate, building envelope, mechanical equipment performance, and occupant behavior, influence the need for AC and its associated energy consumption. In California, approximately 37.5% of homes do not have AC, more than twice the amount in the U.S., reflecting how the state mainly experiences a Mediterranean climate with mild temperatures (National Renewable Energy Laboratory 2024). However, this climate varies widely between subregions, from the Coast to the Central Valley (ASHRAE Climates 3B and C) to the Eastern Sierra (Climate 5B) and beyond. Many coastal homes rely solely on natural ventilation for cooling, making them vulnerable to increasingly intense, frequent, and prolonged heat waves (Ahn and Uejio 2022). Exposure to heat waves can harm human health and well-being by giving rise to heat-related illnesses, ranging from mild effects such as cramps and fainting to more severe effects such as heat exhaustion and strokes (Khan 2019). They also have a disproportionally greater impact on socio-economically vulnerable populations. In almost every county in California, at least half of the population experiences at least one to two components of social vulnerability, including residing in overcrowded homes, experiencing unemployment, and being elderly (United States Census Bureau 2024).

The critical need to assess human health impacts from climate change and to project future growth in the AC market highlights a significant gap in research: building stock energy models (BSEMs) that account for regional variations in building characteristics and operational performance still needs to be developed. Fortunately, it is now possible to model a larger number of buildings, accounting for a comprehensive combination of general building characteristics that influence energy consumption, such as location, number of stories, floor area, and vintage, as well as specific building components like insulation thickness and window type. This approach differs from the commonly used archetypal building energy models (BEMs), which rely on a limited number of typical buildings to represent the building stock for a large area (Swan and Ugursal 2009). Our research aims to assess the indoor temperatures of a representative sample of California buildings and recommend the minimum required AC installations to maintain human comfort and inform building policies. Estimating AC penetration rates at a high spatial resolution allows for more targeted advice, identifying specific counties vulnerable to heatwaves due to a lack of AC or its limited use due to rising energy costs. Understanding AC penetration patterns also aids future grid planning by identifying peak energy hotspots. This study aims to quantify the number of buildings needing AC units and consider the tradeoff of increased energy production from the power grid.

METHODOLOGY

We utilized a large-scale residential energy simulation platform called ResStock (Wilson et al. 2017) to assess the heat resilience of Californian homes. This tool serves two primary purposes: generating a large set of residential dwelling unit models that statistically represent the housing stock at national/state levels and modeling the energy consumption of those dwelling unit models (Present et al. 2024). ResStock draws from multiple sources, including data from the U.S. Census Bureau and the Residential Energy Consumption Survey from the Energy Information Administration, to generate representative samples from high-resolution conditional probability tables (Wilson et al. 2022). The modeling was performed using OpenStudio® and EnergyPlus®, a flagship energy modeling software developed by the U.S. Department of Energy, through the BuildStockBatch workflow on a local laboratory computer. Convergence testing of the simulation results by the National Renewable Energy Laboratory (NREL) established 350,000 models as the optimal number to represent the U.S. housing stock (Wilson et al. 2017). Since California is approximately 10% of the national total dwelling units (U.S. Census Bureau 2020), we conservatively generated approximately 50,000 dwelling unit models to represent the state's housing stock. The dwelling unit models encompass various building types, including single-family, multi-family, and mobile homes. Some data preprocessing was conducted after examining the initial results from a pilot study, which showcased unlikely periods of simultaneous heating and cooling and unusually low or high-temperature setpoints. The primary results we extracted from the simulations are the hourly indoor air temperatures and AC cooling energy consumption during the summer months from May

1st to October 31st. We then used the simulated indoor temperatures to evaluate the overheating risk by determining the number of hours the indoor temperature was above a specified threshold ('exceedance hours'). Figure 1 summarizes the simulation process workflow for our baseline scenario.

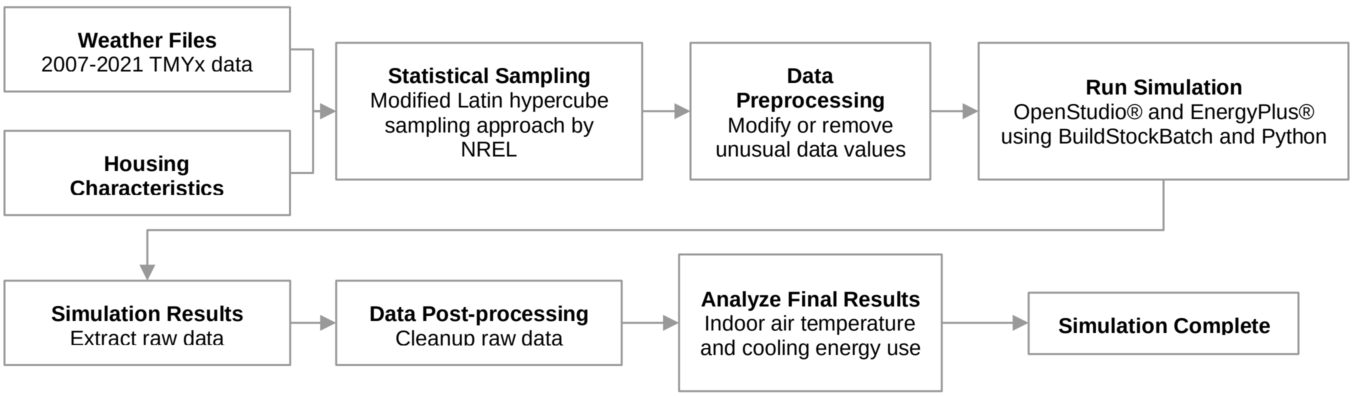
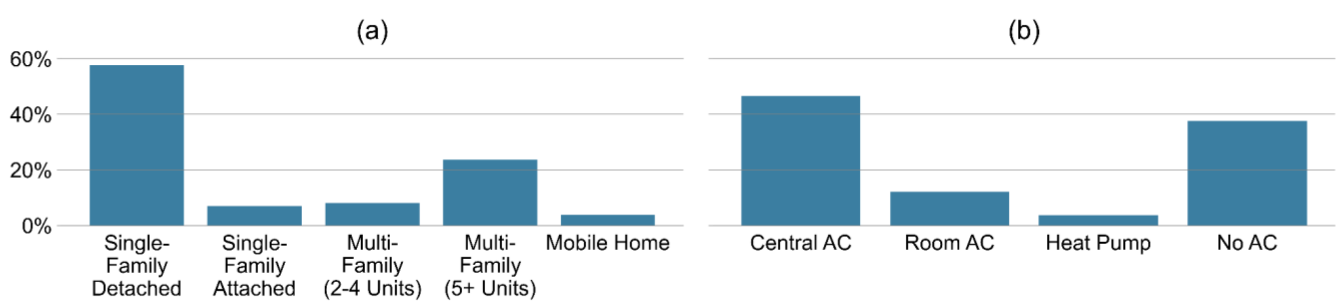


Figure 1: Diagram showing the simulation process workflow.

HOUSING SAMPLE CHARACTERISTICS

Based on the metadata generated by ResStock, most California dwelling units are characterized as single-family detached homes (57.6%), followed by multi-family homes consisting of five dwelling units or more (23.6%). The remaining housing types (18.8%)—single-family attached homes, multi-family homes with less than five dwelling units, and mobile homes—are much less common in California. According to the American Housing Survey, the median age of homes in California was 45 years in 2022, which is noticeably higher than the national average of 40 years and remains mostly unchanged over the last five years (U.S. Census Bureau 2022). Consistent with this report, the housing sample generated by ResStock groups the homes by construction year, displaying a relatively normal distribution with a median around 1960 to 1979. In the past decade, California has constructed around 108,000 new dwelling units annually, significantly lower than the projected housing need by the California Department of Housing and Community Development of 180,000 new homes annually between 2015 and 2025 (Bates et al. 2018). In 2023, there were around 111,800 new home construction permits, which only contributed to an approximate 0.75% increase in the existing housing stock. While almost half of the homes (46.6%) have central AC, with a small number having room AC and heat pumps, a substantial number have no AC access (37.5%). These homes without AC are primarily concentrated in the coastal counties. The County of Los Angeles dominates the sample count by geographic location, representing approximately a quarter of the dwelling units analyzed.



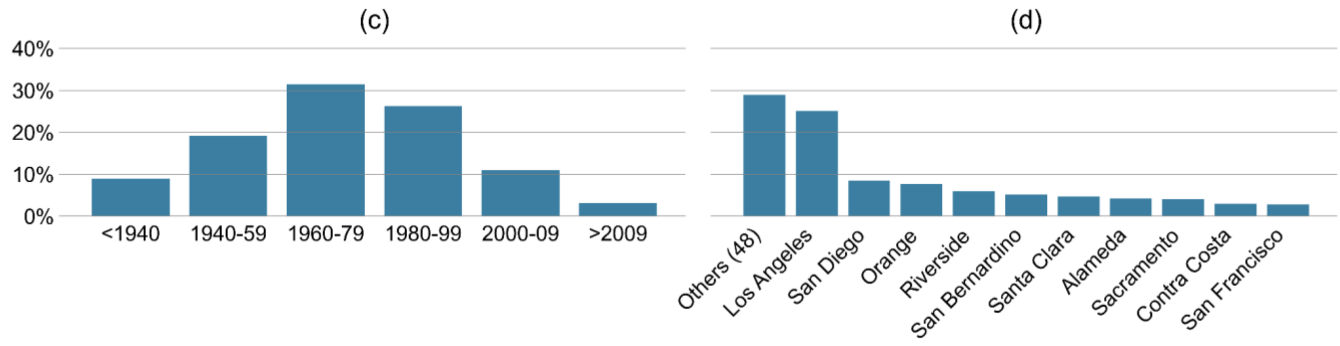
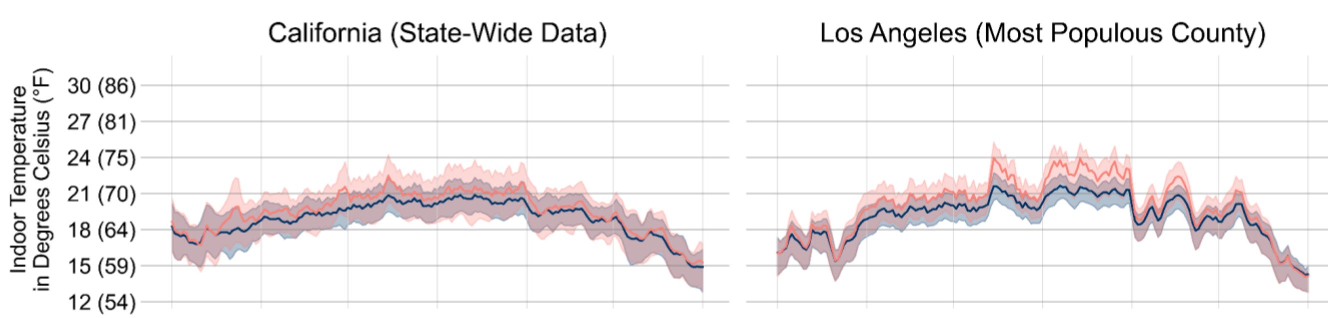


Figure 2: Vertical bar graphs derived from ResStock data (EIA 2020) illustrating key characteristics of dwelling units in the sample. The graphs detail the distribution across (a) housing types, (b) HVAC cooling system types, (c) construction years, and (d) geographic distribution by county. Subplot (d) displays the counties in descending order, starting with the top ten and grouping the remaining counties.

Building characteristics include dependencies, which refer to certain building aspects dependent on other aspects. For example, the likelihood that a building was built after the 1980s depends on its location, affecting the probability of possessing other characteristics such as insulation thickness, window type, and AC efficiency rating.

OVERHEATING RISK ASSESSMENT

In our overheating risk analysis, we simulated indoor air temperatures (T_{in}) for the summer months, from May 1st to October 31st, totaling 4416 hourly timesteps. To improve the graphical clarity of the plotted time series data, we presented daily average indoor temperatures instead of hourly. This method smooths out the typical short-term temperature fluctuations between mornings and afternoons while highlighting long-term trends across the summer months. Furthermore, we utilized the latest Typical Meteorological Year (TMYx) data, which represents typical weather conditions for the current period and is an update to the conventional TMY data, accounting for recent climate changes. Our simulation did not account for extraordinary weather events like intense heat waves or emergency events like power outages. Under these baseline conditions, our observations revealed minimal differences in average indoor temperatures across California between dwelling units equipped with AC and those without, as depicted in Figure 3. Notably, in the top five counties ranging from Los Angeles to San Bernardino—predominantly located in Southern California except for Los Angeles—there is consistently a slight difference exceeding one degree Celsius between dwellings with and without AC. In contrast, counties with milder climates, such as San Francisco, show slight variance, whereas counties with hotter climates, such as Fresno and Imperial, exhibit significant disparities, often more than five degrees Celsius.



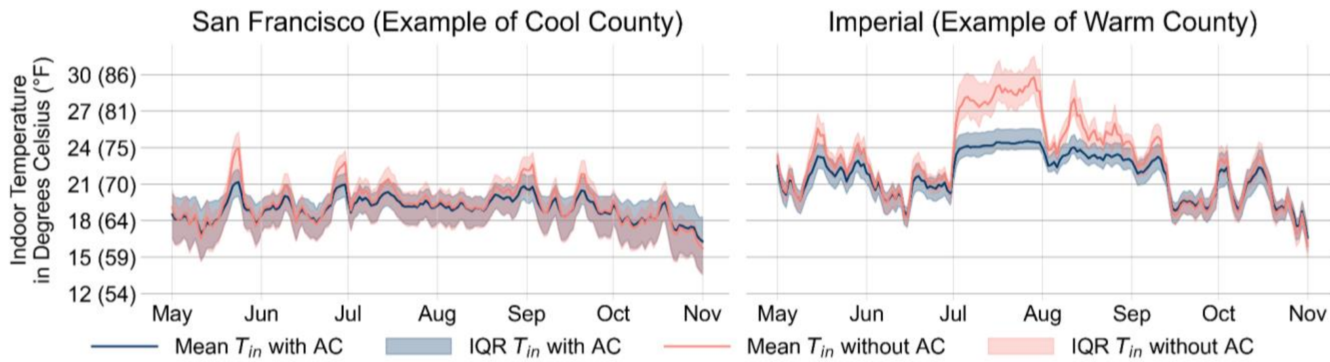


Figure 3: Indoor air dry bulb temperature time series plot for California and selected counties (IQR = interquartile range).

The original hourly time series data were retained to calculate overheating values. As an intermediary step, we calculated the 8-hour rolling average using the hourly indoor air temperatures ($T_{\text{rolling avg.}}$) to stabilize the results before applying the overheating criteria. We then defined 'exceedance hours' as the number of hours $T_{\text{rolling avg.}}$ surpassed a set threshold. A systematic literature review identified five studies that report temperature thresholds—ranging from 26 °C to 32 °C (78.8 °F to 89.6 °F)—beyond which occupant health may decline, though data to establish a definitive threshold remains insufficient (Tham et al. 2020). Therefore, a threshold of 28 °C (82 °F) was selected as it approximates the average within the identified range. We then calculated the 'cooling season hours,' representing the ‘exceedance hours’ as a proportion of the total hours in the simulation period (4416 hours). Figure 4 (a) illustrates the 'AC prevalence'—defined as the proportion of dwelling units equipped with AC relative to the total sample size. We retrieved data from the National Centers for Environmental Information (NOAA National Centers for Environmental Information 2024) to complement this map. Then, we mapped the outdoor temperature variation for each county, as visualized in Figure 4 (b). The map shows each county's average outdoor air temperatures from 1975 to 2023 from May to October. There is a clear positive correlation between high outdoor temperatures and reliance on AC systems. Upon closer inspection, it is also evident that certain regions, particularly the Shasta Cascade and Central Valley, including counties like Trinity, Shasta, Tehama, Glenn, Fresno, and Kern, experience elevated temperatures and are therefore prone to overheating, as shown in Figure 4 (c). Despite its inland location, which could suggest higher temperatures, the Sierra Nevada region exhibits lower overheating risks due to orographic effects—where rising air over mountains cools and condenses moisture. Most notably, Imperial County, known for its desert climate, exhibits the highest overheating hours exceeding the threshold.

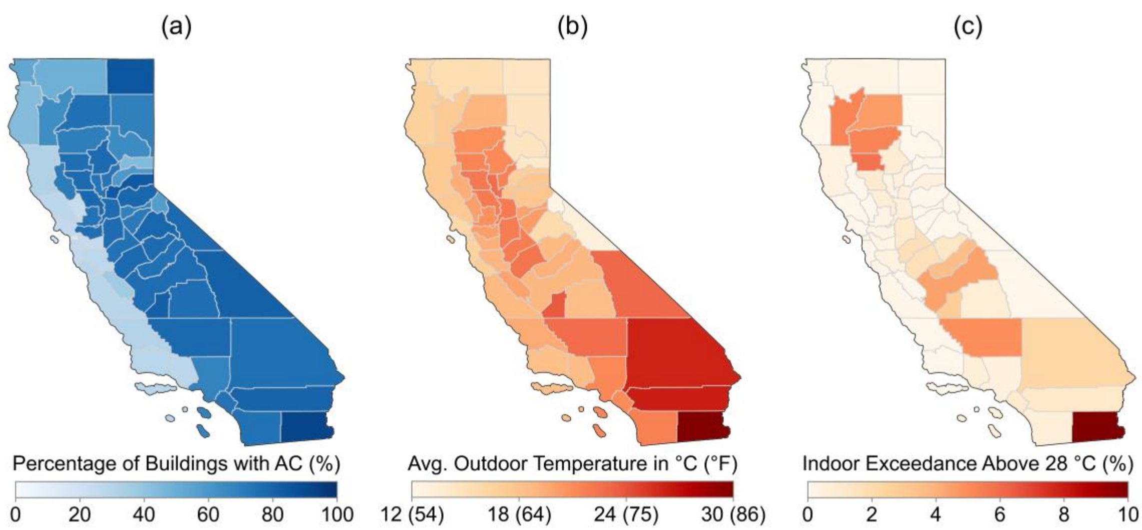


Figure 4: Map of each county in California showing (a) AC prevalence, (b) average summer *outdoor* air temperature from 1975 to 2023, and (c) overheating hours based on simulated *indoor* air temperature for dwelling units without AC. Subplot (c) presents overheating hours as a percentage of total hourly timesteps when indoor temperatures exceed the threshold.

PEAK COOLING ENERGY USE

According to the California Energy Commission (CEC), AC use significantly drives California's peak electricity demand during summer, contributing to 30% of the peak load in residential and commercial sectors (Miller et al. 2008). This presents a dual challenge: identifying residences at risk of overheating and managing the increased energy consumption from potentially retrofitting all these homes with AC units. We analyzed cooling energy usage data from the baseline simulation results (without applying any retrofits), aggregating the hourly data from each of the 52,218 dwelling units in our sample. To scale our results to the number of California housing units, approximately 14.4 million, we multiplied the sample size by a factor of 276 (i.e., 14.4 million divided by 52,218). This calculation yielded a peak cooling energy use close to 3,900 MW, occurring on July 15th at 6 PM, which falls within the typical peak demand period of late afternoon to early evening, between 2:30 and 6 PM (California ISO 2023). The peak load is also within the same order of magnitude as the value of 7,500 MW reported by the CEC (John Proctor 2005). These results are illustrated in Figure 5, which disaggregates peak cooling energy use by the top five most populous counties and groups the remaining counties together. We discovered that each county's contribution to the peak load generally aligns with their proportion in the overall sample size, though there are several exceptions. For instance, Los Angeles County, which comprises approximately a quarter of the sample size, contributed 24.8% to the peak demand. However, Kern County, representing 2.1% of the sample, contributed 2.3% to the peak load, while Contra Costa County, making up 2.9% of the sample, contributed only 2.6%.

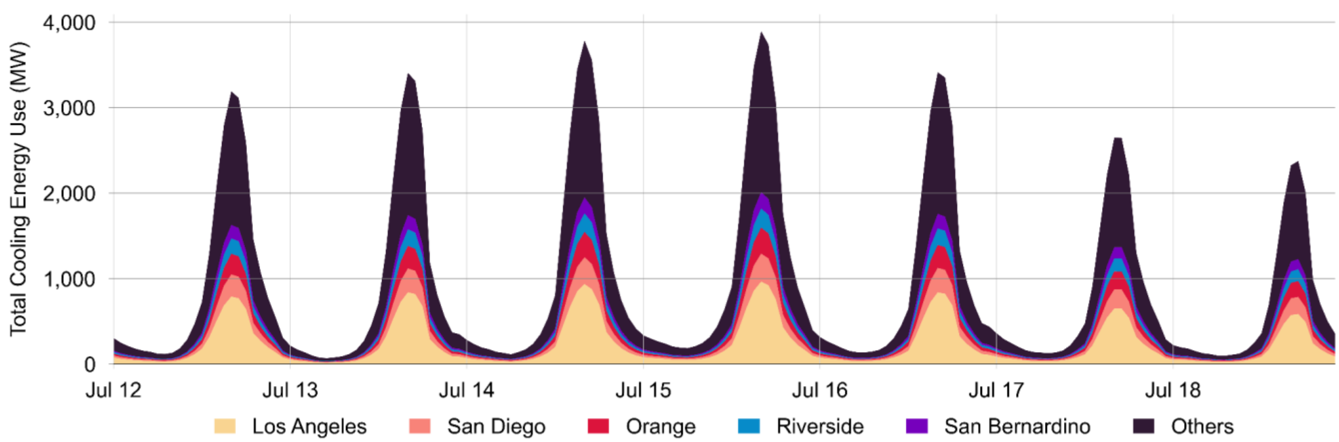


Figure 5: California residential peak cooling energy use delineated by the top five most populous counties and ‘others’, which include the remaining 53 counties.

By integrating our assessments of overheating risk and peak cooling energy use across California, we identified significant needs within the residential sector. Specifically, we found that 29.7% of homes without AC, amounting to approximately 1.6 million dwelling units, require the installation of cooling systems, either AC or passive systems, as appropriate. If entirely AC, this retrofit will increase the state-wide residential peak cooling load by 23% (approximately 886 MW or 3,025 MMBTU/hr) and the total cooling load by 26% (approximately 495,903 MWh). A 2023 California Independent System Operator (ISO) study reported that California’s peak electricity demand reached 44,534 MW across all major end-use sectors, including commercial, industrial, transportation, and residential. The ‘all AC’ retrofit will increase the aggregated peak demand by approximately 2%. This highlights the need for a more strategic approach considering passive and low-energy options before compressor-based AC.

SENSITIVITY ANALYSIS

Based on specific overheating criteria, we evaluated the need for AC installation (or other comfort control measures) in dwelling units lacking such systems. These criteria are defined by three key parameters: threshold temperature, threshold hours, and threshold days. We interpreted the 'threshold temperature' as the maximum allowable indoor dry bulb air temperature that, when exceeded, counts towards overheating duration. Next, we defined ‘threshold hour’ as the minimum number of hours within a day the recorded temperature must exceed the threshold temperature for those hours to be counted towards the overheating duration. Similarly, we defined ‘threshold day’ as the minimum number of days within the 183-day simulation period that the threshold temperature must be exceeded for those days to be counted.

We conducted a sensitivity analysis to understand how variations in these parameters impact the necessity for additional AC units. This analysis involved adjusting the threshold temperature between 25.6 °C to 32.2 °C (78 °F and 90 °F) in 1.1 °C (2 °F) increments. These threshold temperatures were chosen based on local building codes for residential dwellings across various U.S. states. Minimally, the City of Portland, Oregon, specifies that indoor design temperatures for cooling should not exceed 25.6 °C or 78 °F (Portland, Oregon 2024). The City of Palm Springs, California, requires that residential air conditioning systems be capable of maintaining an indoor temperature of no more than 26.7 °C or 80 °F (Palm Springs, California 2024). This standard is also adopted by the building codes of Houston, Texas (Houston, Texas 2024); New Orleans, Louisiana (New Orleans, Louisiana 2024); and Montgomery, Alabama (Montgomery, Alabama 2024), making it a common threshold for states that mandate a lower maximum indoor temperature. Conversely, the City of El Paso, Texas, stipulates that residential cooling systems must keep temperatures below 32.2 °C or 90 °F (El Paso, Texas 2024). These codes reflect the varying environmental conditions and differing local acclimatization to heat across states and counties.

Along with high temperatures, 'exposure time'—defined as the duration of heat exposure—significantly influences the risk of heat-related illnesses. However, the precise relationship between exposure time and heat risk is still not well-established. The National Institute for Occupational Safety and Health has identified this issue as a priority for future research (Jacklitsch et al. 2016) to enhance standards and policies, particularly for outdoor workers. As such, our study provisionally investigated six conditions, labeled C1 through C6, by varying exposure thresholds from two to six hours in two-hour increments and setting duration thresholds at either 21 or 28 days. Figure 6 displays our sensitivity analysis results.

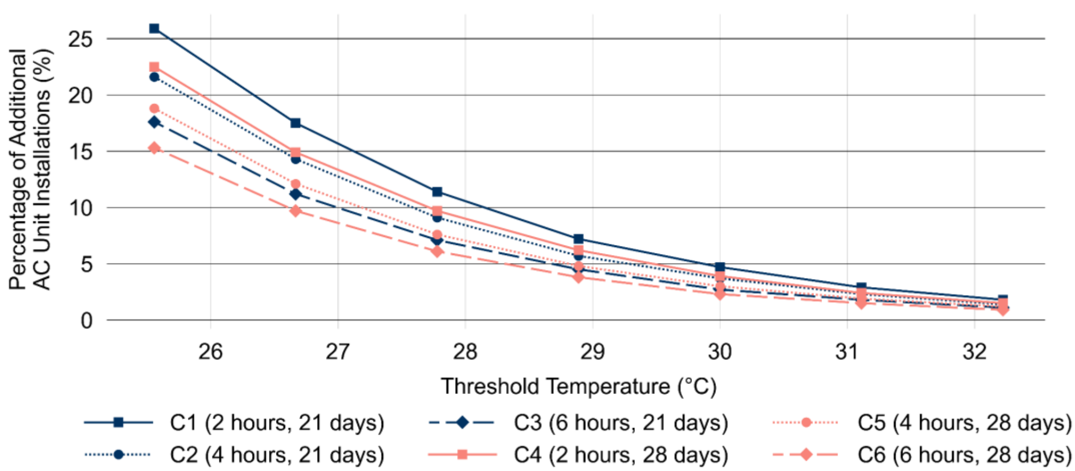


Figure 6: Percentage of additional AC unit installations across California as a function of threshold temperature.

The results indicate that adjustments in threshold hours and days significantly influence the requirement for additional AC installations or other comfort control measures, particularly at lower threshold temperatures. Conversely, changes in threshold hours and days have a less pronounced impact on the necessity for additional cooling systems at higher threshold temperatures. This suggests that the duration parameters regarding the number of hours and days become less critical in determining the need for air conditioning at higher threshold temperatures.

CONCLUSIONS

We investigated the risk of overheating in residential buildings across California under typical climatic conditions using the ResStock BSEM framework and ran the simulations with OpenStudio® and EnergyPlus®. Our primary aim was to identify overheating risk by comparing simulated indoor air temperatures with a defined threshold of 28 °C (82 °F), focusing solely on the magnitude of exceedances without considering their duration. Our analysis showed that overheating typically occurs from late June to late August, with significant geographical differences. Areas like the Shasta Cascade, Central Valley, and Imperial County, located in a desert region, experienced higher indoor temperatures. This insight highlights the need to prioritize these regions in mitigation efforts to optimize resource allocation.

Our review of peak cooling energy demand under existing conditions revealed that the peak load occurs at 6 PM, aligning with expectations, and reaches a magnitude of approximately 3,900 MW, near the values reported by the CEC. After scaling the results, our simulations highlighted that approximately 1.6 million dwelling units in California require cooling systems, a demand expected to increase as global temperatures and electricity demand rise. If these systems include only compressor-based air-conditioning (AC), we estimated an increase in peak electricity demand from the grid by approximately 2%. Our sensitivity analysis further demonstrated that increasing the threshold temperature reduces the number of homes considered at risk, indicating an inverse relationship between threshold temperature and the need for air conditioning or other comfort control measures. Moreover, adjustments in threshold hours and days had minimal influence on outcomes at higher thresholds. Overall, this study provides a comprehensive framework for assessing the heat resilience of households in California using detailed simulation data, which informs targeted cooling strategies.

FUTURE WORK

Our analysis of overheating risk, annual cooling energy use, and peak cooling energy use should be compared with other sources to establish a standard benchmark and determine whether BSEM calibration is needed. While we found that more AC systems are required in California, the widespread increase in AC use contributes to global warming by raising greenhouse gas (GHG) emissions. These systems also enhance localized warming in densely populated urban areas through anthropogenic heat, thus creating a feedback loop that intensifies the need for cooling (Chen et al. 2019). To balance human health with environmental sustainability, future research should explore the effectiveness of passive or low-energy cooling technologies, such as fans (Raftery et al. 2023), cool roofs, and evaporative coolers (Sun et al. 2021). Additionally, it's crucial to consider variations in occupant behavior across different regions instead of relying solely on stochastic models (An et al. 2018). Our study did not account for emergency scenarios like severe heat waves or power outages, which have become more common in California. Future studies should extend our findings to these situations to better understand the retrofit needs for maintaining comfortable indoor conditions, whether through conventional AC systems or low-energy/passive solutions. Our use of the latest TMYx data, spanning 2007 to 2021, supports our current analysis. However, incorporating forward-looking TMY (fTMY) weather files would be beneficial in predicting future retrofit needs more effectively. This would allow our recommendations to be more robust against the impacts of global warming. Lastly, our dataset's representation of smaller counties is limited—48 out of 58 counties had fewer than 1,000 samples. Future efforts should increase the sample size substantially to enhance the reliability of our results, though this will require more computational resources and time.

ACKNOWLEDGMENTS

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CONFLICT OF INTERESTS

The Center for the Built Environment (CBE) at the University of California, Berkeley, with which the authors are affiliated, is advised and funded in part by many partners who represent a diversity of organizations from the building industry, including manufacturers, building owners, facility managers, contractors, architects, engineers, government agencies, and utilities.

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