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ABSTRACT

The compound impacts of heatwaves and power outages pose a serious indoor heat-related health risk for residents living in disadvantaged communities (DACs) with limited or no air conditioning. In this study we selected 13 heat vulnerable multifamily buildings in El Monte, in Los Angeles County, and employed CityBES to evaluate their energy and thermal resilience performance. A retrofit package with seven passive and low-power active measures—cool roof, cool wall, window solar film, air sealing, internal blinds, natural ventilation, and ceiling fan—was evaluated under 2018 weather conditions and projected 2058 future weather conditions. Results show: (1) under the 2018 weather conditions, the retrofit package reduces the peak electricity load by 19 % and reduces the annual energy cost by $183 per housing unit; (2) the housing units without air conditioning would face heat danger conditions throughout the heatwave period. Although the retrofit package could reduce the heat danger hours by 50 % in 2018 and 34 % in 2058, air conditioning is a life-essential need for residents during heatwaves. These results indicate that, during the decision making of energy and climate retrofits for housing in DACs, policymakers and building owners should consider the co-benefits of reducing indoor heat-related mortality while reducing energy cost.

1. Introduction

In recent years, many cities have experienced extreme climate conditions, such as heatwaves with record-breaking high temperatures. These unprecedented extreme climate conditions strain communities, increasing the peak electricity usage from growing cooling demand and causing more frequent power interruptions from the grid. This can expose residents to serious overheating risks as they face a longer duration of high indoor temperatures during heatwave periods; especially when they are coincident with grid power outages (G. Hatvani-Kovacs et al., 2016; G. Hatvani-Kovacs et al., 2016). These challenges have been brought to the attention of cities and local governments when evaluating the energy and resilience performance of existing buildings within an evolving environmental context (Keramitsoglou et al., 2017; Rafael et al., 2016; Mola et al., 2018).

Resilience refers to the ability of a building to recover from and adapt to adverse events (USGBC, 2018). The extreme weather-related events due to climate change have focused increased attention on thermal resilience in buildings, which affects building occupants' health. It is crucial for a building to be able to maintain a comfortable and safe indoor thermal environment for its occupants during extreme weather events, building system disruptions caused by technical failure, or power outages from the grid. To address this, policymakers, governments, and public health agencies need to prepare and develop reliance-oriented design, retrofit programs, codes, and standards, which prioritizes passive solutions as they are effective during power outages (Hong et al., 2023).

People living in disadvantaged communities (DACs) tend to be more vulnerable to extreme heat due to limited resources for adaptation, therefore more attention must be given to DACs to address these climate equity issues. Passive cooling designs such as natural ventilation, window film, and window blinds deserve increased attentions as they significantly improve heat resilience of homes in DACs during the power interruption events (Sun et al., 2021). The global trend to decarbonize the building sector to achieve carbon neutrality drives a reduction in energy use and carbon emissions from the building sector. At the same time, thermal resilience improvements in buildings to mitigate

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Nomenclature

Abbreviation

ACH	Air change per hour
CDD	Cooling degree days
CityBES	City Buildings, Energy, and Sustainability
CST	Cooling setpoint temperature
DAC	Disadvantaged community
ECM	Energy conservation measure
EUI	Energy use intensity
GHG	Greenhouse gas
GIS	Geographic information system
HDD	Heating degree days
HPI	Healthy Places Index
IPCC	Intergovernmental Panel on Climate Change
LADWP	Los Angeles Department of Water and Power
LARIAC	Los Angeles Region Imagery Acquisition Consortium
LEED	Leadership in Energy and Environmental Design
RCP	Representative Concentration Pathway
SET	Standard effective temperature
SoCalREN	Southern California Regional Energy Network
TOU	Time-of-use
USGBC	U.S. Green Building Council

occupants' heat-related health risks is considered as another key element in addition to achieving energy efficiency and a sustainable environment in the future with climate change.

A growing group of studies in recent years has focused on the thermal resilience of buildings in terms of indoor thermal quality. Hong et al. presented 10 research questions on the research topic of thermal resilience of buildings and provided a comprehensive literature review and highlighted the crucial issues regarding the thermal resilience of buildings for occupants living in this era of climate change (Hong et al., 2023). Siu et al. provided a comprehensive review of the quantification of thermal resilience and discussed how thermal resilience can be enhanced in building codes and standards (Siu et al., 2023). Homaei and Hamdy introduced metrics to evaluate the thermal resilience of buildings with various building characteristics and occupancy types under power failure conditions from disruptive events (Homaei & Hamdy, 2021). Krelling et al. investigated how occupants' thermal survivability during extreme hot weather events can be improved by renovating the building envelope (Krelling et al., 2023). Also, a study by Zeng et al. investigated the pre-cooling strategy to see how it can mitigate overheating of residential buildings during heatwaves (Zeng et al., 2022).

Thermal resilience is even more critical for healthcare facilities during power outages under heatwaves and cold snaps. Sheng et al. analyzed the thermal resilience with heat index and heat safety metrics for an assisted living facility and provided recommendations to improve the thermal resilience performance for occupants vulnerable under severe extreme heat and cold climate conditions. The study shows that passive envelope measures improve thermal resilience both for extreme hot and cold events (Sheng et al., 2023). Also, the thermal resilience of a nursing home was studied under power disruption events and examined how passive measures such as natural ventilation and cool envelope strategies can improve under extreme weather events (Sun et al., 2020).

There is an international collaborative effort to improve thermal resilience in buildings. The International Energy Agency's Annex 80: Resilient Cooling of Buildings investigated a framework to support low energy and low carbon solutions for addressing cooling and overheating issues in buildings (IEA, 2023). A study by Samuelson argues for co-benefits of thermal resilience beyond energy performance, promoting regulations or incentive programs to consider occupants' survivability and thermal interaction with urban climate (Samuelson et al., 2020).

Passive cooling strategies are effective for resilient cooling solution of buildings, as they contribute to reducing cooling loads during the summer season while improving thermal resilience (Sun et al., 2021; Krelling et al., 2023; Park et al., 2023; Lee & Levinson, 2023). Under extreme weather conditions, buildings cannot rely on active energy systems, as buildings face power interruption more often. Due to the loss of heating, ventilation, and air-conditioning (HVAC) system services during power outages, it is important to know how passive cooling strategies can improve thermal resilience and mitigate occupant heat-exposure risk. Zhang et al. provided a critical review of resilient cooling strategies and discussed the importance of passive solutions under power outages (Zhang et al., 2021). Passive cooling solutions should be prioritized when buildings are retrofitted; these include cool envelope technologies, green roofs or facades, natural ventilation, solar-control windows, and shading technologies. Cool envelope materials, typically with reflective roof or wall surface products, provide reduced solar heat gain from opaque surfaces of the building envelope (Rosado & Levinson, 2019). Evaporative envelope surfaces typically with green roofs and vegetated exterior walls provide evaporation on the outside of the building envelope, and they are an efficient passive cooling technique to improve thermal resilience (Raji et al., 2015). Natural ventilation is widely adapted to use the cooling potential of outdoor air, which decreases the indoor air temperature and improves occupant thermal comfort via convective heat transfer, increasing the evaporative cooling effect on an occupants' skin Campaniço et al. (2019). Windows with low thermal-infrared emittance (low-E) glazing products effectively reduce solar heat gain while allowing the most daylight (Rubin et al., 1999). Also, thermochromic glazing technologies have solar optical properties that vary with the temperature of the glass, which reduces solar heat gain in the summer season while allowing solar gain in the winter (Aburas et al., 2019). Solar shading systems—including window blinds and drapes installed on the interior and solar screens, fins, and overhangs on the exterior—can be combined with a solar-control window to reduce the solar gain from windows more effectively (Bellia et al., 2014). Resilient cooling strategies with passive measures not only bring reduced energy use but also improve thermal resilience, passive survivability, and urban heat mitigation in buildings. Passive cooling solutions need policymakers' attention as they synergize thermal resilience improvement beyond energy savings when they develop retrofit programs that provide incentive and rebate programs (Sun et al., 2021; Samuelson et al., 2020).

Los Angeles (LA) County, located in the southern part of California, developed a regional residential efficiency program to promote opportunities for energy upgrades in residential buildings for the 10 million people living in the county. The U.S. Department of Energy's (DOE's) Better Buildings Neighborhood Program funded LA County to promote local energy upgrades. These efforts identified DACs, informed homeowners about how to undertake energy upgrades, and provided them with incentives and resources to facilitate the process (IEA, 2014). Along with these efforts, the LA Department of Water and Power (LADWP) developed a program called Comprehensive Affordable Multifamily Retrofits to assist low-income, multifamily property owners. The LADWP's program has offered multifamily property owners efficiency opportunities to help multifamily building owners and their residents save energy and reduce energy costs (Los Angeles Department of Water & Power, 2023).

It is crucial to address the implications of transitioning the building stock toward higher cooling loads due to global warming, and to develop effective strategies to mitigate energy burdens and heat-related health risks from extreme weather events (Hatvani-Kovacs et al., 2018). Existing studies of multifamily buildings lack considerations of the co-benefits of energy retrofits and climate mitigation in DACs. To fill the gap, this study aimed to: (1) identify vulnerable multifamily buildings in DACs subject to climate change-induced risk, (2) analyze how climate change affects energy performance in those multifamily buildings and their occupants' thermal safety under current and future climate conditions, and (3) further quantify how passive and low-energy active energy efficiency retrofits can help reduce the energy burden and health risks. The study also explored how heatwaves impact the heat-related health risk for occupants in multifamily buildings, including homes with air-conditioning (AC) systems and normal cooling setpoint temperature (CST), with AC and increased CST, and without AC systems under grid power on and power outage scenarios. This study's outcomes can inform county policymakers, consultants, building owners, and community-based organizations plan and design building improvement retrofits.

2. Method

We first selected vulnerable multifamily buildings in DACs within LA County but outside the City of LA, then created a dataset of these buildings for use in CityBES (City Buildings, Energy, and Sustainability) (G. LBNL, 2023). CityBES is an open data and computing platform for modeling and analysis of building stock in cities for energy efficiency retrofits, electrification, decarbonization, and climate resilience (G. LBNL, 2023; Hong et al., 2016). CityBES uses EnergyPlus as the simulation engine to evaluate building performance while considering the urban context (e.g., local weather conditions, shading between buildings). EnergyPlus is the U.S. Department of Energy's flagship whole-building energy simulation program to evaluate building energy performance and indoor thermal comfort (G. DOE, 2023). Then, the energy and resilience performance of the baseline and the energy retrofit scenario of the selected buildings were simulated using the CityBES platform.

Fig. 1 shows the selection and simulation workflow. Eight simulation scenarios were considered to comprehensively assess the baseline building energy and resilience performance considering climate and grid power conditions: (1) annual energy simulation of the baseline buildings assuming no power outages for the year 2018 (actual weather data), (2) annual energy simulation of the retrofitted buildings assuming no power outages for the year 2018, (3) a thermal resilience simulation during the heatwave for the baseline buildings using 2018 weather data, (4) a thermal resilience simulation during the heatwave for the retrofitted buildings using the 2018 weather data, and (5 to 8) using the 2058 future projected weather data for scenarios 1 to 4.

2.1. *The data and process to select the vulnerable multifamily buildings*

There are 886 census tracts with multifamily buildings in LA County. As the analysis focus was census tracts in LA County but outside the City of LA, this helped to down-select 391 census tracts. We used environmental and social data mapping tools to screen the census tracts with DACs. These mapping tools include California's CalEnviroScreen 4.0 score (G. OEHHA, 2023), Healthy Places Index (G. OEHHA, 2023), Social Sensitivity Index (LA County, 2021; G. LA County, 2023), and the Equity Explorer Index (G. LA County, 2023). The multifamily buildings at the identified census tracts with DACs were further screened by the total number of housing units that are below the current building code requirements and building construction quality. The construction quality class is a function of all construction features, depending upon the quality of materials, construction methods, and workmanship (California State Board of Equalization, 2020). CalEnviroScreen, a mapping and screening tool that quantifies cumulative impacts in communities, plays a pivotal role in identifying DACs (Faust et al., 2021). The

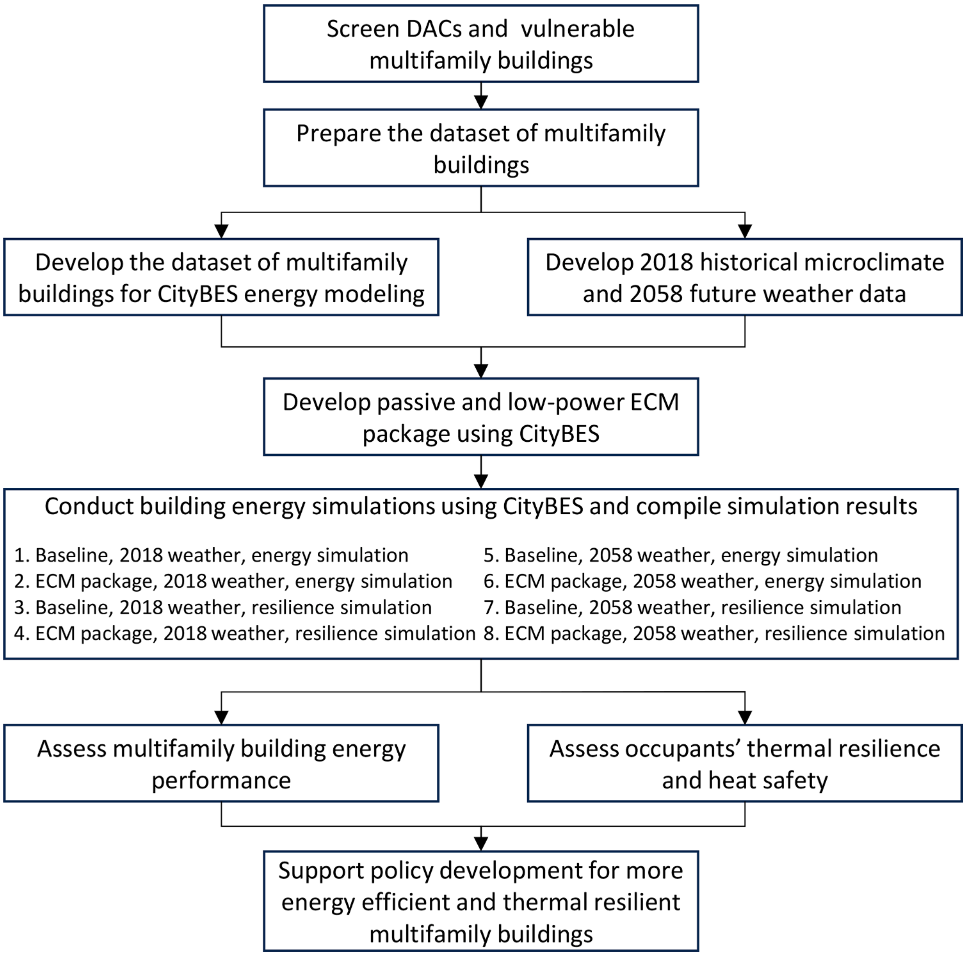

Fig. 1. Workflow to assess energy and thermal resilience performance for multifamily buildings in DACs.

California Healthy Places Index (HPI) measures community well-being at the census-tract level to support health departments and community organizations, with an index rooted in the social determinants of health (Maizlish et al., 2019). LA County provides a Social Sensitivity Index to evaluate a person's sensitivity to climate hazards, and this helps to identify which geographic areas have high proportions of climate-sensitive residents (LA County, 2021). The Equity Explorer, which in 2022 was awarded an Urban and Regional Information Systems Association's Exemplary Systems in Government Award, provides economic, health, environmental, education, demographic, and justice statistics for geographies down to the census tract level overlaid on top of a map of LA County, which enables the identification and prioritization of areas of the highest need (G. URISA, 2022; G. URISA, 2022). There is a vast stock of multifamily buildings (more than 43,000 buildings, holding over 150,000 homes) in LA County that are below the building energy efficiency code requirements. The far larger number assessed as being in a good state of repair also presents good opportunities for scaling energy efficiency policies generally. We used the Los Angeles Region Imagery Acquisition Consortium (LARIAC) Geographic Information System (GIS) dataset to prioritize parcels and buildings for energy efficiency retrofits, incorporating the construction quality rating of each building (G. County of Los Angeles, 2023).

Fig. 2 shows the location of the four selected DACs in El Monte from the CalEnviroScreen 4.0 color-coded map of LA County. Table 1 shows the selected top four census tracts represented in geoid in El Monte with the multifamily housing units that can benefit from retrofits to address environmental and social issues. The selected locations have higher CalEnviroScreen 4.0 scores compared to other census tracts in California indicating that they potentially have great environmental and pollution concerns. The average CalEnviroScreen 4.0 score for the four census tracts is 55.8 which is worse than the average score of 52.4 for locations in LA County but outside the City of LA. The construction quality value of the multifamily buildings in those census tracts is lower than or equal to the code requirement of 5, which indicates that buildings potentially need envelope retrofits to improve thermal performance. Also, these locations have low HPI scores, positioned in the bottom 10 %. The average HPI is −0.85, which is worse than the average of −0.55 for the other LA County census tracts. A Social Sensitivity Index equal to or greater than two means they are socially more vulnerable than other locations. Those census tracts have an Equity Explorer Index greater than 85, indicating a high degree of equity issues. The average Equity Explorer Index is 90 which is worse than the average of 74 for the LA County census tracts.

2.2. Dataset for building modeling

The selected four census tracts have 10 parcels and a total of 13 multifamily buildings. Table 2 presents a summary of the 13 buildings' salient features including built year, building height, number of floors, gross floor area, number of multifamily units, grid cell for the local weather data, and AC penetration status with cooling setpoint temperature (CST) information. These 13 buildings have 108 housing units and a total gross floor area of 11,461 m^2. The average housing unit floor area is 106 m^2. Most of these buildings have two stories and were built in the 1960s.

The 2019 LARIAC GIS data was used for building footprint generation. The assessor's data was used to determine the vintage of the buildings, which assigns the multifamily building's baseline envelope and system efficiency parameter values based on the Title 24 requirements under the specific vintage and the California climate zone

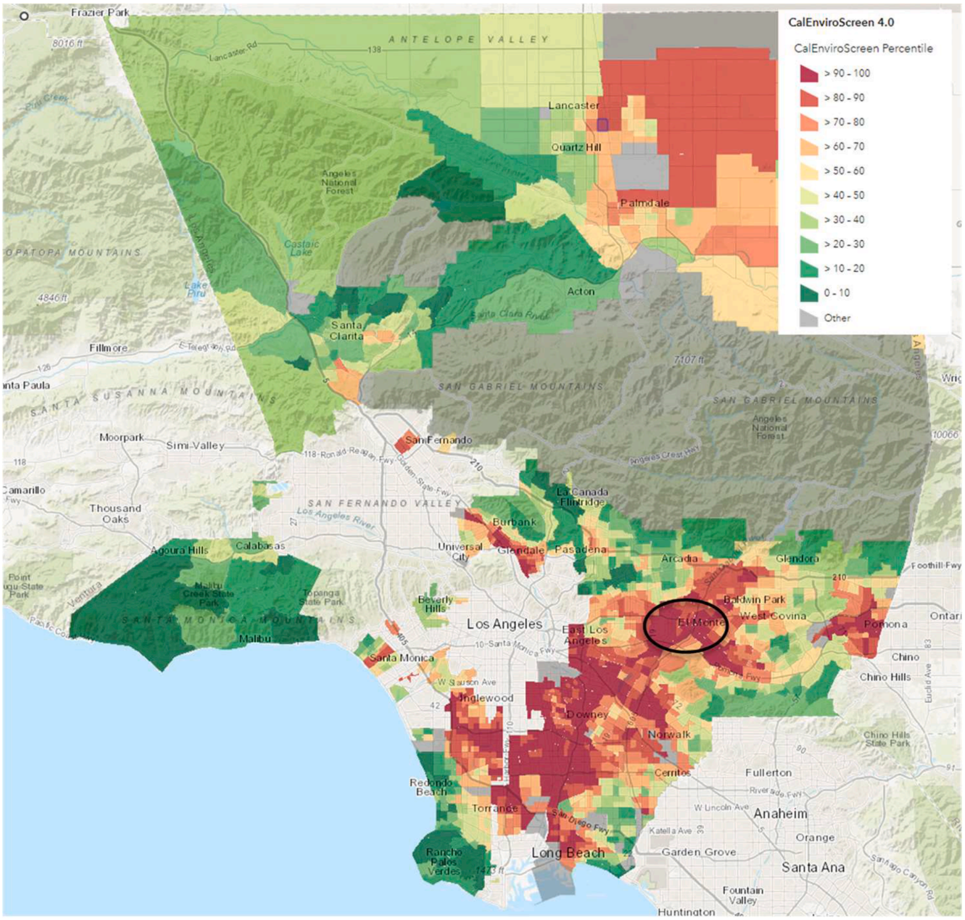

Fig. 2. The location of the disadvantaged communities in El Monte from the CalEnviroScreen 4.0 color-coded map of LA County.

Table 1
Four selected census tracts with the multifamily buildings' construction quality and environmental and social index data.

Geoid	Construction Quality Class Number	CalEnviroScreen 4.0 Score	Healthy Place Index	Social Sensitivity Index	Equity Explorer Index
6,037,433,403	4.75	51.4	−0.81	3	95.9
6,037,432,802	5.00	64.3	−0.94	2	97.1
6,037,433,305	5.00	52.2	−0.88	3	84.8
6,037,433,402	5.00	55.5	−0.78	2	80.4

Table 2
Summary of 13 multifamily buildings in four selected DACs of El Monte.

Building ID	Built year	Height [m]	Number of floors	Gross floor area [m^2]	Number of units	Microclimate grid	AC status	Cooling setpoint temperature [°C]
7,805,385	1963	6.4	2	452	4	78	Yes	23.9
7,805,386	1963	7.7	2	1690	15	78	Yes	23.9
7,805,387	1963	6.7	2	894	8	78	Yes	25.6
7,805,388	1963	6.5	2	451	4	78	Yes	23.9
7,805,389	1959	7.0	2	806	8	78	No	NA
7,805,390	1959	7.1	2	802	8	78	Yes	25.6
7,805,391	1958	7.2	2	548	6	92	Yes	23.9
7,805,392	1959	7.2	2	823	8	78	Yes	23.9
7,805,393	1964	6.7	2	2052	22	92	Yes	25.6
7,805,394	1960	5.0	2	900	9	92	No	NA
7,805,399	1937	3.7	1	269	5	79	Yes	23.9
7,805,400	1988	6.4	2	1212	5	79	No	NA
7,805,419	1955	4.5	1	562	6	78	Yes	23.9

(CZ 06) where the buildings are located. The roof and wall albedo values were from the dataset prepared by the urban heat island impact research task (G. LBNL, 2023). All multifamily buildings were built before 1980, which indicates poor envelope insulation and construction quality. We used the LA County parcel dataset – the construction quality data fields – as a prioritization filter for identifying appropriate parcels and buildings (G. County of Los Angeles, 2023). This study assumed a realistic AC system penetration scenario. Three out of 13 multifamily buildings, 22 units (20.4 %), were assumed to have no AC system installed. The remaining 10 multifamily buildings have mechanical cooling systems. Among them, seven buildings with 48 units (44.4 %) have a CST of 23.9 °C, reflecting normal AC operation, and three buildings with 38 units (35.2 %) have an increased CST of 25.6 °C, assuming some residents in the DAC choose to raise their cooling setpoint to reduce their utility bill. Table 2 shows the AC penetration scenario and microclimate weather data where the building is located.

2.3. Weather data

The weather data used in the EnergyPlus simulations of this study was derived from the hourly Thermodynamic Global Warming (TGW) dataset v1.0.0 (Jones et al., 2023), with the 12 km spatial resolution, in the

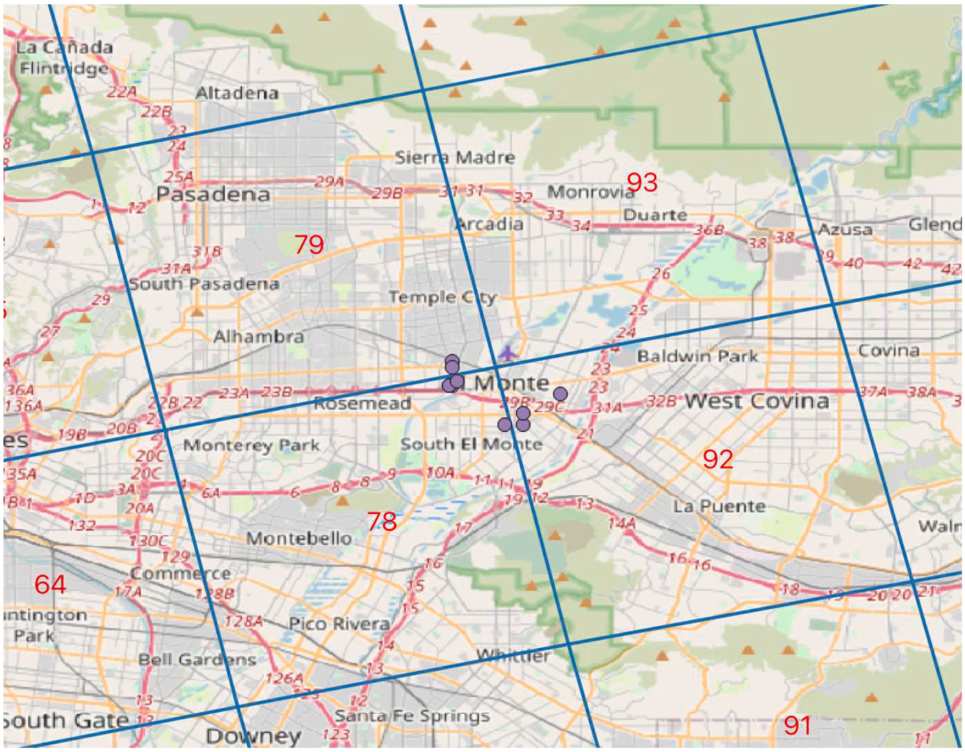

Fig. 3. Microclimate grid cells with a spatial resolution of 12 km x 12 km to cover each multifamily building's local climate conditions.

NetCDF format of weekly duration per file. The TGW dataset is dynamically downscaled from the WRF (Weather Research and Forecasting) model (version 4.2.1). The NetCDF data was converted to the EnergyPlus weather files (.epw) using the script from this repository - https://github.com/LBNL-ETA/im3-wrf/. The 2018 weather data uses the "historic" scenario and the 2058 weather data uses the "rcp85hotter" projected climate change scenario in the TGW dataset. WRF Version 4.2.1 is used in downscaling the European Centre for Medium-Range Weather Forecasts version 5 re-analysis (ERA5) over 40-year periods, from 1980 to 2019, 2020 to 2059, and 2060 to 2099. The GCMs (general circulation models) are selected based on skill scores and data availability. A thermodynamic global warming procedure is adopted for the climate simulations of future scenarios. In the climate simulations, four sources of land cover data are used to improve the urban cover representation.

Fig. 3 illustrates three microclimate grid cells (78, 79, and 92) covering the locations of 13 multifamily buildings (marked as purple dots) in El Monte. We assigned these three microclimate grids' weather data to each building energy model in CityBES to reflect the local climate conditions in building energy simulations.

Based on Ouzeau's method to determine heatwaves (Ouzeau et al., 2016), we selected a heatwave from the 2018 and 2058 weather data, which starts on July 6 and ends on July 10 for both years.

Table 3 provides the summary of 2018 and 2058 weather data for El Monte. The 2018 weather data reflects microclimate conditions for the three grid cells of 78, 79, and 92 from Fig. 4. The weather data summary shows that the annual average outdoor air temperature and the heatwave period average temperature in 2058 are both greater than those in 2018. Due to climate change, 2058 shows reduced heating degree days (HDD). Although the 2018 Grid 92 has the greatest peak temperature of 46.3 °C at 1 pm on July 6 of that year, 2058 has the highest average temperature during the heatwave period. Fig. 4 illustrates the outdoor air temperature during the heatwave period in 2018 and 2058.

2.4. Building model creation and simulation

Building energy modeling plays a key role in evaluating energy performance with the climate change scenarios and predicting climate-related thermal resilience performance (Xu et al., 2022; Moazami et al., 2019). We used CityBES to create the building energy models and run EnergyPlus simulations. Fig. 5 shows the 3D building shape of the targeted 13 multifamily building models visualized in CityBES. The building geometry and energy model input dataset was prepared in GeoJSON format, an open standard designed for representing simple geographical features along with their non-spatial attributes.

2.5. Utility rate and environmental factors

The electricity services of the selected multifamily buildings are provided by Southern California Edison. The natural gas is provided by Southern California Gas Company. We used the May 2023 utility tariff information for energy cost analysis. The electricity rate is based on the time-of-use (TOU) rate structure, and TOU-d-4–9 PM is the current rate for residential homes; it has a peak electricity usage rate between 4 pm and 9 pm both for summer and winter seasons. The electricity rate ranges from \$0.23/kilowatt-hour (kWh) to \$0.31/kWh (OpenEI, 2023). The natural gas rate is \$1.25/therm based on May 2023 (SoCalGas, 2023).

For carbon emission factors, we used the 2021 California state average carbon dioxide equivalent (CO_2e) emission factor of 272 gs (g)/kWh for electricity and 225 g/kWh for natural gas based on the California data from Emissions & Generation Resource Integrated Database (GTI Energy, 2023; ISO, 2017). California has more renewable and hydropower sources for electricity generation than other states, yielding an electricity emission factor lower than the U.S. average CO_2e emission factor of 451 g/kWh (GTI Energy, 2023).

2.6. Energy conservation measures

There are a wide variety of energy conservation measures covering major building systems and components that can help improve energy efficiency and thermal resilience of buildings. For this study, we focused on passive and low-power energy conservation measures (ECMs) for the selected multifamily buildings. Passive measures are building technologies or design strategies to improve the heat related thermal resilience as they function without the need of energy under power outages (Zhang et al., 2021; Attia et al., 2021). Passive ECMs aim to reduce solar heat gains through windows, reduce air infiltration, and enable natural ventilation with operable windows. Cool envelope technologies, solar-controlled window films, and solar shading from fixed exterior shading devices and interior window blinds are effective to reduce solar heat gains during the hot weather conditions (Shin et al., 2022). Natural ventilation helps maintain the indoor operative temperature lower than the outdoor air temperature during the heatwave period (Alessandrini et al., 2019). Indoor air movement using ceiling fans is an energy-efficient and occupant-responsive cooling solution that has not in the past been part of conventional HVAC design. Recently the positive effects of air movement from ceiling fans have been addressed in standards with their benefits in design and retrofit practice (Levinson et al., 2023). Ceiling fans are considered to be a low-cost active cooling measure. The study selected seven widely applied ECMs among passive strategies and applied them in the EnergyPlus models generated by CityBES for building energy simulations. Table 4 lists the selected measures with their measure ID from CityBES and technical descriptions.

2.7. Performance metrics

For energy performance analysis, CityBES simulations report annual site energy use, peak electricity demand, annual source/primary energy, annual greenhouse gas (GHG) emissions, and monthly energy use. For thermal resilience analysis, we used heat index (HI) and standard effective temperature (SET) to evaluate the occupants' thermal comfort and heat exposure under the heatwave events. The heat index combines indoor dry-bulb air temperature and relative humidity (US, 2022), which measures how hot people feel if the relative humidity is factored in with the actual air temperature in a building. The heat index provides an approximation of how the human body perceives the temperature (Steadman, 1979).

The heat index is expressed in temperature and categorized into five levels:

- Safe: less than 26.7 °C. No risk of heat hazard.

Table 3
Summary of weather data for El Monte in 2018 and projected for 2058.

El Monte Weather Data	Annual Average Temperature [°C]	Annual CDD Base 18 °C	Annual HDD Base 18 °C	Heatwave Period Average Temperature [°C]	Heatwave Period Peak Temperature [°C]
2018 – Grid 78	18	968	967	30.9	45.7
2018 – Grid 79	18.3	975	857	31.5	45
2018 – Grid 92	18.4	1048	890	31.5	46.3
2058	18.7	985	740	32.7	45.4

Note: CDD is cooling degree day and HDD is heating degree day.

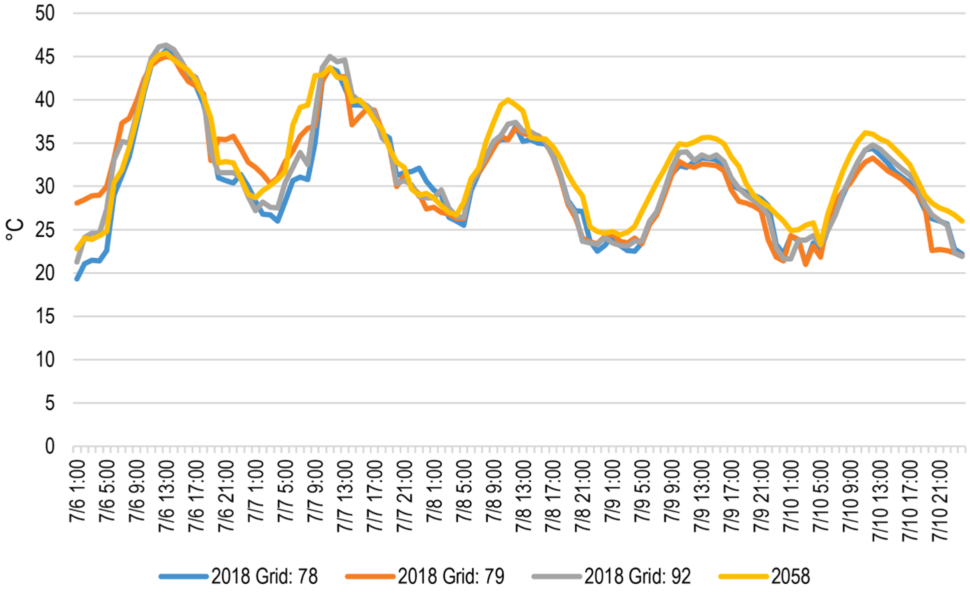

Fig. 4. Outdoor air temperature during the heatwave period for 2018 and 2058.

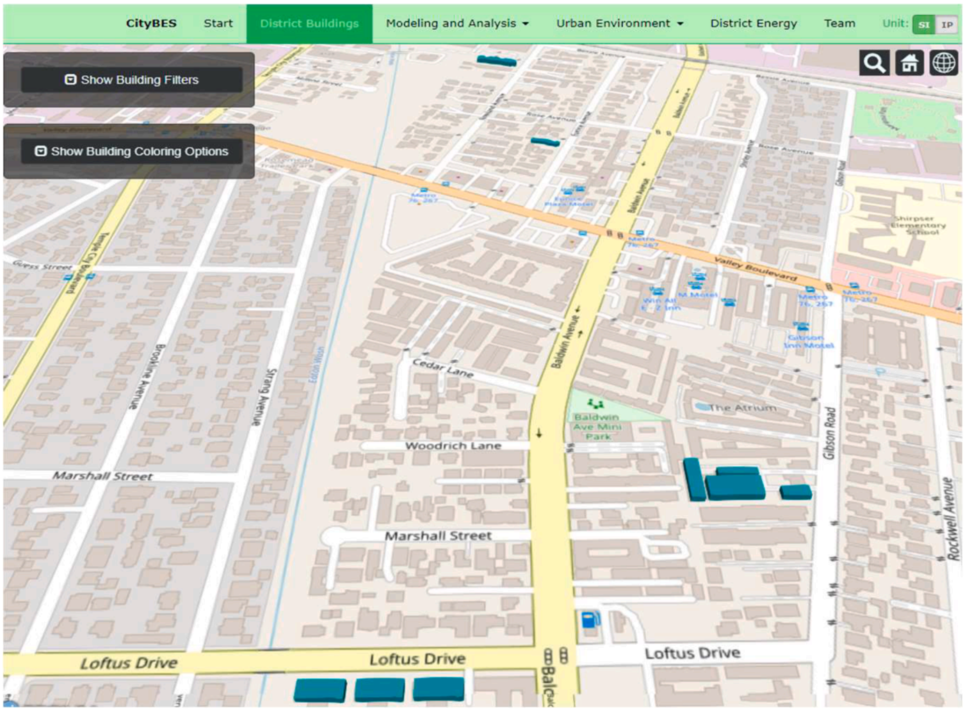

Fig. 5. Screen capture of a subset of multifamily buildings modeled in CityBES.

- Caution: 26.7 °C–32.2 °C. Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
- Extreme caution: 32.2 °C–39.4 °C. Heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke.
- Danger: 39.4 °C–51.7 °C. Heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity.
- Extreme danger: over 51.7 °C. Heat stroke is imminent.

The SET is adopted in ASHRAE thermal comfort standard 55–2017 (ASHRAE, 2017) to evaluate the human response to heat stress. *SET* is defined as the equivalent dry bulb temperature of an isothermal environment at 50 % relative humidity while wearing clothing standardized for the activity concerned. A SET threshold of 30 °C for free-running buildings or mechanically cooled buildings without grid power outages is used to calculate the heat stress exceedance hours during a heatwave (Sun et al., 2021). Credit for passive survivability, defined based on SET degree-hours, is adopted in the U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED) Green Building rating systems (Wilson, 2015).

3. Results and analysis

3.1. Building energy performance

3.1.1. Under the 2018 weather conditions

We analyzed the energy performance of the multifamily buildings for

Table 4
Passive and low-power ECMs applied to the multifamily buildings.

Measure Type	Measure Name	Measure Description
Passive measure	Cool wall coating	ECM 87: Envelope - Exterior wall - Apply cool wall coating with wall solar reflectance of 0.6
	Cool roof coating	ECM 103: Envelope - Roof - Apply cool roof with asphalt shingle to pitched roof with roof solar reflectance of 0.6
	Solar film for windows	ECM 86: Envelope - Window - Add window film with solar film specification of u-factor 4.94 W/m^{2}K and solar heat gain coefficient 0.45
	Interior shading (blinds)	ECM 43: Envelope - Window - Use window shades with blinds during the summer months (May–September) daytime (10 am–7 pm)
	Air sealing	ECM 13: Envelope - Infiltration - Add air sealing to seal leaks that reduce infiltration from 1 air change per hour (ACH) to 0.3 ACH
	Natural ventilation	ECM 88: Envelope - Window - Enable natural ventilation for rooms with window(s) with an effective opening fraction 0.4
Low power measure	Ceiling fan	ECM 104: HVAC - Ventilation - Add ceiling fan in residential buildings, allowing an increased CST to 28 °C during the summer season

the baseline condition and the improved condition with ECMs implemented as a retrofit under the 2018 weather conditions. Table 5 shows the summary of the energy performance for each multifamily building baseline condition, as well as the retrofit condition in 2018. In Fig. 6, the left box and whisker plot (boxplot) shows the distribution of the baseline electricity and natural gas usage intensity for the 13 multifamily buildings, and the right plot shows the retrofit condition. The box shows the quartiles of the dataset while the whiskers extend to show the rest of the distribution. Whiskers are drawn to the farthest datapoint within 1.5 times interquartile range. The baseline buildings have a higher median heating natural gas energy use intensity (EUI) of 21.3 kWh/m^2 than a median cooling electricity EUI of 16.3 kWh/m^2. The baseline buildings have a median electricity, natural gas, and site EUI of 71 kWh/m^2, 66 kWh/m^2, and 139 kWh/m^2, respectively. The retrofits with the ECM package have a median electricity, natural gas, and site EUI of 61 kWh/m^2, 100 kWh/m^2, and 157 kWh/m^2, respectively. This results in a 17 % savings of annual electricity but a 53 % increase in annual natural gas usage, leading to a 12 % increase in annual site energy usage.

It should be noted that we assumed a diverse profile of AC system operations for the buildings. We assumed an AC system penetration scenario with 44.4 % (48 units) of normal AC operation with CST, 35.2 % (38 units) with an increased CST, and 20.4 % (22 units) with no AC systems. These assumptions, although trying to represent the social-economic status of the residents in the disadvantaged communities, may potentially underestimate the annual cooling energy usage. It should be noted that among the measures in the ECM package, cool roof, cool wall, and solar film for windows reduce the cooling energy usage during the summer, but they contribute to the greater increase in heating load during the winter season in El Monte under the 2018 climate conditions. Fig. 7 shows the average EUI by end-use type for the baseline and retrofit conditions. The ECM package contributes to cooling energy savings but increases heating energy consumption. Fig. 8 shows the distribution of cooling electricity and heating natural gas EUI for the baseline and retrofit scenarios. The median cooling EUI decreases from 16 kWh/m^2 to 6 kWh/m^2 by 62 %, and the median healing EUI increases from 21 kWh/m^2 to 56 kWh/m^2 by 63 %.

The peak electricity load of 400 kW for the 13 multifamily baseline buildings occurs on the hottest day July 6, 2018 at 6 pm. Fig. 9 shows the distribution of the peak electricity load intensity for the baseline and retrofit conditions. The median peak electricity power intensity for the retrofit condition is 34 W/m^2, which is a 19 % decrease compared to the median of the baseline (42 W/m^2). The peak electricity reduction mainly comes from the decreased cooling and fan electricity. The passive and

Table 5
Summary of energy performance of the multifamily buildings under the 2018 weather conditions for the baseline and retrofit conditions.

Building ID	2018 Baseline							2018 Retrofit						
	Peak electricity [kW]	Annual electricity usage [kWh]	Annual natural gas usage [kWh]	Annual site energy usage [kWh]	Annual electricity cost [$]	Annual natural gas cost [$]	Annual total energy cost [$]	Peak electricity [kW]	Annual electricity usage [kWh]	Annual natural gas usage [kWh]	Annual site energy usage [kWh]	Annual electricity cost [$]	Annual natural gas cost [$]	Annual total energy cost [$]
7,805,385	20	33,595	43,428	77,022	$8718	$1853	$10,571	16	27,089	61,362	88,452	$7030	$2618	$9648
7,805,386	69	119,604	101,012	220,616	$31,740	$4309	$36,049	57	102,023	132,506	234,529	$27,075	$5653	$32,728
7,805,387	38	63,235	61,277	124,513	$16,217	$2614	$18,831	30	50,218	89,763	139,981	$12,878	$3829	$16,708
7,805,388	21	36,573	33,871	70,443	$9389	$1445	$10,834	17	27,717	52,823	80,540	$7115	$2254	$9369
7,805,389	11	39,076	49,816	88,892	$9343	$2125	$11,468	11	39,507	65,219	104,726	$9446	$2782	$12,228
7,805,390	28	53,953	48,693	102,646	$13,702	$2077	$15,779	23	42,681	69,627	112,308	$10,839	$2970	$13,809
7,805,391	30	49,828	40,474	90,302	$12,742	$1727	$14,468	24	36,473	67,841	104,313	$9327	$2894	$12,221
7,805,392	38	62,369	53,914	116,283	$16,141	$2300	$18,441	31	48,203	85,384	133,587	$12,475	$3643	$16,117
7,805,393	66	126,562	112,810	239,372	$32,665	$4813	$37,478	51	107,007	149,419	256,426	$27,618	$6375	$33,992
7,805,394	12	43,625	48,751	92,377	$10,429	$2080	$12,509	12	43,794	54,831	98,625	$10,469	$2339	$12,808
7,805,399	13	21,200	27,171	48,371	$5471	$1159	$6631	10	16,139	40,351	56,490	$4165	$1721	$5887
7,805,400	16	57,202	56,652	113,854	$13,680	$2417	$16,097	16	57,362	62,716	120,078	$13,719	$2676	$16,395
7,805,419	38	54,479	51,261	105,740	$13,914	$2187	$16,101	30	37,362	94,527	131,889	$9543	$4033	$13,575
Total	400	761,301	729,130	1490,431	$194,151	$31,106	$225,257	330	635,576	1026,369	1661,945	$161,698	$43,787	$205,485

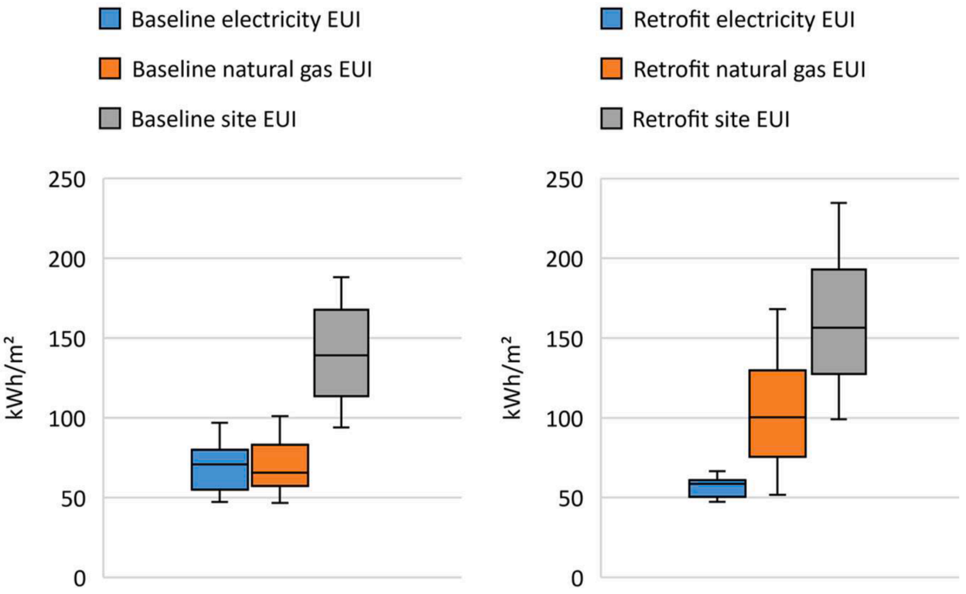

Fig. 6. Site, electricity, and natural gas EUI boxplot for multifamily buildings with baseline (left) and retrofit (right) conditions under 2018 weather conditions.

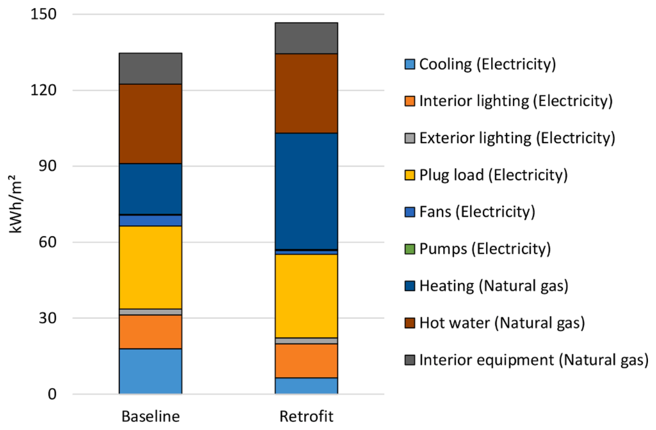

Fig. 7. Average energy usage intensity (EUI) by end use for the baseline and retrofit multifamily buildings under the 2018 weather conditions.

low power measures in the ECM package greatly contribute to the cooling load reduction.

Fig. 10 shows the CO_2e emission intensity boxplots for the baseline and retrofit conditions. The emission intensity is calculated by multiplying electricity consumption by the electricity CO_2e emission factor, and the same for the natural gas. Then, the total CO_2e emission is the sum of the electricity and natural CO_2e emissions. The electricity CO_2e emission factor (272 g/kWh) is 20 % greater than that of natural gas (225 g/kWh). Although the retrofit condition has electricity savings, the greater increase in natural gas consumption brings an increase to the CO_2e emission with the retrofit condition. The median CO_2e emission intensity shows that the retrofit condition (38 kg/m^2) is 9 % greater than the baseline condition (35 kg/m^2).

Fig. 11 shows the electricity and natural gas cost savings from retrofitting. The electricity saving from the retrofit yields a median electricity cost saving of $2863 per multifamily building and a total of $35,452 for all 13 buildings. However, there is a median natural gas cost increase of $893 per building—a total of $12,681 for all buildings due to the increased natural gas consumption. Table 6 presents the average

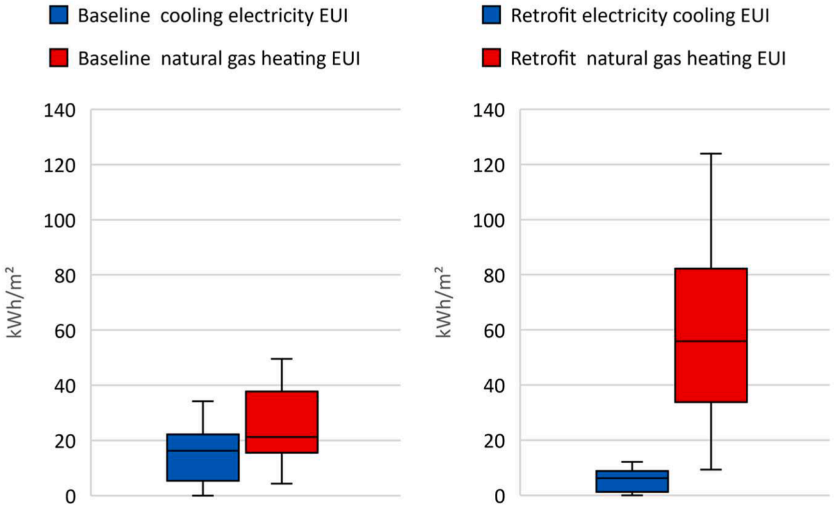

Fig. 8. Cooling electricity and heating natural gas EUI boxplot for the multifamily buildings with baseline (left) and retrofit (right) conditions under the 2018 weather conditions.

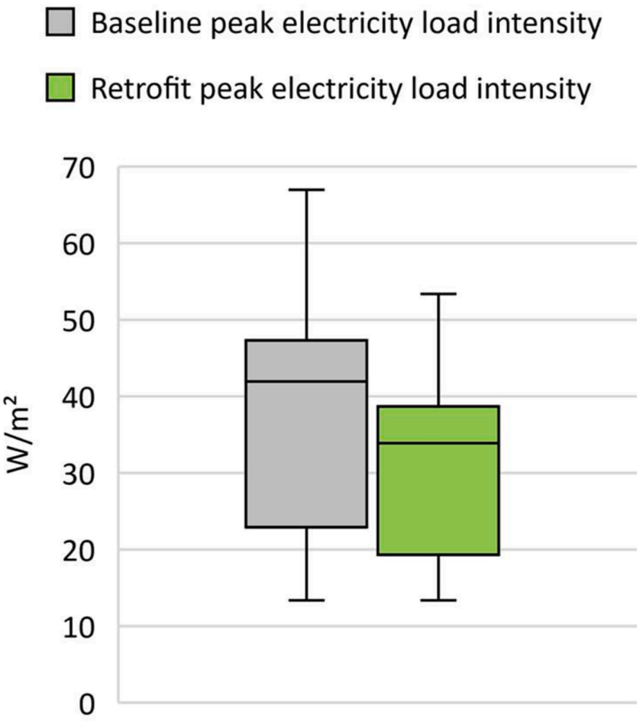

Fig. 9. Peak electricity load intensity boxplot for the multifamily buildings with baseline and retrofit conditions under the 2018 weather conditions.

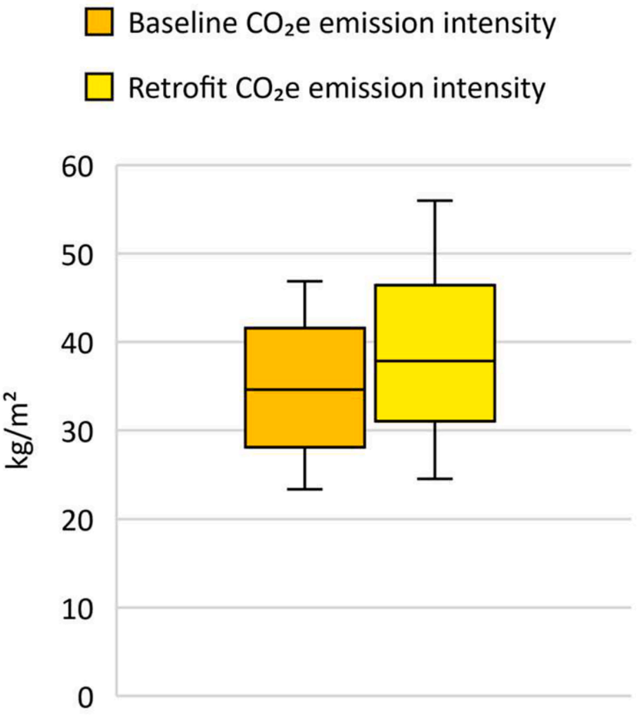

Fig. 10. CO_2e emission intensity boxplot for multifamily buildings with baseline and retrofit conditions under 2018 weather conditions.

energy cost saving of $183 per multifamily housing unit from the electricity and natural gas consumption changes due to the retrofits.

3.1.2. Under the projected 2058 weather conditions

Table 7 presents the energy performance for the baseline and retrofit scenarios of each multifamily building under the projected 2058 weather conditions. Fig. 11 presents the electricity, natural gas, and site EUI change boxplot from the weather data change for the baseline condition from 2018 to 2058 weather (left), and for 2058 from the baseline to the retrofit condition (right). The climate change reflected in 2058 future weather data shows that multifamily buildings will bring a 26 % increase in cooling electricity EUI to 21 kWh/m^2 and a 31 % reduction in heating natural gas EUI to 15 kWh/m^2 compared to the baseline EUI in 2018. In Fig. 12, the left boxplot shows that 2058 future weather brings in the median electricity EUI increase of 7 % and a median natural gas reduction of 8 %, resulting in the median site EUI reduction of 2 % compared to the 2018 weather data. The right side of Fig. 11 shows the energy usage changes if buildings are retrofitted in 2058, showing electricity savings of a median of 14 kWh/m^2 (11 %) and a natural gas usage increase of 32 kWh/m^2 (47 %) compared to the baseline condition. As observed in the 2018 retrofit scenario, the retrofit brings the site energy usage increase in 2058, caused by the greater increase in natural gas usage than the electricity saving.

Fig. 13 shows the peak electricity power intensity change for the baseline condition from 2018 to 2058 weather (left) and from baseline to retrofit condition in 2058 (right). Fig. 12 (left) shows the median 1 W/m^2 peak electricity increase by 2 % from the weather change in 2058 for the baseline condition, and (right) that the retrofit in 2058 can reduce the median peak electricity intensity of 4 W/m^2 by 9 %.

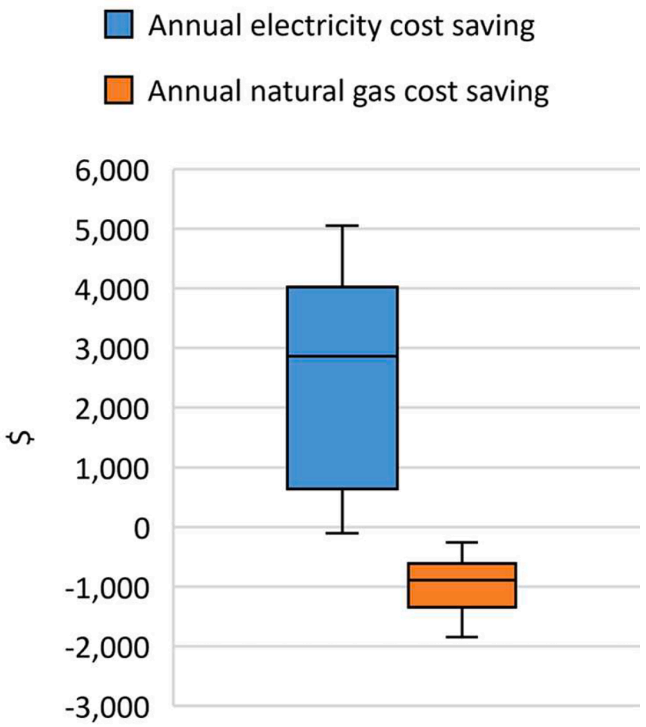

Fig. 11. Electricity and natural gas cost saving for multifamily buildings with baseline and retrofit conditions under 2018 weather conditions.

3.2. Indoor heat exposure

Figs. 14, 15, and 16 show the distribution of hours for multifamily units with the heat index levels in the danger and caution conditions. For the heat index metric-based analysis, we included the extreme danger

Table 6
Annual electricity and natural gas cost saving per multifamily housing unit.

Annual electricity cost saving per unit	Annual natural gas cost saving per unit	Annual total energy cost saving per unit
$300	- $117 (an increase)	$183

Table 7
Summary of energy performance of multifamily buildings under the 2058 weather for the baseline and retrofit conditions.

Building ID	2058 Baseline							2058 Retrofit						
	Peak electricity (kW)	Annual electricity usage (kWh)	Annual natural gas usage (kWh)	Annual site energy usage (kWh)	Annual electricity cost ($)	Annual natural gas cost ($)	Annual total energy cost ($)	Peak electricity (kW)	Annual electricity usage (kWh)	Annual natural gas usage (kWh)	Annual site energy usage (kWh)	Annual electricity cost ($)	Annual natural gas cost ($)	Annual total energy cost ($)
7,805,385	20	35,863	38,068	73,931	$9677	$1624	$11,301	18	29,385	56,353	85,738	$7929	$2404	$10,333
7,805,386	72	125,024	94,095	219,119	$34,795	$4014	$38,809	62	107,031	125,874	232,905	$29,787	$5370	$35,157
7,805,387	38	67,166	54,574	121,741	$17,854	$2328	$20,182	35	54,110	82,803	136,913	$14,384	$3533	$17,916
7,805,388	22	38,446	29,711	68,158	$10,351	$1268	$11,618	19	30,122	48,509	78,631	$8110	$2069	$10,179
7,805,389	11	38,941	45,519	84,460	$9564	$1942	$11,506	11	39,336	59,999	99,335	$9661	$2560	$12,221
7,805,390	28	56,167	44,103	100,270	$14,842	$1882	$16,724	26	44,790	64,084	108,874	$11,836	$2734	$14,570
7,805,391	31	52,771	35,892	88,663	$14,195	$1531	$15,726	27	40,703	62,317	103,020	$10,949	$2659	$13,608
7,805,392	39	64,897	48,631	113,528	$17,757	$2075	$19,831	33	51,623	79,389	131,013	$14,125	$3387	$17,512
7,805,393	67	134,312	104,847	239,159	$35,767	$4473	$40,239	60	112,085	139,948	252,034	$29,848	$5970	$35,818
7,805,394	12	43,541	46,056	89,596	$10,674	$1965	$12,639	12	43,696	51,764	95,460	$10,712	$2208	$12,920
7,805,399	13	22,585	23,623	46,207	$6028	$1008	$7036	12	17,201	37,544	54,745	$4591	$1602	$6193
7,805,400	16	57,166	55,599	112,766	$13,958	$2372	$16,330	16	57,310	61,118	118,428	$13,993	$2607	$16,600
7,805,419	39	57,621	43,876	101,497	$15,459	$1872	$17,331	34	41,853	89,062	130,915	$11,229	$3800	$15,028
Total	407	794,500	664,593	1459,094	$210,921	$28,353	$239,274	365	669,245	958,766	1628,011	$177,153	$40,903	$218,056

and danger levels as "danger," and included extreme caution and caution as "caution." The heat index was calculated in each hour of the five heatwave days (a total of 120 h) between July 6 and 10 for the 2018 and projected 2058 weather data. We calculated the number of hours under different heat index levels for the buildings with normal AC operation, AC operation with increased CST, and no AC operation. We analyzed the heat index metrics of the buildings under the baseline and retrofit conditions with grid power available and power outage during the heatwave period.

Fig. 14 presents the number of hours occupants potentially face the extreme danger or danger level based on the heat index. Fig. 14A, B, D, and E show that multifamily units with AC and either normal or increased CST do not face a danger level if there are no power outages. However, if multifamily units do not have AC, but still are connected to the power grid, they may face a heat danger condition of 113 h (94 % of time) in 2018 and 120 h (all the time) in 2058. Multifamily units still use electric appliances during the heatwave period, and this causes the indoor air temperature to increase, which cannot be suppressed without an AC system. If they are retrofitted with the aforementioned ECM package, the danger hours can be reduced to 57 (by 50 %) in 2018 and 79 h (by 34 %) in 2058. This confirms that AC is a life-essential need for residents during heatwaves.

Fig. 15 shows the heat index danger hours under the 2018 and 2058 heatwave and power outages for the buildings with baseline and retrofit conditions. The points outside the whisker lines are determined to be outliers. If buildings lose power from the grid during the heatwave event, 90 % of multifamily units may face danger conditions with a median of 21 h in 2018, and the same would be true for 95 % with a median of 50 h in 2058. If they are retrofitted, they would not face danger conditions during the heatwave period coincident with power outage. Although the retrofitted buildings do not face the danger risk, they may face heat caution.

Fig. 16 and Fig. 17 show the distribution of the number of heat stress hours when the buildings are facing the heatwave event. The heat stress hours are derived based on the sum of hours when the SET exceeds 30 °C during the heatwave event between July 6 and 10 under the 2018 and 2058 weather data. We calculated the heat stress hours for the buildings with normal AC operation, AC operation with increased CST, and no AC operation for the baseline and retrofit conditions under the scenarios of grid power available and power outage during the heatwave period.

Fig. 16 presents the distribution of heat stress hours for the buildings with grid power available during the heatwave event. Fig. 16A and D are for buildings with normal AC operation scenarios in 2018 and 2058. The baseline buildings may face heat stress hours, with a median of five hours in 2018 and six hours in 2058. Fig. 15B and E show the increased CST AC operation scenario, and the baseline buildings may face heat stress hours with a median of 18 h in 2018 and 22 h in 2058. However, if those buildings are retrofitted, no heat stress risk is observed.

Fig. 16C and F illustrate the distribution of heat stress hours for the buildings without mechanical cooling systems but still connected to the power grid. These buildings still have power available for other electric equipment, such as lighting and appliances, but no AC system. The electric energy usage contributes to the internal heat gain, thus observing increased SET during the heatwave period. This results in the buildings experiencing a heat stress risk of 120 h, which means they are under heat stress all the time during the five-day heatwave event. If these buildings are retrofitted, the heat stress risk can be reduced to a median of 59 h in 2018 and 79 h in 2058. This confirms that AC is needed to ensure the thermal safety of residents in the buildings and also that the retrofits can significantly reduce heat stress hours.

Fig. 17 shows the heat stress hours under the 2018 and 2058 heatwave and power outages for multifamily buildings with baseline and retrofit conditions. If buildings lose power from the grid during the heatwave event, all housing units would face heat stress conditions, with a median of 109 h in 2018 and 112 h in 2058. If they are retrofitted, the heat stress hours would be reduced by 62 % to a median of 41 h in 2018,

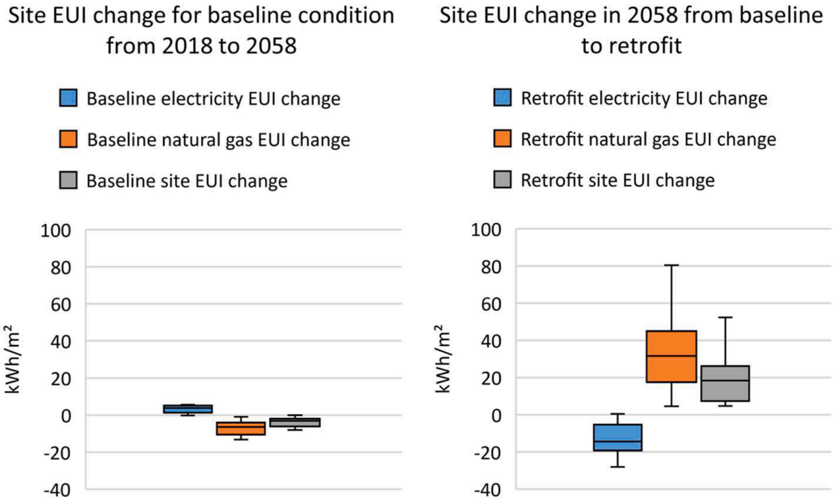

Fig. 12. Electricity, natural gas, and site EUI change boxplot from the weather data change for (left) the baseline condition from 2018 to 2058 weather, and (right) 2058 from the baseline to retrofit condition.

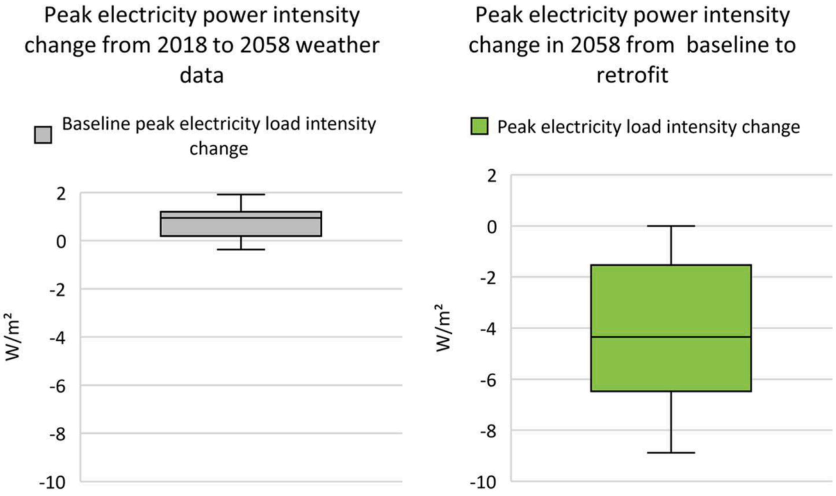

Fig. 13. Peak electricity power intensity change boxplot from the weather data change for (left) the baseline condition from 2018 to 2058 weather and (right) 2058 from the baseline to retrofit condition.

and by 46 % to a median of 61 h in 2058.

4. Discussion

4.1. *Major findings*

The baseline multifamily buildings in disadvantaged communities in El Monte under 2018 weather conditions show a higher heating natural gas EUI (median 21.3 kWh/m^2) than the electricity EUI for cooling (median 16.3 kWh/m^2). The climate change reflected in 2058 future weather conditions shows that the buildings will have a 26 % increase in cooling electricity EUI (to 20.6 kWh/m^2) and a 31 % reduction in heating natural gas EUI (to 14.8 kWh/m^2) compared to the baseline EUI in 2018. This tells us there needs to be more attention given to the increased cooling load from buildings in the future. The climate change results in an annual total electricity usage increase of 7 % and a natural gas reduction of 8 % for the multifamily buildings from 2018 to 2058.

Under the 2018 weather conditions, the retrofit ECM package, composed of seven measures (cool roof, cool wall, window solar film, blinds, natural ventilation, air sealing, and ceiling fan), brings an electricity use savings of 17 %. Also, the package contributes to a 19 % peak electricity demand reduction. However, this package increases natural gas usage by 53 %, resulting in a site energy increase of 12 %. Among the measures in the ECM package, the cool roof, cool wall, and solar film for windows reduce cooling energy usage during the summer, but they contribute to a greater increase in heating load during the winter. The retrofit package reduces the peak electricity load by 19 % and reduces the annual energy cost by $183 per housing unit. The peak electricity load occurs on the hottest day 7/6/2018 at 6 pm. The study uses the TOU-based electricity rate structure with a peak electricity usage rate between 4 pm and 9 pm (OpenEI, 2023). Aligned with California's load flexibility program, the electricity load shifting from peak hours (expensive hours) to less peak hours (cheap hours) can contribute to mitigating the grid burden and resident electricity costs even further (G. CEC, 2023).

California has more renewable and hydropower sources for electricity generation than any other state in the U.S., yielding electricity CO_2e emission factors lower than the U.S. average. The CO_2e emission factor is 272 g/kWh for electricity and 225 g/kWh for natural gas for California. Although the site energy increases by 12 %, the increase of the CO_2e emission intensity is reduced to 9 %. Therefore, California has a less favorable CO_2e emission reduction from the electricity savings compared to other U.S. states.

Heat exposure under the heat danger and caution conditions can be

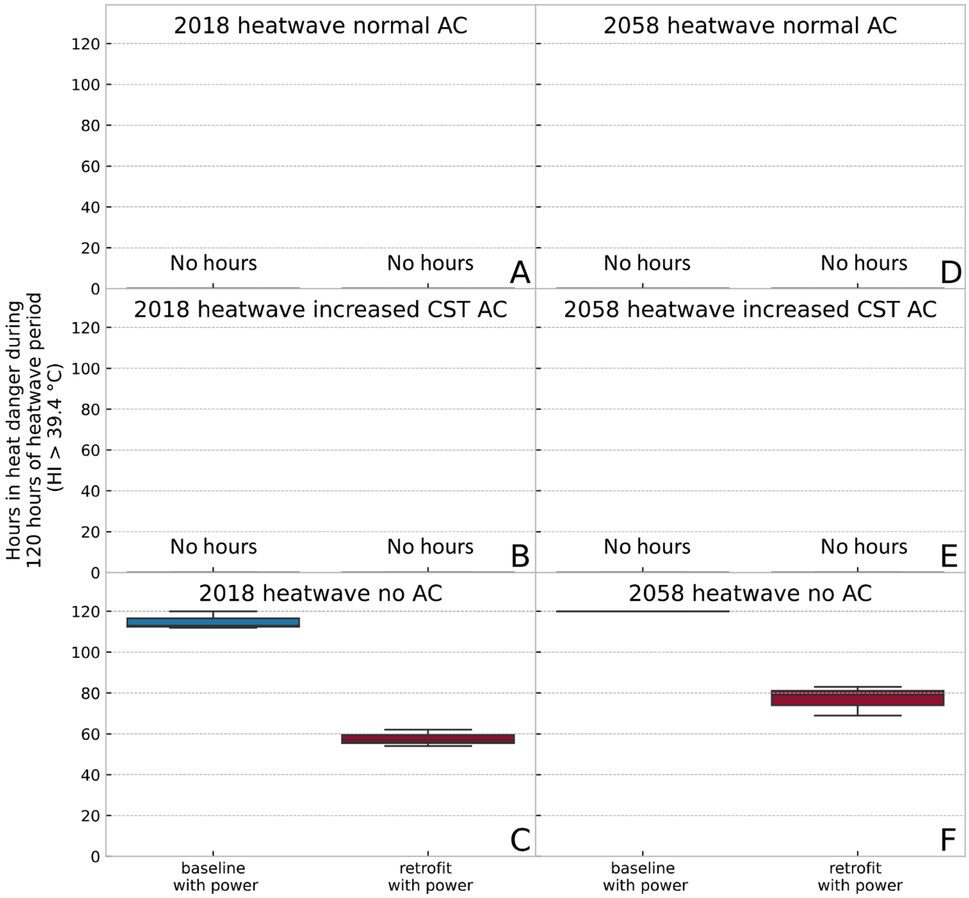

Fig. 14. Hours in danger boxplots for multifamily buildings in baseline and retrofit condition with (A) normal AC during the 2018 heatwave period, (B) AC operation with increased CST during the 2018 heatwave period, (C) no AC operation during the 2018 heatwave period, (D) normal AC during 2058 heatwave period, (E) AC operation with increased CST during the 2058 heatwave period, and (F) no AC operation during the 2058 heatwave period.

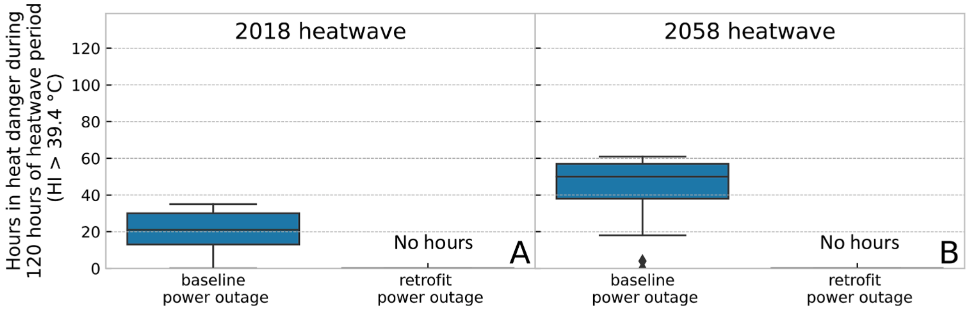

Fig. 15. Hours in danger boxplots for multifamily buildings of baseline and retrofit condition during the power outage in (A) the 2018 heatwave period, and (B) the 2058 heatwave period.

evaluated using the heat index metric. During the five days (120 h) of heatwave events of July 6 to 10 in 2018 and 2058, if buildings had grid power and were mechanically cooled by either normal CST or increased CST, they would not face any heat danger or caution conditions. However, if buildings were connected to the power grid but not mechanically cooled (no AC), they would face the heat danger conditions all the time. This is partly caused by the internal heat gains from appliance usage. During a heatwave event, it is strongly recommended to minimize the use of appliances to reduce internal heat gains. The retrofit could reduce the heat danger hours by 50 % in 2018 and 34 % in 2058 for the housing units with grid power but without mechanical AC systems.

If the buildings lose power due to the grid power interruption during the heatwave period, about 90 % of the housing units would experience about 21 h of heat danger conditions and 91 h of heat caution conditions in 2018, which would increase to about 50 h of danger and 64 h of caution with the 2058 future weather. The retrofit helps to eliminate the heat danger condition, but many hours of heat caution conditions remain. Among the measures from the ECM package, natural ventilation contributes the most to mitigating the heat-related danger risk during the power outages, as indoor temperature is higher than outdoor temperature, especially during night hours. Ceiling fans increase air movement near human skin, helping occupants maintain thermal comfort under the increased indoor air temperatures (Luo et al., 2021). However, there is a limitation to use the heat index metric for the ceiling fan measure, as it does not reflect the elevated air speed when evaluating heat-related health risk levels.

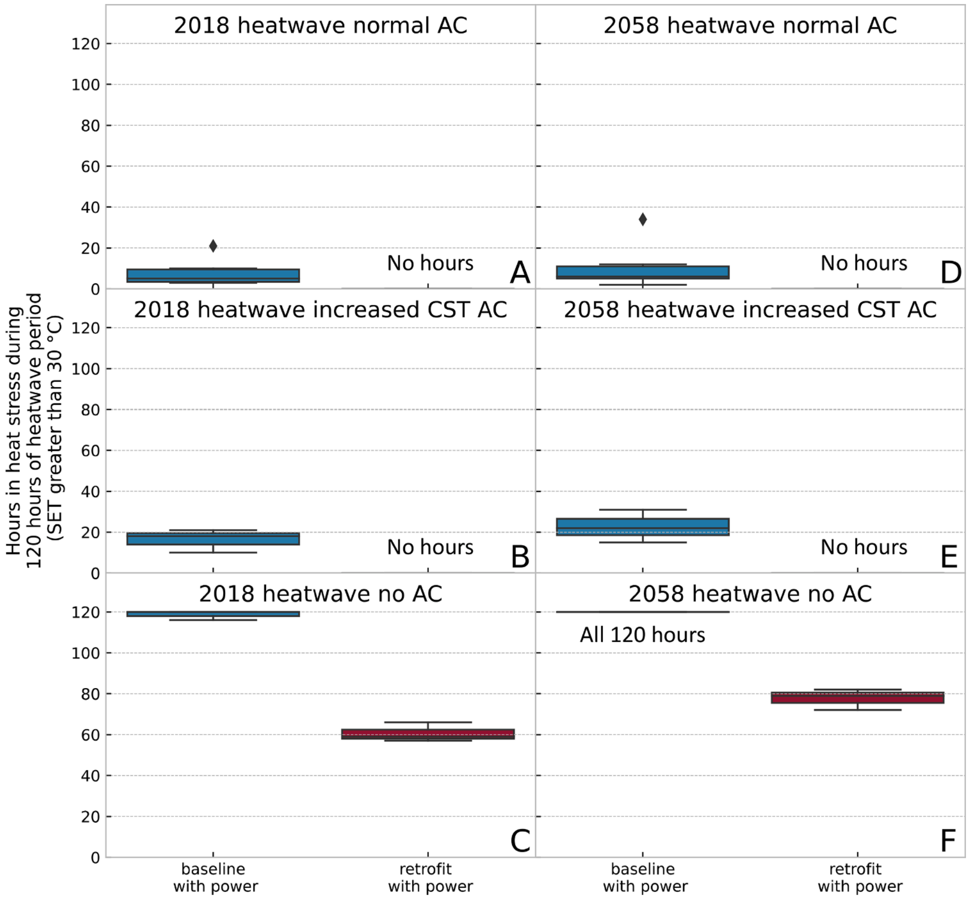

Fig. 16. Hours in heat stress (SET greater than 30 °C) boxplots for the buildings in baseline and retrofit condition with (A) normal AC during the 2018 heatwave period, (B) AC operation with increased CST during the 2018 heatwave period, (C) no AC operation during the 2018 heatwave period, (D) normal AC during the 2058 heatwave period, (E) AC operation with increased CST during the 2058 heatwave period, and (F) no AC operation during the 2058 heatwave period.

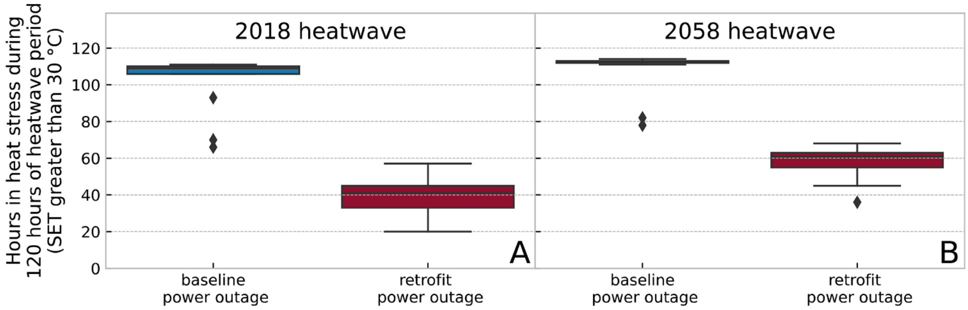

Fig. 17. Hours in heat stress boxplots for multifamily buildings of baseline and retrofit condition during the power outage in (A) the 2018 heatwave period, and (B) the 2058 heatwave period.

Heat stress also can be evaluated during the heatwave period using the SET metric. If AC systems can be operated normally during the heatwave event, the housing units face about five heat stress hours. If buildings can run AC with the increased CST, they may face 18 heat stress hours. As the SET metric includes the indoor air temperature as a key factor, increasing the CST from 23.9 °C to 25.6 °C leads to slightly more heat stress hours (about 10 h out of the entire 120 h of the heatwave period) for the baseline multifamily buildings. Nevertheless, the CST increase serves as an effective demand response strategy during the heatwave period to mitigate grid burden. If the multifamily units with AC systems are retrofitted, they would not experience heat stress conditions. However, if buildings have power but do not have AC, occupants would be exposed to heat stress hours all the time during the heatwave period. This is partly caused by the internal heat gains from appliance use. The retrofit can reduce 34 % of the heat stress hours for these buildings. If buildings are under power outage conditions, all units would face the heat stress condition all the time (120 h). If retrofitted, the heat stress hours would be reduced to 41 h (a 62 % reduction in 2018) and to 61 h (a 46 % reduction in 2058).

4.2. Policy implications for LA County's Socalren multifamily program

Findings of the energy and thermal resilience performance of the studied buildings have implications on LA County's multifamily program under the Southern California Regional Energy Network (SoCalREN) (G. County of Los Angeles, 2023).

Utility company-oriented programs run by investor-owned utilities typically focus on a carbon-centric lens. However, SoCalREN and other new movements towards equity-oriented programs tend to take a more human-centric approach (SoCalREN, 2022). The human-centric lens that considers non-energy benefits will be critical for SoCalREN equity programs. If SoCalREN is considering adding the ECM package to their multifamily program, they may want to complement this offering with behavior or other changes like fuel switching that could reduce natural gas use. The funding for high-efficiency electric appliances, including heat pumps for space heating and cooling, is available from the federal Inflation Reduction Act for low-income households by DOE and CEC (G. CEC, 2023; G. DOE, 2023). In a carbon-centric world, the benefits of the ECM package with passive and low power measures do not outweigh the costs. This paper points out that the passive and low power measures would lead to increased energy use at the site level, and as a result increases in CO_2 emissions. This is true for both the 2018 and 2058 timeframe. When considering a human-centric view (including non-energy benefits such as health benefits), passive and low power measures lead to both energy cost savings and decreases in dangerous heat conditions. When installed as a package, the measures lead to a $183 decrease in energy bills per unit and can significantly reduce the number of hours in danger for households—especially those without AC. If the buildings are retrofitted with the studied ECM package, the heat-related health risks decline significantly.

In a human-centric lens, it is vital that programs support AC in multifamily buildings that currently do not have it. SoCalREN may want to offer equitable AC (for homes without AC) for health reasons. AC, ideally coupled with ECMs, is a life-essential need during heatwaves. Households without AC experience an extraordinarily high number of hours in danger of heat-related risks, and this is expected to increase significantly by 2058. It is critical to consider the very real threat of potential power outages. SoCalREN may want to work towards both ECM measures and options that support reliable energy sources because when power outages occur almost every summer, all multifamily units in this study are potentially at risk of heat-related danger conditions.

When assessing the benefits, it is important to consider not only current impacts but also future impacts, given changing temperatures due to climate changes. SoCalREN should take a forward-looking view. Heat stress will increase due to climate change, thus the benefits of installing these measures improve over time. That is, over time, the increase in site energy use and carbon emissions decreases due to the heating energy reduction and cooling energy increase caused by rising temperatures. The latest LA County board report addressed the importance of the heat-related risk and indicated a plan to develop measures for heat-resilient buildings from future climate change (County of Los Angeles Excutive Office Board of Supervisors, 2023).

Given a SoCalREN program view, there is the case for including passive and low power measures, but notably, the study treats these as a package of measures rather than as individual options; thus the results apply only to programs that install the full package of measures. SoCalREN may consider using findings from the study for program design, which include the energy efficient measures as a group. All results presented here are based on the inclusion of all seven measures in the analysis. Program benefits would be much less if only a few of the measures were installed. Currently, among measures included in the analysis, air sealing measure is deemed to have savings and costs already determined. The program would need to determine savings and costs associated with any added custom measure or submit papers for deemed savings.

The studied ECM package would also require revamping the program to focus on heat mitigation. Any revamp of the program may take significant resources to begin to include some of the different measures included in the study. Additionally, the program would need to determine how to include some of the measures (e.g., cool walls), as painting large multifamily buildings requires a different skill set. There are cautions for inclusion of ceiling fan measures in the program and adding ACs for vulnerable multifamily homes. The use of ceiling fans has been shown to enable lower AC energy costs while still maintaining the temperature felt by occupants. However, ceiling fans alone should not be used when indoor temperature is high (United States Environmental Protection Agency, 2006; Fraserhealth, 2023). The presence of AC in tenant units removes the danger of heat during heatwaves, as long as there is power to the AC. If the program were to add ACs to tenant units currently without cooling for heat mitigation, decision makers should carefully weigh the benefit against the added costs associated with running those AC units, especially for low-income households. On the positive side, the use of interior shading with blinds and natural ventilation from windows are measures that are behavioral, assuming blinds are present and the windows can be opened. As such, the program could begin to include those measures without much trouble, albeit with low potential impact.

5. Conclusions

This paper summarizes the methodology and main findings from the modeling and analysis of multifamily buildings located in disadvantaged communities in LA County. We screened all census tracts in LA County and ranked them to down-select four census tracts in the city of El Monte that need more attention. Thirteen multifamily buildings with 108 units were selected in those four census tracts for the study. We developed a baseline building dataset in CityBES to model the 13 buildings for energy and resilience performance. Then we developed an ECM package with seven passive and low-power ECMs for the retrofit scenario: cool roof, cool wall, solar film in windows, air sealing, internal blinds for windows, natural ventilation, and ceiling fan. We conducted building energy simulations using the 2018 actual microclimate data and the projected 2058 future weather data based on the IPCC RCP 8.5 climate change scenario.

The future climate conditions lead to an increase in annual electricity usage by 7 % due to cooling load increase, and a decrease in natural gas usage by 8 % from the reduced heating load due to climate warming in 2058 compared to the 2018 weather condition. Under the 2018 weather condition, the retrofit scenario with the ECM package can save 17 % of annual electricity consumption from the reduced cooling loads but increase 53 % of the annual natural gas due to the heating penalty during the winter season, resulting in a 12 % annual site energy increase in 2018. The ECM package reduces the peak electricity load by 19 % and reduces the annual energy cost by about $183 per housing unit. Under the 2058 projected weather, the ECM package can achieve an 11 % annual electricity savings but with a 47 % increase in annual natural gas usage, resulting in an overall 10 % increase in the annual total site energy.

We evaluated the heat exposure of residents under the danger and caution conditions using the heat index metric, and under heat stress hours using the SET metric for the five-day (120-hour) heatwave from July 6 to 10. If the buildings have grid power and are mechanically cooled, they would not face any heat danger or caution conditions. This confirms that AC is a life-essential need for residents during a heatwave. The multifamily buildings without AC systems but still connected to the power grid would face heat danger conditions and heat stress hours almost all hours during the heatwave period, both in 2018 and 2058. During a heatwave event, it is strongly recommended to minimize the use of electric appliances, to reduce internal heat gains. If the multifamily buildings were retrofitted with the ECM package, the number of danger hours could be reduced by 50 % in 2018 and 34 % in 2058.

If the current baseline multifamily buildings lose power from the grid during the heatwave event, occupants would face significantly more heat-related danger conditions, from a median of 21 h in 2018 to a median of 50 h in 2058 due to the change in climate. However, if the buildings are retrofitted, they would not face danger conditions based on the heat index metric during the heatwave period coincident with power outages in current and future weather conditions. If using the SET metric, all the baseline multifamily housing units would face the heat stress condition all the time during the five-day heatwave period (120 h) due to a power outage. If retrofitted, the heat stress hours would be reduced to 41 h in 2018 (a 62 % reduction) and to 61 h in 2058 (a 46 % reduction).

In summary, multifamily apartment units in disadvantaged communities in LA County, especially those without AC, are facing a growing risk of indoor overheating during hot summer days. The heat stress risk increases due to climate change. Retrofitting these housing units with passive envelope measures and low-energy active measures (such as a ceiling fan) can reduce utility costs for households, and more importantly can significantly reduce danger-level heat risk during the worst case: a heatwave with coincident power outages. When making decisions about the retrofits (energy efficiency upgrades, decarbonization) of buildings to reduce utility costs and carbon emissions, policymakers and building owners should consider the co-benefits of occupant health and thermal safety.

Future work can assess energy and thermal resilience impacts from California's statewide decarbonization efforts of switching from gas heating to heat pumps. Further modeling and analysis in the future work includes: 1) quantifying energy savings and heat-related impact for each individual passive or low-power measure to be prioritized for SoCalREN, 2) evaluating impacts of fuel switching with all electric systems for heating, service hot water, and cooking on the peak demand of the grid, 3) evaluating how electric load shifting from peak demand hours to less demand hours contribute to mitigating the grid burden from the residential building sector and reduce the residents' electric cost under the TOU rate structure, and 4) expanding the energy, carbon, and heat-related impact analysis for more multifamily buildings at a broader scale in LA County.

CRediT authorship contribution statement

Sang Hoon Lee: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Tianzhen Hong:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Minh Le:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Lujuana Medina:** Writing – review & editing, Project administration, Conceptualization. **Yujie Xu:** Writing – review & editing, Investigation, Data curation. **Alastair Robinson:** Writing – review & editing, Project administration, Methodology, Data curation. **Mary Ann Piette:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

All co-authors declare there is no conflict of interest in the reported work.

Data availability

Data will be made available on request.

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References

Aburas, M., Soebarto, V., Williamson, T., Liang, R., Ebendorff-Heidepriem, H., & Wu, Y. (2019). Thermochromic smart window technologies for building application: A review. *Applied Energy, 255*, Article 113522. https://doi.org/10.1016/j.apenergy.2019.113522

Alessandrini, J. M., Ribéron, J., & Silva, D. Da (2019). Will naturally ventilated dwellings remain safe during heatwaves? *Energy and Buildings, 183*, 408–417. https://doi.org/10.1016/j.enbuild.2018.10.033

ASHRAE, ANSI/ASHRAE Standard 55-2017 Thermal Environmental Conditions for Human Occupancy, (2017).

Attia, S., Levinson, R., Ndongo, E., Holzer, P., Kazanci, O. Berk, Homaei, S., Zhang, C., Olesen, B. W., Qi, D., Hamdy, M., & Heiselberg, P. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. *Energy and Buildings, 239*, Article 110869. https://doi.org/10.1016/j.enbuild.2021.110869

Bellia, L., Marino, C., Minichiello, F., & Pedace, A. (2014). An overview on solar shading systems for buildings. *Energy Procedia, 62*, 309–317. https://doi.org/10.1016/j.egypro.2014.12.392

California State Board of Equalization, California state board of equalization, residential building costs - Assessors Handbook section ah 531.30., 2020.

Campaniço, H., Soares, P. M. M., Cardoso, R. M., & Hollmuller, P. (2019). Impact of climate change on building cooling potential of direct ventilation and evaporative cooling: A high resolution view for the Iberian Peninsula. *Energy and Buildings, 192*, 31–44. https://doi.org/10.1016/j.enbuild.2019.03.017

CEC, California Adopts Goal to Make More Electricity Available Through Smarter Use, (2023). https://www.energy.ca.gov/news/2023-05/california-adopts-goal-make-more-electricity-available-through-smarter-use (accessed December 4, 2023).

CEC, Inflation reduction act residential energy rebate programs in California, (2023). https://www.energy.ca.gov/programs-and-topics/programs/inflation-reduction-act-residential-energy-rebate-programs-california (accessed December 4, 2023).

County of Los Angeles, LARIAC Los Angeles Region Imagery Acquisition Consortium, (2023). https://lariac-lacounty.hub.arcgis.com/(accessed November 20, 2023).

County of Los Angeles, SoCalREN Programs, (2023). https://socalren.org/(accessed November 20, 2023).

County of Los Angeles Excutive Office Board of Supervisors, REPORT BACK ON DEVELOPING A COUNTY EXTREME HEAT ACTION FRAMEWORK, 2023.

DOE, EnergyPlus, (2023). https://energyplus.net/.

DOE, About the Home Energy Rebates, (2023). https://www.energy.gov/scep/home-energy-rebates-programs (accessed December 4, 2023).

Faust, John, August, Laura, Slocombe, Andrew, Prasad, Shankar, Wieland, Walker, & Cogliano, Vincent (2021). Carol Monahan Cummings, California's environmental justice mapping tool: Lessons and insights from calenviroscreen. *Environmental Law Reporter, 51*, 10684–10687.

Fraserhealth, Fans in Extreme Heat FAQ, (2023). https://www.fraserhealth.ca/-/media/Project/FraserHealth/FraserHealth/Health-Topics/Sun-and-heat-safety/Fans_in_Extreme_Heat_FAQ.pdf?la=en&rev=504b5365d9b94b3bb4d b6a992e3a93e9&hash=B8B28840CFFB046D3961C5A157B142C7AE2ECD2E#:~:Text=Fans%20do%20not%20cool%20the,your%20body%20to%20 get%20hotter.&text=to%20blow%20cooler%20air%20from%20outside%20into%20a%20room.&text=Do%20not%20use%20a%20fan,or%20higher%20than%20indoor%20temperature. (accessed November 20, 2023).

GTI Energy, Source Energy and Emissions Analysis Tool Residential Buildings, (2023). https://cmicseeatcalc.gti.energy/ResidentialBuildings.

Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J., & Boland, J. (2016a). Drivers and barriers to heat stress resilience. *The Science of the Total Environment, 571*, 603–614. https://doi.org/10.1016/j.scitotenv.2016.07.028

Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J., & Boland, J. (2016b). Heat stress risk and resilience in the urban environment. *Sustainable Cities and Society, 26*, 278–288. https://doi.org/10.1016/j.scs.2016.06.019

Hatvani-Kovacs, G., Bush, J., Sharifi, E., & Boland, J. (2018). Policy recommendations to increase urban heat stress resilience. In *Urban Climate, 25* pp. 51–63). https://doi.org/10.1016/j.uclim.2018.05.001

Homaei, S., & Hamdy, M. (2021). Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric. *Building and Environment, 201*, Article 108022. https://doi.org/10.1016/j.buildenv.2021.108022

Hong, T., Chen, Y., Lee, S.H., Piette, M.A. CityBES: A Web-based Platform to Support City-Scale Building Energy Efficiency, in: 2016: P. 10.

Hong, T., Malik, J., Krelling, A., O'Brien, W., Sun, K., Lamberts, R., & Wei, M. (2023). Ten questions concerning thermal resilience of buildings and occupants for climate adaptation. *Building and Environment, 244*, Article 110806. https://doi.org/10.1016/j.buildenv.2023.110806

County of Los Angeles, Energy Upgrade California - Retrofit California: Better Buildings Program Overview, 2014. https://doi.org/10.2172/1126788.

IEA, IEA EBC Annex 80 - Resilient Cooling of Buildings, (2023). https://annex80.iea-ebc.org/.

ISO, ISO 52000-1:2017 Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures, 2017.

Jones, Andrew D., Rastogi, Deeksha, Vahmani, Pouya, Stansfield, Alyssa, Reed, Kevin, Thurber, Travis, Ullrich, Paul, Rice, Jennie S., IM3/HyperFACETS Thermodynamic Global Warming (TGW) Simulation Datasets (v1.0.0) [Data set] MSD-LIVE Data Repository, (2023). https://doi.org/10.57931/1885756.

Keramitsoglou, I., Sismanidis, P., Analitis, A., Butler, T., Founda, D., Giannakopoulos, C., Giannatou, E., Karali, A., Katsouyanni, K., Kendrovski, V., Lemesios, G., Myrivili, E., Ordoñez, D., Varotsos, K. V., Vlastou, G., & Kiranoudis, C. T. (2017). Urban thermal risk reduction: Developing and implementing spatially explicit services for resilient cities. *Sustainable Cities and Society, 34*, 56–68. https://doi.org/10.1016/j.scs.2017.06.006

Krelling, A. F., Lamberts, R., Malik, J., & Hong, T. (2023). A simulation framework for assessing thermally resilient buildings and communities. *Building and Environment, 245*, Article 110887. https://doi.org/10.1016/j.buildenv.2023.110887

LA County, LA County Climate Vunlnerability Assessment, 2021.

LA County, Los Angeles County Climate Vulnerability Assessment - Web Tool, (2023). https://lacounty.maps.arcgis.com/apps/webappviewer/index.html?id=c78e929d004846bb993958b49c8e8e65.

LA County, Equity Explorer, (2023). https://experience.arcgis.com/experience/9d7a43397ea84ab98a534be5b5376fba.

LBNL, CityBES, (2023). https://citybes.lbl.gov/(accessed May 26, 2023).

LBNL, Google, Los Angeles County Internal Services Department, Los Angeles County Urban Heat Island and Building Performance Research Project, 2023.

Lee, S. H., & Levinson, R. (2023). *Cool envelope benefits in future typical weather and heatwave conditions for single-family homes in Los Angeles (accepted)*.

Levinson, R., Arens, E., Bozonnet, E., Corrado, V., Gilbert, H., Holzer, P., Jaboyedoff, P., Krelling, A., Machard, A., Miller, W., Tootkaboni, M. P., Selkowitz, S., & Zhang, H. (2023). *Policy recommendations from iea EBCAnnex 80: Resilient cooling of buildings*. LBNL. https://doi.org/10.20357/B7288C

Los Angeles Department of Water and Power, Comprehensive Affordable Multifamily Retrofits Program, (2023). https://ladwpcamr.com/.

Luo, M., Zhang, H., Wang, Z., Arens, E., Chen, W., Bauman, F. S., & Raftery, P. (2021). Ceiling-fan-integrated air-conditioning: Thermal comfort evaluations. *Building Cities, 2*. https://doi.org/10.5334/bc.137

Maizlish, N., Delaney, T., Dowling, H., Chapman, D. A., Sabo, R., Woolf, S., Orndahl, C., Hill, L., & Snellings, L. (2019). California healthy places index: Frames matter. *Public Health Reports, 134*, 354–362. https://doi.org/10.1177/0033354919849882

Moazami, A., Nik, V. M., Carlucci, S., & Geving, S. (2019). Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions. *Applied Energy, 238*, 696–720. https://doi.org/10.1016/j.apenergy.2019.01.085

Mola, M., Feofilovs, M., & Romagnoli, F. (2018). Energy resilience: Research trends at urban, municipal and country levels. *Energy Procedia, 147*, 104–113. https://doi.org/10.1016/j.egypro.2018.07.039

OEHHA, CalEnviroScreen 4.0, (2023). https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-40.

Public Health Alliance of Southern California, California Healthy Places Index, (2023). https://www.healthyplacesindex.org/.

OpenEI, Southern California Edison Co TOU-d-4-9PM, (2023). https://apps.openei.org/USURDB/rate/view/62d9763989f9d92b914b5a2b#1_Basic_Information.

Ouzeau, G., Soubeyroux, J. M., Schneider, M., Vautard, R., & Planton, S. (2016). Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble. *ClimateSERV, 4*, 1–12. https://doi.org/10.1016/j.cliser.2016.09.002

Park, Jiwon, Ho Lee, Kwang, Lee, Sang Hoon, & Hong, Tianzhen (2023). Benefits assessment of cool skin and ventilated cavity skin: Saving energy and mitigating heat and grid stress (accepted). *Building and Environment*.

Rafael, S., Martins, H., Sá, E., Carvalho, D., Borrego, C., & Lopes, M. (2016). Influence of urban resilience measures in the magnitude and behaviour of energy fluxes in the city of Porto (Portugal) under a climate change scenario. *The Science of the Total Environment, 566–567*, 1500–1510. https://doi.org/10.1016/j.scitotenv.2016.06.037

Raji, B., Tenpierik, M. J., & Van Den Dobbelsteen, A. (2015). The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews, 45*, 610–623. https://doi.org/10.1016/j.rser.2015.02.011

Rosado, P. J., & Levinson, R. (2019). Potential benefits of cool walls on residential and commercial buildings across California and the United States: Conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. *Energy and Buildings, 199*, 588–607. https://doi.org/10.1016/j.enbuild.2019.02.028

Rubin, M., Powles, R., & Von Rottkay, K. (1999). Models for the angle-dependent optical properties of coated glazing materials. *Solar Energy, 66*, 267–276. https://doi.org/10.1016/S0038-092X(99)00029-8

Samuelson, H. W., Baniassadi, A., & Gonzalez, P. I. (2020). Beyond energy savings: Investigating the co-benefits of heat resilient architecture. *Energy, 204*, Article 117886. https://doi.org/10.1016/j.energy.2020.117886

Sheng, M., Reiner, M., Sun, K., & Hong, T. (2023). Assessing thermal resilience of an assisted living facility during heat waves and cold snaps with power outages. *Building and Environment, 230*, Article 110001. https://doi.org/10.1016/j.buildenv.2023.110001

Shin, D. H., Kim, S. H., Kim, J. H., & Kim, S. (2022). Experimental analysis of low-cost energy retrofit strategies for residential buildings to overcome energy poverty. *Case Studies Thermal Engineering, 32*, Article 101874. https://doi.org/10.1016/j.csite.2022.101874

Siu, C. Y., O'Brien, W., Touchie, M., Armstrong, M., Laouadi, A., Gaur, A., Jandaghian, Z., & Macdonald, I. (2023). Evaluating thermal resilience of building designs using building performance simulation – A review of existing practices. *Building and Environment, 234*, Article 110124. https://doi.org/10.1016/j.buildenv.2023.110124

SoCalGas, NATURAL GAS RATES EXPLAINED, (2023). https://www.socalgas.com/pay-bill/understanding-your-bill/natural-gas-prices-explained.

SoCalREN, Southern California Regional Energy Network Energy Efficiency 2024-2031 Portfolio Plan, 2022. https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M460/K301/460301904.PDF.

Steadman, R. G. (1979). The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *Journal of Applied Meteorology and Climatology, 18*, 861–873. https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2

Sun, K., Specian, M., & Hong, T. (2020). Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. *Building and Environment, 177*, Article 106842. https://doi.org/10.1016/j.buildenv.2020.106842

Sun, K., Zhang, W., Zeng, Z., Levinson, R., Wei, M., & Hong, T. (2021). Passive cooling designs to improve heat resilience of homes in underserved and vulnerable communities. *Energy and Buildings, 252*, Article 111383. https://doi.org/10.1016/j.enbuild.2021.111383

United States Environmental Protection Agency, Excessive heat events guidebook, 2006. https://www.epa.gov/sites/default/files/2016-03/documents/eheguide_final.pdf (accessed November 20, 2023).

URISA, 2022 URISA ESIG Award Equity Explorer, County of Los Angeles, (2022). https://www.urisa.org/clientuploads/directory/Documents/ESIG/2022_Winners/LACounty_EquityExplorer_ESIG2022.pdf (accessed November 16, 2023).

URISA, Excellence In GIS - Los Angeles County (California): Equity Explorer Tool Tell a Friend About This EventTell a Friend, (2022). https://urisa-portal.org/events/EventDetails.aspx?id=1735667 (accessed November 16, 2023).

US D.O.E., EnergyPlus Version 22.2.0 Documentation Engineering Reference, 2022.

USGBC U.S. Green Building Council, Resilient by Design: USGBC Offers Sustainability Tools for Enhanced Resilience, 2018. https://www.usgbc.org/resources/resilient-design-usgbc-offers-sustainability-tools-enhanced-resilience.

Wilson, A. (2015). *LEED pilot credits on resilient design adopted*. Brattleboro, VT, USA: Resilient Design Institute, Resilient Design Institute. https://www.resilientdesign.org/leed-pilot-credits-on-resilient-design-adopted/.

Xu, L., Tong, S., He, W., Zhu, W., Mei, S., Cao, K., & Yuan, C. (2022). Better understanding on impact of microclimate information on building energy modelling performance for urban resilience. *Sustainable Cities and Society, 80*, Article 103775. https://doi.org/10.1016/j.scs.2022.103775

Zeng, Z., Zhang, W., Sun, K., Wei, M., & Hong, T. (2022). Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves. *Building and Environment, 210*, Article 108694. https://doi.org/10.1016/j.buildenv.2021.108694

Zhang, C., Kazanci, O. B., Levinson, R., Heiselberg, P., Olesen, B. W., Chiesa, G., Sodagar, B., Ai, Z., Selkowitz, S., Zinzi, M., Mahdavi, A., Teufl, H., Kolokotroni, M., Salvati, A., Bozonnet, E., Chtioui, F., Salagnac, P., Rahif, R., Attia, S., Lemort, V., Elnagar, E., Breesch, H., Sengupta, A., Wang, L. L., Qi, D., Stern, P., Yoon, N., Bogatu, D.-I., Rupp, R. F., Arghand, T., Javed, S., Akander, J., Hayati, A., Cehlin, M., Sayadi, S., Forghani, S., Zhang, H., Arens, E., & Zhang, G. (2021). Resilient cooling strategies – A critical review and qualitative assessment. *Energy and Buildings, 251*, Article 111312. https://doi.org/10.1016/j.enbuild.2021.111312