Cooling – not weatherization – ensures access to livable indoor conditions for residential buildings in Los Angeles

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ABSTRACT

Exposure to extreme indoor air temperatures can lead to lower productivity, health issues, increased medical costs, and in some cases death. Using Los Angeles as a case study, we use the residential building stock model, ResStock^{TM}, to understand the thermal comfort conditions in the existing building stock. We found that some households are more at risk than others because they may not use or have access to cooling technologies when outdoor temperatures become dangerously hot. To mitigate the risks associated with unsafe indoor conditions, we simulated a suite of building envelope and cooling technology upgrades to understand their effect on thermal conditions, especially for those households that currently do not have or use cooling. Given the results, we found that for Los Angeles households envelope improvements by themselves do not lead to meaningful improvements in indoor thermal conditions. However, the installation and use of any cooling system substantially increases the time households spend in "livable" thermal conditions. This study provides novel comparison between housing upgrades that provide mechanical cooling and building weatherization. Furthermore, it provides quantitative data to support ongoing qualitative research on the importance of access to cooling. This research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure.

Introduction

One major impact of climate change is the increased frequency and severity of heat waves (Field et al. 2014). This will only exacerbate the fact that the most common weather-related event resulting in death in the U.S. is extreme heat (US Department of Commerce 2022). Therefore, reducing heat exposure in residential buildings is imperative to public health. There are many barriers to reducing heat exposure in homes – poor building conditions, lack of access to cooling technologies, or an inability to pay the utility bills associated with cooling. To ensure the health and safety of all households, it is critical to understand the different strategies available to reduce heat exposure.

Heat exposure has serious health consequences. Exposure to extreme heat can increase heat-related illnesses like heat strokes and can aggravate pre-existing conditions, which may require hospitalization, increase medical bills, or even cause death (Fraser et al. 2017; Berko 2014; Luber and McGeehin 2008). For those working at home, high indoor air temperatures can lower productivity, and increase medical care costs and sick leave (Flouris et al. 2018; Seppänen and Fisk 2005). Highly urbanized areas suffer from increased summer temperatures through the increased heat production of concentrated human infrastructure along with the heat retention of asphalt and concrete (Oke 1973). Excessive heat-related illnesses and deaths occurred during a heat wave in St. Louis and Kansas City in 1980, the 1995 heat wave in Chicago, and the 2003 heat wave in Europe (Jones et al. 2023; Dematte et al. 1998; Kosatsky 2005).

Thermal comfort indices have been developed to understand the conditions under which humans are comfortable while living and working in buildings. A variety of thermal comfort indices have been developed to suit a range of needs in this field (Carlucci and Pagliano 2012). ASHRAE Standard 55 outlines acceptable thermal comfort conditions for buildings and other occupied spaces (American Society of Heating, Air-Conditioning Engineers, and American National Standards Institute 2004). One aspect of ASHRAE Standard 55 is the use of Standard Effective Temperature (SET), first proposed by Gagge et al. (Gagge 1973), to normalize varying environmental conditions into a single thermal comfort metric. The SET of single thermal zone in a building is calculated using indoor air temperature, mean radiant temperature, water vapor pressure, air velocity, occupant metabolic rate, and their clothing level (Equation 1) (Ji et al. 2022). These variables are used in conjunction to calculate the dry-bulb temperature of a hypothetical standard environment at 50% relative humidity, where air and skin temperature are the same.

$$SET = T_{sk} - \frac{Q_{sk} - wh_{es}\left(P_{sk} - 0.5P_{s,SET}\right)}{h_{ws}}$$

Equation 1: General equation for standard effective temperature (SET).

Where h_{ws} is the comprehensive heat transfer coefficient of the standard environment (W/m^2-°C); T_{sk} is the skin temperature (°C); wh_{es} is the comprehensive evaporative heat transfer coefficient of the standard environment (W/m^2-Pa); P_{sk} is the vapor pressure on the skin surface (Pa); $P_{s,SET}$ is the steam pressure corresponding to SET °C and 50% relative humidity (Pa); and Q_{sk} is the skin heat loss (W/m^2).

The existing literature that leverages SET as a thermal comfort metric can be broken into three areas. The first area is the use of SET in conjunction with other thermal comfort models to develop adaptive thermal comfort models for a particular building or region of interest. These field studies compare occupant comfort survey data with the measured building conditions (e.g., temperature, humidity) to develop a comfort model that gives a range of comfortable conditions (Nguyen, 2012). These models have been used in a variety of applications including office buildings (Cena and de Dear 2001; Han et al. 2007; Omrani et al. 2017; Takasu et al. 2017), prefabricated buildings (Zheng et al. 2021), and transitional spaces (Fang et al. 2021). These studies allow building managers to understand the current conditions experienced by occupants in their buildings. Furthermore, results from these studies outline the levers that can be adjusted to ensure that indoor conditions remain inside a range that will be comfortable for occupants. However, one limitation to these studies is that they do not consider the impacts different building upgrades would have on the thermal comfort.

The second area is the use of SET is in building energy simulations to approximate the thermal comfort conditions in both existing and planned buildings to inform baseline conditions and the impact of different building upgrades on thermal comfort. In many of these studies, one or more of the variables in Equation 1 are assumed and the results from these studies are less rigorous compared to the measured data collected in field studies. The impact on thermal comfort of a wide variety of building characteristics have been evaluated in this way including impact of HVAC presence and operation (Chowdhury, Rasul, and Khan 2008; Silva, Ghisi, and Lamberts 2016), window shading and glazing (Tzempelikos et al. 2010) , roof materials and shapes (Dabaieh et al. 2015), and photovoltaic-Trombe walls (Xiao, Qin, and Wu 2023). These studies demonstrate that using SET in building energy modeling can help improve not only building energy performance but also ensure occupant comfort given the building design or retrofits. However, these studies are limited in that they are case studies and do not examine population-level effects.

The final area, with smallest existing research, is the use of SET in building stock energy modeling to simulate the widespread change in thermal comfort of upgrades across a larger building stock. Mavrogianni et al. (Mavrogianni et al. 2014) simulated nearly 30,000 unique buildings by varying the building and occupant characteristics of 15 residential building geometry archetypes. The thermal comfort within each building was calculated under a variety of occupant behavior patterns using different ventilation schedules and shading scenarios. This study found that occupant window operation behavior along with daytime shading and night cooling were significant factors in mitigating indoor overheating risk. While the study provides insights on thermal comfort as a function of occupant behavior and building characteristics, it does not address the impacts of building upgrades on thermal comfort.

An advantage of using SET in building energy models is the ability to predict the change in baseline thermal comfort given certain upgrades. Mavrogianni et al. took the use of SET in building energy modeling beyond isolated case studies and applied it to an entire building stock (Mavrogianni et al. 2014). However, no study currently exists that has modeled the thermal comfort characteristics of an entire building stock and described the improvement from the baseline of these thermal comfort characteristics under specific upgrade scenarios (Figure 1).

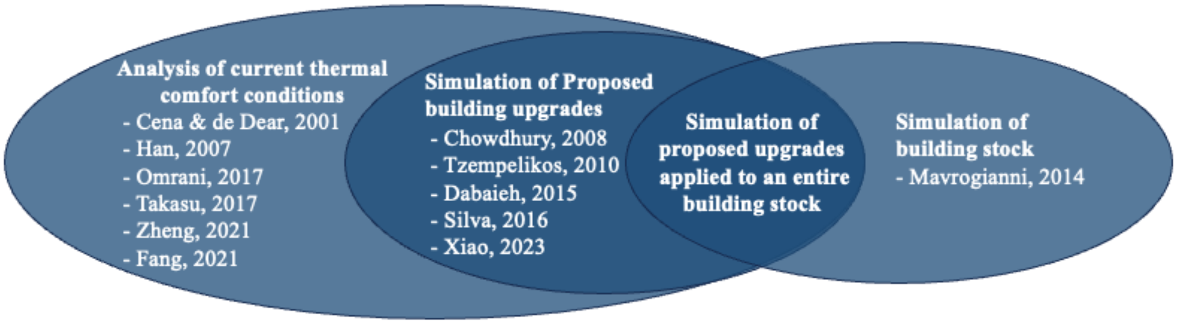

Figure 1: Trends and gaps in the use of standard effective temperature as a thermal comfort index

This study addresses this gap in two ways. First, we use a building stock energy model to simulate the energy performance and thermal conditions of a large existing building stock. Second, we analyze the impact of various upgrades on improving thermal conditions. The research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure.

Methods

To achieve the aims of this study, we developed a four-part methodology. First, we outlined the reasons for choosing the City of Los Angeles, hereinafter referred to simply as Los Angeles. Second, we developed a customized building stock energy model to simulate the indoor thermal comfort and energy use of the current residential building stock in Los Angeles. Second, we developed and simulated a set of energy retrofit upgrade packages that improve baseline thermal comfort conditions. Finally, we developed the Universal Cooling Thermal Comfort Model that assesses the change in thermal comfort created by each combination of the upgrade packages.

Los Angeles as a Case Study

Los Angeles has many characteristics that make it an ideal case study to understand the impact of residential building upgrades on thermal comfort. Los Angeles is one of the largest metropolitan areas in the United States; more than 1% of the U.S. population lives in Los Angeles ("U.S. Census Bureau QuickFacts: Los Angeles City, California," n.d.). Thus, any change to the thermal comfort across its building stock will benefit a significant portion of the California and U.S. populations. Furthermore, Los Angeles shares a similar climate with other major cities in southern California, northwestern Mexico, the Mediterranean, southwestern South Africa, and western Australia. Thus, the findings from this study can be extrapolated and used in these areas as well. Finally, in the LA100 Equity Strategies study conducted by the National Renewable Energy Laboratory (NREL) and the University of California Los Angeles (UCLA), representatives from various community-based organizations were involved in a series of meetings regarding the city's efforts to decarbonize its energy, transportation, industrial, and building sectors. In those meetings some of the most common concerns included access to cooling, health and safety of current residential buildings, and the quality of current infrastructure in marginalized communities to support any proposed upgrades ("LA100 Equity Strategies," n.d.).

Custom Los Angeles ResStock™ Model

ResStock ™ is a physics-based, bottom-up, white box, residential building stock energy model developed by NREL (Wilson, 2017). ResStock defines the national relative probability of 157 residential building characteristics (e.g., wall insulation R-value) through a set of conditional probability tables synthesized from 11 different national sources. For this study, the probability of some of these national characteristics were customized to Los Angeles.

The custom Los Angeles ResStock model included refined probability distributions for model geography, appliance saturation, and weather. We improved the ResStock model geographic resolution from the U.S. Census Bureau's Public Use Microdata Areas to the census tract level. We revised the appliance saturation levels, which are based on the U.S. Energy Information Agency's 2015 Residential Energy Consumption Survey, using the 2019 California Residential Appliance Saturation Study (Palmgren et al. 2022). These new saturation levels were correlated to both income and renter/owner status to improve the characterization of housing in low-to-moderate income and disadvantaged communities. Finally, we adjusted the model to simulate the weather using a typical metrological year weather file for each of the four California Energy Commission (CEC) climate zones found in Los Angeles—zones 6, 8, 9, and 16.

With these customizations, we were able to simulate the hourly energy use of all major energy end uses for a representative sample of dwelling units in the Los Angeles. First, ResStock sampled 50,000 dwelling units to approximate the residential building stock of Los Angeles. Second, the characteristics and weather files associated with each dwelling unit are fed into the building energy modeling platform OpenStudio®, which leverages the EnergyPlus™ modeling engine and NREL's high-performance computer to generate hourly energy use for all major end uses ("OpenStudio," n.d.). These hourly load profiles are then validated against Load Research Data provided by LADWP. Finally, we downselected this building stock to only include occupied dwelling units. This process produced the baseline scenario and the ability to understand the current thermal conditions of residential buildings across Los Angeles. Lastly, we configured the ResStock model to output each of the variables needed to calculate SET (Equation 1) and to output the hourly SET for each household for the entire year.

Scenario Upgrade Development

With the baseline scenario simulated, we defined a set of upgrade scenarios focused on improving indoor thermal conditions. To improve thermal comfort from the baseline, we explored two types of building upgrade packages: 1) improving envelope characteristics, and 2) adding or upgrading the efficiency of cooling systems in homes. Based on the literature, both these strategies are shown to improve thermal comfort (Hu et al. 2023; Ma et al. 2021; Kravchenko et al. 2013; Semenza et al. 1996; Luber and McGeehin 2008; Berko 2014; Bouchama et al. 2007a). These upgrade packages are described in following paragraphs.

We implement three envelope upgrade packages. The first envelope upgrade is the deployment of cool roofs. Cool roofs are considered because they are both required by the Los Angeles Municipal Code for all new construction and roof replacement and because community-based organizations advocated for their utilization in marginalized communities in Los Angeles (*Ordinance No. 187208* 2021; "LA100 Equity Strategies," n.d.). The second envelope upgrade is based on the findings from Wilson et al., which identified drill-and-fill wall cavity insulation for frame constructions and a 25% reduction in infiltration through air sealing as two of the most cost-effective building envelope improvements (Wilson et al. 2017). The final envelope upgrade package is to bring all existing building up to code with the 2022 CEC Residential Building Standards for new constructions. The CEC building standards set the minimum requirement for wall, attic, and roof insulation, windows, and infiltration ("2022 Building Energy Efficiency Standards for Residential and Nonresidential Buildings" 2022). Additionally, CEC building standards require mechanical ventilation for any residential building that has an air leakage value below 7 ACH50. Therefore, mechanical ventilation is added to any dwelling unit that achieved this infiltration level in the second and third envelope upgrade packages. Table A1 in Supporting Information outlines each of the three envelope upgrade packages in detail.

We implemented four different HVAC upgrade packages based on system type and efficiency. The first system type is composed of traditional AC systems: room AC and central AC systems. The second type is composed of heat pump technologies; air-source heat pumps (ASHP) for ducted households, and mini-split heat pumps (MSHP) for non-ducted households. For the low-efficiency traditional cooling technologies, we used the minimum AC standards from the 2022 CEC building code ("2022 Building Energy Efficiency Standards for Residential and Nonresidential Buildings" 2022). For the high-efficiency traditional cooling technologies, we based the non-ducted selection on the highest efficiency, commercially available product listed on the Air-Conditioning, Heating, and Refrigeration Institute's (AHRI) Directory of Certified Product Performance, and we based the ducted selection on the recommendations by Wilson et al. ("AHRI Certification Directory" 2024; Wilson et al. 2017). For the low-efficiency heat pump cooling technologies, we took the guidelines for minimum efficiency heat pump technologies based on 2022 CEC building code standards for residential retrofits ("2022 Building Energy Efficiency Standards for Residential and Nonresidential Buildings" 2022). For the high-efficiency heat pump cooling technologies, we based our selection on the highest efficiency, commercially available products listed in the aforementioned AHRI directory ("AHRI Certification Directory" 2024). We sized the AC systems to meet the entire cooling load of the dwelling unit at design temperature following the Air Conditioning Contractors of America's (ACCA) Manual J (Rutkowski 2016). For heat pumps, they are sized to cooling plus some oversizing for heating per ACCA Manual S (*Manual S - Residential Equipment Selection* 2016). Table A2 in the Supporting Information outlines each of the four cooling upgrade packages in detail.

Table 1 outlines the 19 upgrade scenarios we simulated by combining these different envelope and HVAC upgrade packages. These upgrade scenarios are compared to the baseline scenario to determine how the thermal conditions within Los Angeles residential buildings change due to these upgrades.

Table 1: Upgrade scenario parameterization based on cooling and envelope upgrade packages

	HVAC System Type and Efficiency Level				
Envelope Improvement	*No Change (H0)*	*Low Efficiency Traditional AC (H1)*	*High Efficiency Traditional AC (H2)*	*Mid Efficiency Heat Pump (H3)*	*High Efficiency Heat Pump (H4)*
No Change (E0)	Baseline	H1E0	H2E0	H3E0	H4E0
Cool Roof (E1)	H0E1	H1E1	H2E1	H3E1	H4E1
Low-Cost Envelope (E2)	H0E2	H1E2	H2E2	H3E2	H4E2
Title 24 Envelope (E3)	H0E3	H1E3	H2E3	H3E3	H4E3

Model Generated Data Analysis

To understand how the various upgrade packages impacted thermal comfort and their relative costs, the results from the baseline and upgrade scenarios simulated by the custom Los Angeles ResStock model were assessed by two metrics: maximum SET to assess acute thermal stress and the annual SET distribution to assess chronic thermal stress.

The Athena query subroutine obtained the hourly SET timeseries stored on the Amazon Web Services (AWS). This subroutine performs two functions. First, it determined the maximum SET experienced by each household throughout the year. Second, it summed the number of hours each household experienced across an array of SET ranges. This subroutine created a distribution of SETs across the entire year for each household. Importantly, this function allows us to calculate the number of hours each household in a "livable temperature." For this analysis, the "livable temperature" threshold is a SET of 86°F, as defined by U.S. Green Buildings Council ("LEED v4 for Building Design and Construction" 2019).

Results and Discussion

Thermal Comfort and Cooling Use in Los Angeles

We analyze the thermal comfort results from the baseline scenario in two different ways. First, we determine the maximum SET experienced by each dwelling unit (Figure 2). These results give insights into the most acute thermal stress experienced in each dwelling unit.

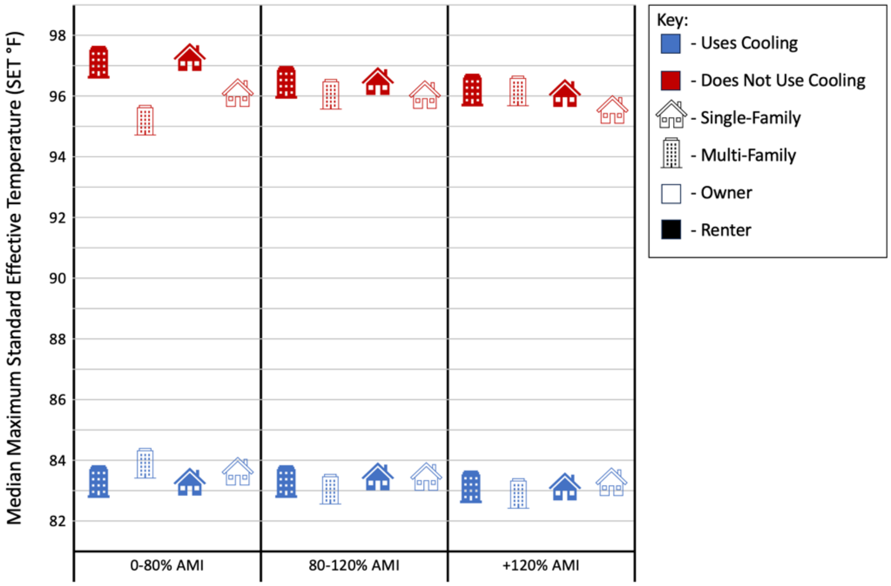

Figure 2: Median maximum SET disaggregated by cooling use, income, building type, and renter/owner status

Figure 2 shows that the most significant factor impacting acute thermal discomfort is whether a household uses cooling. This includes households that only cool a portion of their total home area. The average difference between the maximum SET experience by a household that uses cooling and one that does not is nearly 13°F. Over 99.9% of households that do not use cooling will experience a SET above 86°F and over 67% these residents will experience a maximum SET above 95°F. While there are differences in households with different incomes, renter/owner status, and building type, those differences are negligible compared to cooling use.

The second way we analyzed thermal comfort in the baseline scenario was by calculating the frequency each dwelling unit spent in various SET °F ranges (Figure 3). These results allow us to understand if there is chronic thermal stress experienced by certain households. Figure 3 sums the hours each simulated household spends in a series of SET °F ranges and then disaggregates these households' cooling use.

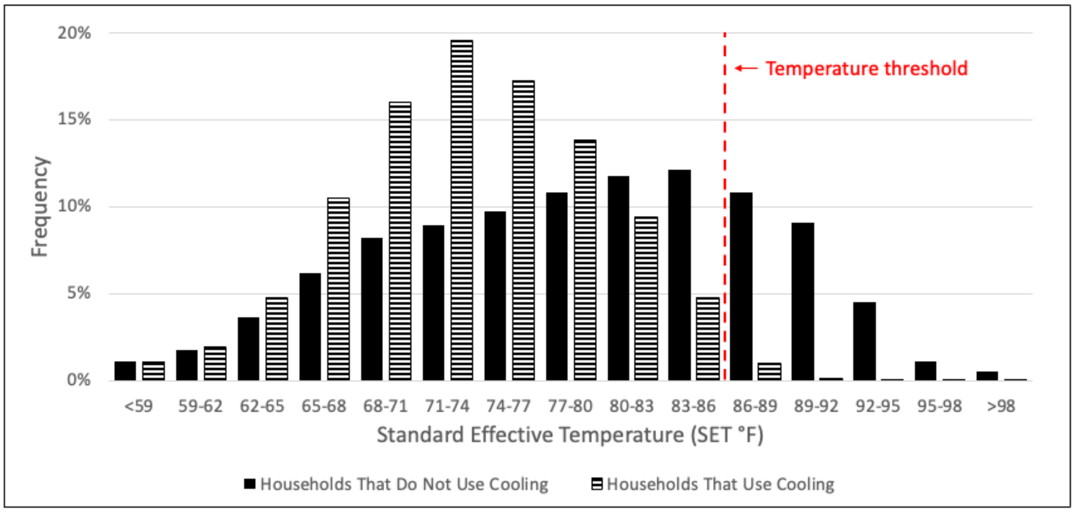

Figure 3: Annual hourly SET distribution disaggregated by cooling use

Along with the acute thermal stress experienced by households that do not use cooling (Figure 1), Figure 3 shows these households also experience chronic thermal stress throughout the year. These results show that households that do not use cooling experience a SET above 86°F 17.8% of the year; this equates to approximately 65 days. Those who do use cooling experience these same conditions only 1.1% of the year; this account for just over 4 days above threshold. Given these results, we know that there are buildings across Los Angeles that experience temperatures above "livable" conditions for many weeks, if not months, of the year.

These results show that the most important factor in determining thermal comfort in a household is whether a household uses cooling. This issue is critical because over 48% of Los Angeles households do not have or use their cooling equipment ("Residential Energy Consumption Survey (RECS)," n.d.). While income level and renter/owner status do not significantly impact the results of acute or chronic thermal stress, 15% more low-income households do not use cooling compared to high-income households, 11% more renter-occupied households do not use cooling compared to owner-occupied households, and 5% more households in multi-family residences do not use cooling compared to those living in single family residences. Therefore, more of these household types will experience higher indoor air temperature for longer periods of time throughout the year. Upgrades to residential buildings across Los Angeles are imperative to reduce both the acute and chronic thermal stress currently being experienced by many households.

Impact of Upgrades on Thermal Comfort

The first set of upgrades that could be deployed to improve the thermal comfort of Los Angeles residents are improvements to the building envelope (i.e., H0E1, H0E2, and H0E3 scenarios). As previously noted, if a household used cooling in the baseline scenario, then they were far less likely to experience SETs above a "livable temperature" threshold. Given this, most of these households do not need significant intervention to ensure safe and comfortable home temperature. Therefore, when analyzing the impacts of these upgrades, we only examined those households that do not have or do not use cooling in the baseline scenario. Figure 4 shows the frequency of hours spent in various SET °F bins of all the households that do not use cooling in the baseline scenario compared to the envelope only upgrade scenarios (H0E1, H0E2, and H0E3 scenarios).

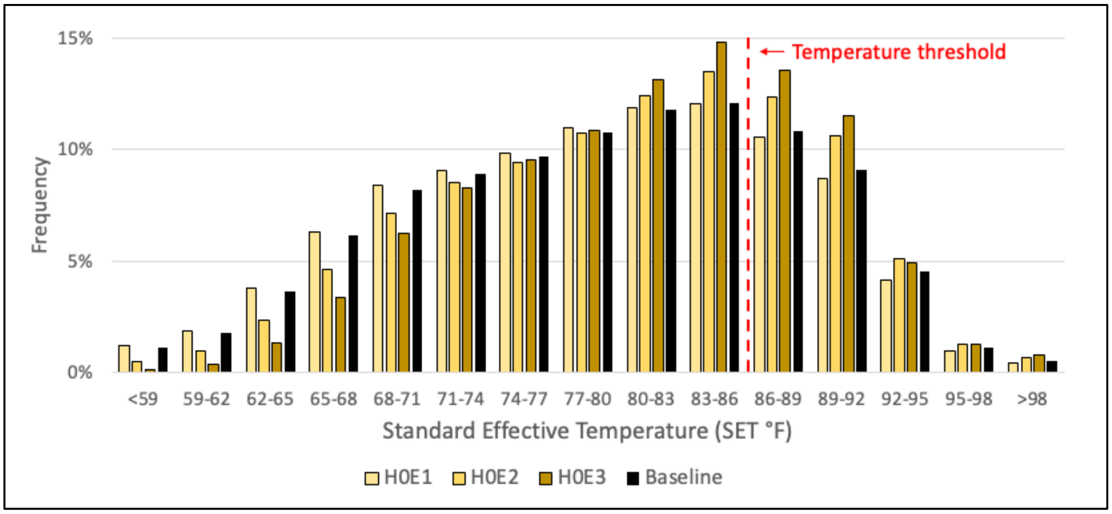

Figure 4: Annual hourly SET distribution for households without cooling in the baseline scenario compared to those households after envelope only upgrade scenarios (H0E1, H0E2, H0E3).

Based on the results in Figure 4, improving the envelope characteristics of households that do not use cooling in the baseline scenario does not significantly improve thermal comfort. In fact, the upgrade scenarios that improve the insulation and air tightness of households, H0E2 and H0E3, increase the frequency of unsafe SET. While seemingly counter-intuitive, we found that improving these envelope characteristics is not only more effective in keeping warm air out, but it just as effective at keeping it trapped inside. Given Los Angeles' climate, in our simulations, during the warmer months, natural cooling from the late evenings through the early mornings is reduced by increasing the envelope performance. In practice this could be mitigated to some extent by increased natural ventilation through purposeful occupant behavior (e.g., opening of windows and doors), which is not explicitly modeled in this study. Installing cool roofs, upgrade scenario H0E1, marginally decreases the number of hours above a SET above 86°F compared to the baseline scenario because this upgrade reduces the amount of solar heat gain without insulating or air sealing the envelope.

Given these results, upgrades beyond envelope improvements alone must be implemented to improve the thermal comfort of households that do not use cooling. Figure 5 shows the frequency of hours spent in various SET °F bins of all the households that do not use cooling in the baseline scenario compared to the H1E0 scenario, which models upgrading households without cooling in the baseline with the lowest efficiency traditional AC systems.

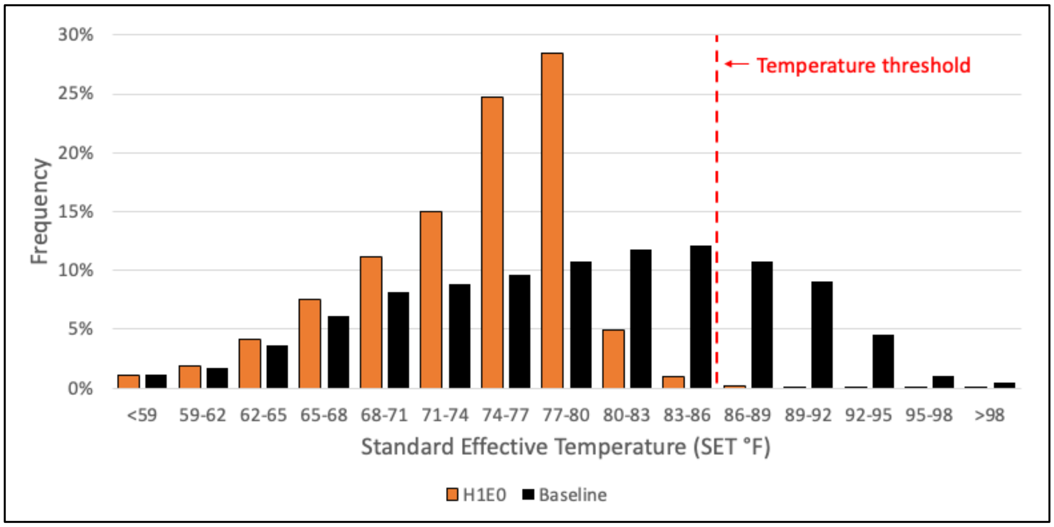

Figure 5: Annual hourly SET distribution for households without cooling in the baseline scenario compared to the low-efficiency traditional AC upgrade (H1E0).

Figure 5 shows that the addition of even the lowest efficiency cooling technology significantly increases the number of hours spent within the "livable temperature" threshold for households without cooling. This is true even without improved envelope characteristics. In our simulations, if a cooling technology is installed or upgraded, the new system will always attempt to meet the cooling load of the household regardless of household's behavior in the baseline scenario. Beyond this, any type of cooling upgrade also decreases the median maximum SET experienced by households without cooling (See Table B1 in the Supporting Information). Therefore, we conclude that exposure to both chronic and acute thermal stress can be mitigated by the addition and use of any type of mechanical cooling system for homes in Los Angeles. This may not be the case of all households, especially those with high energy burdens who may not be able to pay for cooling even if they have access to cooling technologies ("LA100 Equity Strategies," n.d.).

To better understand the relationship between envelope characteristics and cooling upgrades on thermal comfort, Figure 6 compares the baseline scenario with the scenarios with the highest performance envelope improvements (H0E3), the highest-efficiency heat pump (H4E0), and these two upgrade packages combined (H4E3).

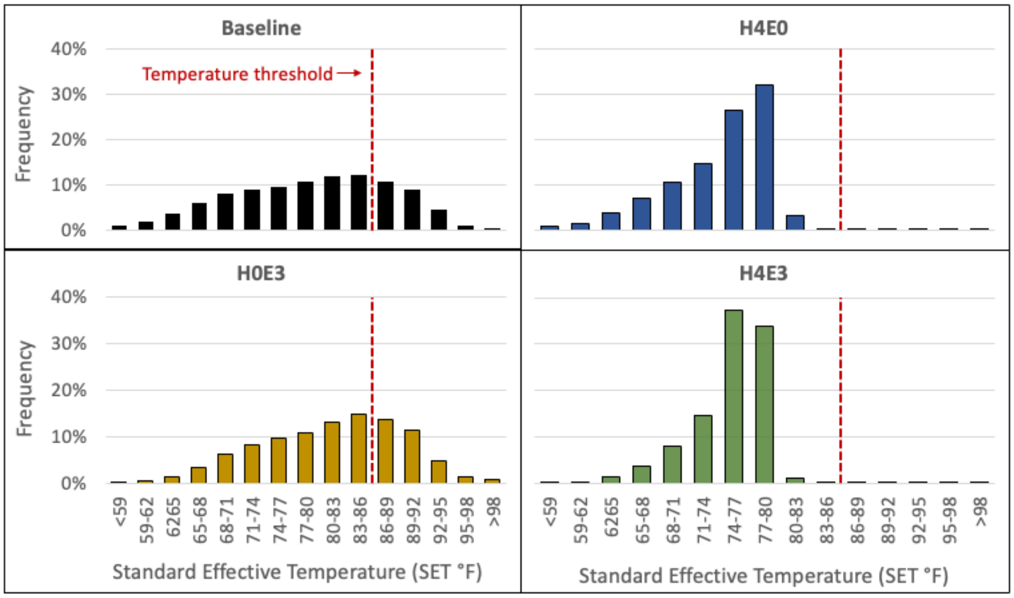

Figure 6: Factor analysis of annual hourly SET distribution for households without cooling in the baseline scenario compared to the upgrades with greatest envelope and cooling packages.

The factor analysis in Figure 6 shows that are some synergistic benefits to pairing cooling access with building envelope improvements. Scenario H4E3 exhibit the most narrow distribution of SET of any scenario. Not only are the hours spent in extremely high SETs eliminated through the addition of mechanical cooling, but there are also even fewer hours spent in extremely low SETs due to the improved envelope characteristics. It is critical that this synergy is further explored for building stocks in more extreme climates.

Limitations and Future Work

This study is limited by the ResStock modeling framework, the scenario development process, and the cost modeling assumptions. First, given the current ResStock model articulation, we cannot accurately calculate SET for partial space conditioning systems. Thus, we are unable to calculate the baseline thermal comfort of those households who utilize partial space conditioning strategies in their homes. Additionally, due to this limitation we chose to model all upgrades with full space conditioning to be able to calculate SET for these upgrades. This is not a realistic representation of how households will necessarily choose to cool their homes. Another limitation in household characteristics sampled by ResStock is that the income associated with each household is associated with the tenants and not the landlord. Given this, we cannot be certain that a household's landlord would or would not qualify for certain incentives.

Second, using the Internal Consistency and Diversity Comparative Framework set out by Sandoval et al., we found that the stakeholder involvement process conducted in this study could be improved (Sandoval, 2023). While the authors did consider comments and concerns from community-based organization representatives from Los Angeles, the authors were not part of the selecting of these individuals and organizations and therefore could not influence the selection process. More purposeful and selective stakeholder engagement would serve to improve the quality of the scenario development process and any subsequent findings. See Table C1 in the Supporting Information for full documentation of the scenario development analysis of this work.

Finally, there were multiple aspects of the cost modeling that could be altered to improve accuracy. In calculating marginal capital costs, a limitation of this study is that we assumed that each household would have capacity in their electric panel to accommodate this additional circuit. Therefore, while we were trying to quantify total fuel switching costs, in some cases we did not capturing the necessary expense of an electric panel upgrade, which could increase upgrade costs by thousands of dollars. Similarly, when upgrading natural gas heating system, 4% of affected households would become fully electric. For these households, when considering the marginal operating costs, we did not subtract the daily meter charges that these households would not pay. Finally, we only considered households with natural gas heating systems when upgrading to heat pump technologies. Propane and other heating fuel sources were ignored because they represent less than 2% of the building stock.

Conclusion

In this work, we use Los Angeles as a case study to demonstrate the ability to model the thermal conditions of an existing residential building stock using the ResStock model. Given these baseline results, we investigate a set of building envelope and mechanical cooling upgrade packages to mitigate extreme chronic and acute thermal stress in homes. These results provide quantitative data to support ongoing qualitative research on the importance of access to cooling. This research has implications for building science researchers who seek to improve building energy and comfort models at a population scale as well as policymakers who seek to mitigate health risks due extreme heat exposure. The conclusions from this research are:

- Nearly half of Los Angeles residents do not have access to or do not use cooling. This number is increased if a household is low-income, rents, or lives in a multi-family residence. These households experience both acute and chronic thermal stress throughout the year and it is critical that interventions are implemented to ensure that these households have access to functioning systems and have the means to use them during warm periods of the year.
- The installation and/or the use of any cooling technology has the ability, given full operation, to reduce the maximum SET to within the range of a “livable temperature” as defined by the U.S. Green Buildings Council. This finding supports observational data that the main deterrent to heat-related mortalities in the home is the access to and use of air conditioning (Bouchama et al. 2007b; Luber and McGeehin 2008).
- In Los Angeles, building envelope performance improvements do not improve thermal comfort by themselves, nor do they synergistically improve thermal comfort in conjunction with cooling systems. In some cases, these envelope improvements can have a dampening effect that can increase chronic thermal stress. Importantly, Los Angeles has an ordinance in place that requires the installation of a cool roof if a roof need to be

replaced. However, we found that this upgrade also increases the number of hours a household spends below a typical heating setpoint and will thus increase heating loads during colder periods of the year. Despite these increases, we do see a net decrease in annual energy use.
- Adding cooling will add costs. For those with an existing system, using it throughout the year will increase annual utility bills, especially during the summer months. For those without systems, cooling will require both capital expenses and additional utility costs. However, in Los Angeles massive envelope improvements do not need to accompany these expenses to make these systems worthwhile.

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Supporting Information

Appendix A: Methods

Table A1: Envelope Upgrade Packages

Upgrade Package	Upgrade Technology	Applicability
E1 – Cool Roofs	White or reflective roof material	All roof types (singles, metal, tile)
E2 – Cost Effective	25% Infiltration Reduction	All dwelling units
	Drill and Fill Wall Insulation	Dwellings with wood stud construction and below R-13 wall insulation.
	Mechanical Ventilation	Dwelling units upgraded to an infiltration level of 7 ACH 50 or less.
E3 – Title 24 New Construction	Infiltration Reduction to 5 ACH50	All dwelling units over 5 ACH50 before upgrades.
	Wall insulation	All dwelling type with wall insulation levels below Title 24 new construction requirements based on wall construction, building type, and CEC climate zone.
	Windows	All dwellings with windows below the Title 24 new construction requirements based on Solar Heat Gain Coefficient and area-weighted average U-factor.
	Attic Insulation	All dwelling type with attic insulation levels below Title 24 new construction requirements based on building type and CEC climate zone.
	Roof Insulation	All dwelling type with attic insulation levels below Title 24 new construction requirements based on roof finish and building type.
	Mechanical Ventilation	All dwelling units.

Table A2: Scenario parameterization based on HVAC efficiency and envelope improvement.

	Low-Efficiency Systems		High-Efficiency Systems	
System Type	Ducts	No Ducts	Ducts	No Ducts
Traditional	H1 Upgrade Package		H2 Upgrade Package	
	Central AC: SEER2 15	Room AC: CEER 10.7	Central AC: SEER2 18	Room AC: CEER 12.0
Heat Pump	H3 Upgrade Package		H4 Upgrade Package	
	ASHP: SEER2 15, 9 HSPF2	MSHP: SEER2 17, 9.5 HSPF2	ASHP: SEER2 24, 10.8 HSPF2	MSHP: SEER2 33.1, 13.5 HSPF2

Appendix B: Additional Results

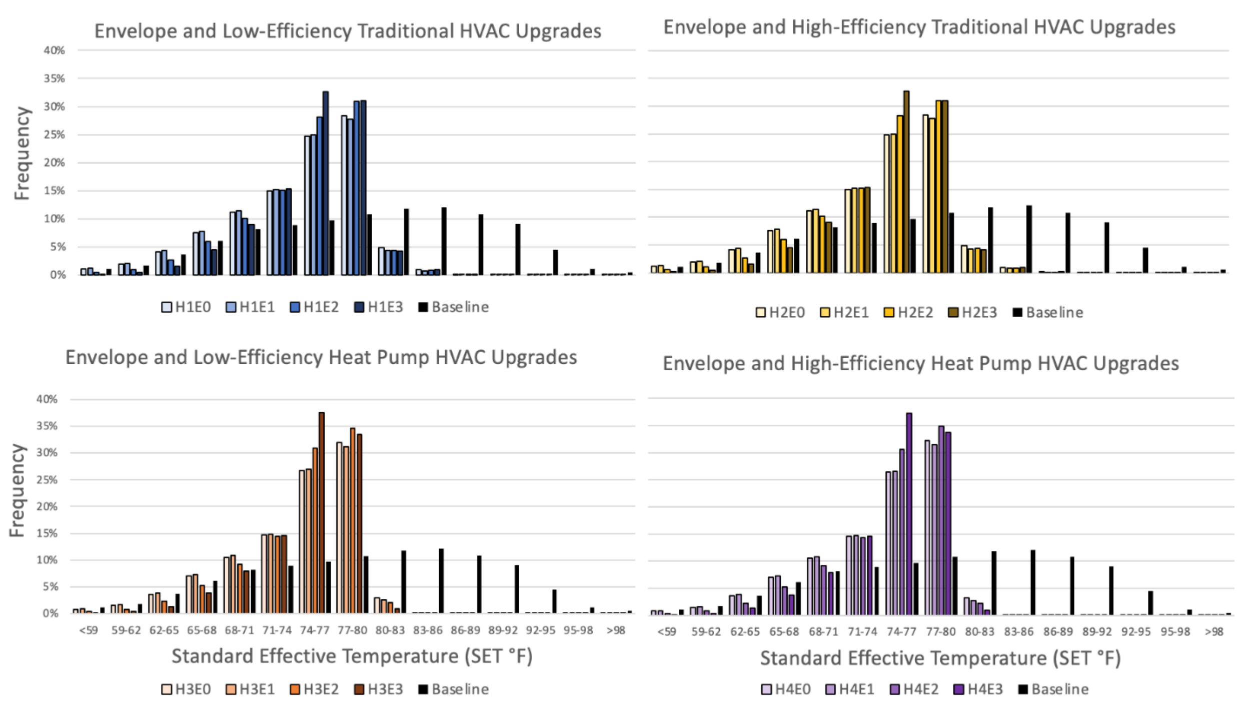

Figure B1: Annual hourly SET distribution for households without cooling in the baseline scenario compared to those households with envelope and cooling system upgrades.

Table B1: Median maximum standard effective temperature (SET) for households without cooling in the baseline for the baseline scenario and all scenarios with only cooling upgrade packages (H1E0, H2E0, H3E0, H4E0)

	0-80% AMI				80-120% AMI				120%+ AMI			
	Multi-Family		Single-Family		Multi-Family		Single-Family		Multi-Family		Single-Family	
	Renter	Owner	Renter	Owner	Renter	Owner	Renter	Owner	Renter	Owner	Renter	Owner
Baseline Scenario	97.0	95.4	97.1	96.3	96.4	96.1	96.4	96.0	96.3	96.3	96.0	95.6
H1E0 Scenario	83.9	83.5	84.2	84.0	83.8	83.5	83.8	83.8	83.6	83.1	83.9	83.6
H2E0 Scenario	83.9	83.4	84.1	83.9	83.6	83.4	83.8	83.6	83.5	83.0	83.8	83.4
H3E0 Scenario	82.4	81.8	82.4	82.3	82.1	82.0	82.2	82.1	82.0	81.5	82.2	81.9
H4E0 Scenario	82.4	81.7	82.1	82.2	82.3	81.9	82.0	82.1	82.0	81.7	82.1	81.9

Appendix C – Limitations and Future Work

Table C1 - Internal consistency and Diversity Scenario Development comparative framework auto-analysis results

Metric	Classification	Rationale
Stakeholder Involvement	Purposeful	Stakeholders in this project include scientists and engineers at the National Renewable Energy Laboratory, a group of advisory committee members from Los Angeles Department of Water and Power, and a group of steering committee members who are representatives from Los Angeles community-based organization. While this represents a diverse array of perspectives that aided in the development of these scenarios, especially the types of envelope and cooling technology upgrades, the authors of this study did not partake in selecting the individuals and organizations of these committees and thus cannot comment on the selection process of these stakeholders.
Narrative Complexity	Detailed	A detailed description of the purpose for each variable (envelope and cooling technologies) is available in the methods section.
Data Utilization	Detailed	A detailed description of the data used to represent each variable (envelope and cooling technologies) is available in the Methods section. Information about the ResStock™ model and all data used in the model are available on Github.
Public Availability	N/A	Will depend on publication.
Ease of Access	High	All scenario information can be found in the Methods section and Appendix A.
Variable Type	Only demand Side variables	The inclusion of only demand side variable is sufficient to answer the research questions of this study because the research questions only pertain residential building envelope and cooling technology characteristics and their impact on thermal comfort in said buildings and the energy demand change as a result. This study does not investigate demand response or any grid interactive building technologies that might necessitate mixed or supply side variables.
Variable Control	Internal and Limited variables	This study features multiple internal control variables, where the types of envelope (e.g., cool roofs) and cooling technology (e.g., code-minimum equipment) upgrades are governed by current laws. This study also features limited control variables looking at upgrades that residents can currently opt into. This study did not look into external control variables because the purpose of this study is to examine different building upgrades that would improve thermal comfort. These types of upgrades are all within some stakeholder control and so external control variables were unnecessary.
Scenario Outlook	Descriptive	All the scenarios in this study aim to understand what would happen given the implementation of certain building upgrades. We were not trying to achieve a certain thermal comfort level or a certain cost/payback minimum. Therefore, we did not find it necessary to include a normative scenario.

Scenario Progression	Trend and Disruptive	This study includes both trend scenarios whose projections are based on the current status quo or current laws (e.g., cool roofs), and normative scenarios (e.g., Title 24) that show the impact of a massive disruptive in the characteristics of the building stock on thermal comfort and energy costs.