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Assessing Thermal Resilience of an Assisted Living Facility during Heat Waves and Cold Snaps with Power Outages

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Abstract

Extreme hot and cold weather events are becoming more frequent, intense, and longer due to climate change. When these events occur coincidentally with power outages, the resulting extreme indoor temperatures pose a severe health hazard for occupants. This study conducted a holistic modeling and analysis of an assisted living facility, where senior residents live, to assess its thermal resilience performance under a six-day heat wave in 2015 and a three-day cold snap in 2021 with power outages. Impacts of 13 energy efficiency measures on thermal resilience and backup power capacity of the facility were evaluated. Three thermal resilience metrics: the SET (standard effective temperature) degree-hours, the Heat Index, and the Hours of Safety, were used and calculated from the EnergyPlus simulation models. Major findings are: (1) the facility would suffer from extreme temperatures during the cold and hot events without a power supply, not meeting the passive survivability requirements; (2) most passive envelope measures improve thermal resilience for both hot and cold events, but making the building envelope airtight results in conflicting performance between the hot and cold events; (3) natural ventilation is an effective measure to mitigate summer indoor overheating; and (4) the energy efficiency package can reduce backup power capacity by 19% for the three-day cold snap. It is recommended that building technologies and design strategies be evaluated to consider co-benefits of energy use, thermal resilience, and backup power needs through building energy codes or policies for existing and new buildings, which are transitioning for decarbonization and climate resilience.

Keywords

Thermal resilience, energy efficiency, passive survivability, backup power, assisted living facility, extreme temperature event

1. Introduction

1.1 Background

The impacts of climate change have been felt across the globe, exposing populations to more frequent and more severe weather events, including heat waves, wildfires, floods and storms (Howe, 2021; USGCRP, 2018). In 2020 and 2021, the U.S. experienced 42 independent, billion-dollar weather-related disasters, most notably unprecedented heat waves and wildfires in California, Oregon and Washington during fall 2020, a drought and heat wave in Colorado in summer and fall of 2021, and a winter storm in the southwest in February 2021 (NOAA, 2021; NOAA, 2022). Compound events—the occurrence of multiple hazards, disruptions, and/or extreme weather events—account for the growing impact of disasters (Field et al. 2012). As the primary driver of major power outages, extreme weather events pose a particular threat to energy infrastructure and critical services depending on power, compromising the operational capacity of buildings to maintain safe indoor environments. Treated as an extensive infrastructure, buildings are a fundamental component to the resilience of communities and the built environment. According to the United Nations Environment Programme (UNEP), resilience in buildings is “the ability of a building to meet the occupant’s needs and provide for a safe, steady and comfortable use in response to changing conditions outside” (UNEP, 2021).

In recent years, more and more events have exposed underlying vulnerabilities across the U.S. building stock. In 2017, a Florida nursing home experienced a three-day loss of main air conditioning because of the power system failure during Hurricane Irma, which led to 12 patient deaths due to the excess indoor temperature (Reisner et al. 2017). More recently, the 2021 Winter Storm Uri in Texas and the southern U.S. set off a series of power failures as the grid struggled to meet unanticipated demand due to record low temperatures. In Texas alone, more than four million homes and businesses lost power for multiple days. The prolonged drop in indoor temperatures led to over $18 billion in property damage primarily driven by burst pipes (Despart et al. 2021). Furthermore, recent analysis reveals that the death toll in Texas alone might have exceeded 702 deaths, nearly five times higher than the state’s official death toll (Lawrence 2021).

The physical and socioeconomic impacts of the winter storm were significantly amplified by the widespread blackouts, the result of multiple failures across Texas’ energy infrastructure system (Busby et al. 2021). Researchers anticipate an increase in extreme weather events will further strain key grid components, inducing more widespread outages and longer recovery times (Larsen et al. 2018). According to the EIA, the average U.S. household experienced an average of eight hours of power disruptions in 2020, doubling the average from five years prior. Beyond more frequent disruptions, major outage events have also risen. Since 2000, major power outages events (defined as affecting at least 50,000 customers and lasting one hour or more) due to weather-related events have increased by over 67%, impacting 83% of all U.S. utility customers (Shield et al., 2021). The median restoration time from such events is 117.5 hours—about five days.

Vulnerable and elderly populations are more subject to adverse health impacts due to the concurrence of heatwaves and power outages, especially with extreme hot days projected to increase in both intensity and magnitude (Dahl et al. 2019).   Heat risk presents the greatest threat to older populations, young children, pregnant women, as well as people with underlying medical conditions. (Belova et al., 2021). In the U.S., the population of people 65 years old and above was 54.1 million in 2019, representing 16% of the U.S. population (The Administration for Community Living & U.S. Department of Health and Human Services, 2021).

The emergence of compound disaster events necessitates solutions across all scales of infrastructure—from energy infrastructure systems to individual buildings. The resilience of a building is tied to the availability of reliable power; particularly for vulnerable populations dependent on power for medical devices and stable temperature environments, disruptions to the grid compromise critical building services. Outside of physical disruptions, the grid faces further stresses due to increasing energy demand, particularly during peak demand periods. Researchers found that blackouts were nearly four times more likely to occur during late afternoon periods due to the overlap between storm activity and increased electricity demand (Shield et al., 2021). Weather and temperature are two of the biggest drivers that dictate building energy use and inform utility projections to satisfy energy demand (Wuebbles et al. 2017). In the United States, cooling energy represents almost 30% of the peak load, yet is responsible for only 15% of annual electricity consumption (IEA and OECD 2018). Modeling these impacts in three U.S. cities, new research estimates that compound heat wave and grid failure events would expose over two-thirds of urban residents to dangerous heat stresses (Stone et al., 2020).

. Building energy resilience characterizes the ability to perform building energy services, such as heating, cooling, ventilation, critical plug loads, and shelter, during and in response to a major disruption. However, building codes and standards do not usually mandate backup power for buildings, outside of certain critical facilities. In Texas, on-site permanent generators are not required for senior housing or assisted living facilities, but are only required at nursing facilities where life-support systems are used (Rogalski, 2021). During the 2021 Winter Storm, more than 100 long-term care facilities in the Greater Houston area reported emergencies due to the power outages during the winter storm. Thirty-three facilities had to evacuate or transfer residents, and 25 of those reported having no backup power generators. Although many cities have designated public cooling centers for extreme heat emergencies, their cooling centers do not have backup power generators to maintain the continual operation of cooling systems in the event of an outage (Stone et al., 2021).

The lack of thermal resilience criteria within building codes makes it difficult for the public sector to explicitly consider alternative design strategies at the planning stage. Economics and environmental impacts aside, the consequences of high building energy consumption are relatively less critical than endangering the well-being of occupants (O’Brien & Kesik, 2020). Nevertheless, unlike energy code requirements, which either set building design specifications or specify the minimum energy efficiency level based on code-minimum for a particular building type in a particular climate, the thermal performance of buildings during power outages is missed in codes (O’Brien & Kesik, 2020). Although some guidelines, for example, the LEED BD+C v4.1 Passive Survivability credits by the U.S. Green Building Council (USGBC), have thresholds of livable indoor temperature, building codes and standards do not state any mandatory requirements for minimal or maximal indoor temperature and do not have clear, systematic thermal resilience metrics.

1.2 Previous resilience studies

The study of building energy efficiency is predominantly centered around energy performance under normal conditions; a limited number of studies explore thermal resilience for scenarios of power disruption. On the positive side, more studies on building thermal resilience have been conducted globally. Under the International Energy Agency’s Energy in Buildings and Communities Program, a large group of researchers have been collaborating under the Annex

80 project (https://annex80.iea-ebc.org/), resilient cooling of buildings, aiming to develop, assess and communicate solutions of resilient cooling and overheating protection (Zhang et al. 2021; Miller W. et al. 2021; Attia et al. 2021). Annex 80 defined resilient cooling as “low-energy and low-carbon cooling solutions that strengthen the ability of individuals and our community as a whole” to withstand and even prevent thermal impacts due to climate change (Attia et al., 2021). However, while existing research explored what measures and strategies are effective to improve resilience, there is still a lack of technical understanding of the intersection between building energy efficiency and thermal resilience, in particular, how energy efficiency technologies and building designs influence thermal resilience (Baniassadi et al. 2019; Baniassadi et al. 2022).

What’s also missing in existing research is the comprehensive modeling and analysis of mitigation measures for improving thermal resilience under both extreme hot events and cold events. Some passive energy efficiency strategies, like natural ventilation, natural night cooling, cool walls, cool roofs, and windows with low solar heat gain coefficient, have been proven to relieve thermal stress in extreme hot events in several studies (Sengupta et al., 2020; Gupta et al., 2021; Gamero-Salinas et al., 2021). For extreme cold events, building efficiency measures that yield increased insulation, mitigate heat loss and air infiltration, and maximize solar heat gain are shown to have the greatest impact. In many instances these measures may in fact conflict with optimal design strategies for extreme heat (van Hooff et al. 2016). And while extreme cold events are less common than heatwaves in the southern part of the United States, recent evidence suggests that extreme cold events will continue due to shifting atmospheric patterns in the Northern Hemisphere (Athienitis et al., 2020; Cohen et al. 2021). Further research is needed to assess the impacts of energy efficiency measures on building thermal resilience across both extreme heat and cold events, as well as for future climate scenarios.

Although multiple passive strategies can improve building resilience and lower energy consumption, active cooling systems, including but not limited to air conditioning and indoor fans, are still necessary to maintain indoor thermal comfort in warmer climates (Rajput et al., 2022; Gupta et al., 2021; Liu et al., 2020; Malik et al., 2022). The effectiveness of some passive cooling strategies, like natural ventilation, may be offset by the net increase in extreme heat days (Gupta et al., 2021). Therefore, on-site energy generation and storage may play a larger role in adapting buildings to future climate risks (Kennedy & Pape-Salmon, 2020). Particularly as rooftop PV and battery storage systems come down in cost, more research is needed to assess the balance between passive and active building design measures to maintain thermal resilience.

A few recent studies have developed metrics and benchmarking framework to quantify building thermal resilience. Two studies using very similar approach were conducted by Ji et al. (2022) and Homaei and Hamdy (2021) in hot and cold weather events respectively. Homaiei and Hamdy used indoor operative temperature as the performance indicator and proposed a multi-zone metric based on resilience trapezoid model. The metric captures building thermal resilience during disruptive event and recovery after the event. The metric was demonstrated in a case study under a typical cold weather in Norway. Similarly, Ji et al. used the resilience trapezoid model to develop a metric called Thermal Resilience Index, using the standard effective temperature as the performance indicator. This metric was used in a case study of a long-term care facility during an extreme hot event. Both metrics are labeled with different classes to quantify thermal resilience performance. However, both studies only used a single performance indicator to build their models and weigh their metrics, and which indicator should be used in order to capture as many environmental factors as possible were not discussed. In addition, their models are limited to certain climate zones, as the coefficients in their models need to be adjusted accordingly. Although Ji et al. performed a case study on an assisted living facility, they did not discuss what threshold of its Thermal Resilience Index is acceptable for vulnerable population like senior people.

Although thermal resilience has attracted attention in industry and academia, there is still a lack of standardized methodologies for assessment, especially for policies, protocols and procedures development. The planning and design of thermal resilience has not been formalized yet, as it takes time for the professionals to craft appropriate responses (Kesik et al., 2020). In the U.S., some municipalities use Heat Vulnerability Indices (HVI) to assess intra-city heat vulnerability with spatial varieties. However, many HVIs used by the public sector overlook housing characteristics, including building age, thermal mass and air conditioning functionality, as well as how they mediate indoor heat exposure, thus failing to assess thermal resilience comprehensively (Samuelson et al., 2020). Hence, it is necessary to develop a comprehensive, simulation-based approach for codes and standards to indicate absolute temperature thresholds or overheating/underheating duration, forcing the industry and governments to incorporate thermal resilience in planning (O’Brien & Kesik, 2020).

1.3 Scope of this study and contributions

In recognition of the discussed research gaps, this study analyzes the impacts of building energy efficiency technologies and strategies on the thermal resilience of an assisted living facility (ALF) under extreme hot and cold weather events coinciding with power outage. We selected a real ALF in the Greater Houston area for our case study. During the 2021 winter storm, this facility had to evacuate 40 residents due to the low indoor temperature causing health and safety concerns. Residents in ALFs are mostly seniors and have some health issues, which makes this population group more vulnerable to extreme weather events. In particular, their exposure to very high or low indoor temperatures may lead to dangerous or even life-threatening risks during extreme hot or cold temperature events with extended power outages.

This study is part of a research project which aims to develop a standardized methodology to assess valuation of energy efficiency for energy resilience (Reiner et al. 2022). This study contributes to the existing body of knowledge on thermal resilience through a holistic modeling and analysis framework to answer a few essential research questions on thermal resilience, including the following:

- How resilient is current ALF under extreme hot and cold temperature events without any power supply? What is the method and modeling framework using building performance simulation to quantify thermal resilience?

- What are the impacts of energy efficiency measures on thermal resilience of the ALF? Which energy efficiency measures result in conflicting impacts on thermal resilience between hot and cold events?
- How much backup power is needed to maintain services of the ALF during an extreme temperature event coincident with a power outage? How much do energy efficiency measures reduce the backup power capacity needed?
- How can current building energy codes and standards, building performance rating systems, and building energy policies be improved to consider requirements and benefits of thermal resilience in addition to the building energy use and carbon emissions?

The remainder of the paper is structured as follows. Section 2 describes the method. Section 3 presents the results. Section 4 discusses the results and policy implications. Finally, Section 5 offers conclusions.

2. Method

2.1 Characterization of the baseline facility

The ALF is a two-story building with 97 single-person bedroom suites and a total floor area of 10,800 square meters (Figure 1) located in the Houston metropolitan area. We adopted a previously developed nursing home EnergyPlus model (Sun et al., 2020) and adjusted the building footprint and total floor area, efficiency levels of envelope, lighting and HVAC systems, operating schedules, and conditions to match the characteristics of the Houston facility. The construction of the ALF was completed in 2018. The facility was built to comply with the efficiency requirements of ASHRAE standard 90.1-2013. Therefore, the energy efficiency requirements of standard 90.1-2013 were used as inputs to the baseline ALF model. Detailed envelope performance parameters are listed in Table 3.

The ALF has multiple types of building spaces: resident bedrooms, common areas (e.g., living, kitchen, entertainment), and circulation area (corridor). The common areas of the building are served by packaged rooftop units with single-duct, variable air volume air terminals with reheat, while each bedroom suite is served by a packaged terminal air conditioner. Heating is provided by a natural gas boiler connected with the packaged rooftop units for common areas, and the bedroom packaged terminal air conditioner is equipped with an electric heating coil. The HVAC equipment capacities were autosized using the EnergyPlus model as actual equipment capacity data was not available. The building is equipped with LED lighting and has no major medical equipment except oxygen machines. The cooling temperature setpoint varies within 21.1°C–22.2°C (70°F–72°F) and the heating temperature setpoint varies within 22.2°C–22.8°C (72°F–73°F) for common areas and bedrooms. Residents also have control of the temperature setpoint in their bedrooms. Residents are able to partially open their own windows based on the interview with the facility manager. As mentioned earlier, the ALF does not have on-site power generation or backup power system.

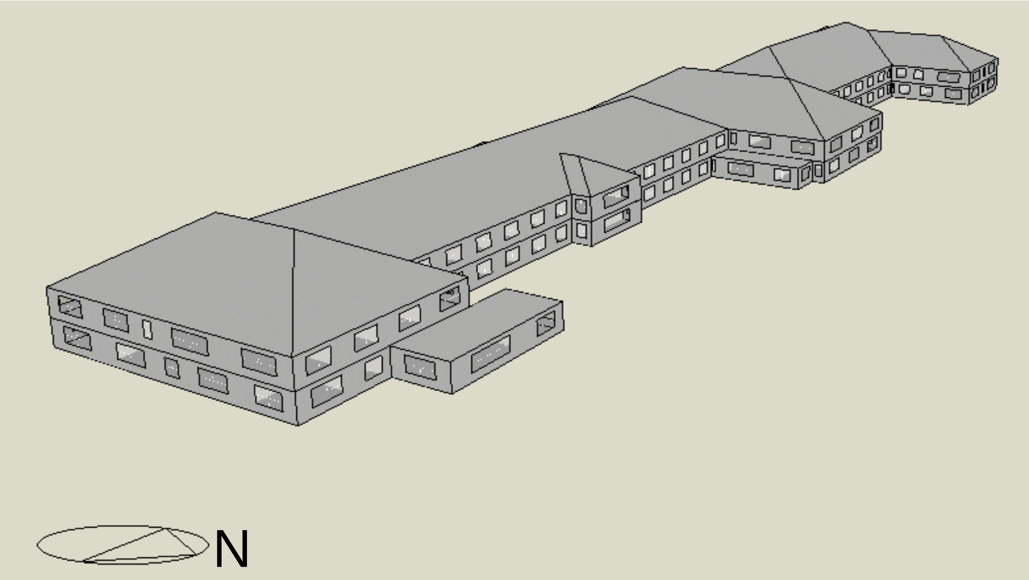


Figure 1. 3D illustration of the baseline model of the ALF

2.2 Thermal Resilience Metrics

Multiple thermal resilience metrics are found across research and current industry standards for different purposes and stakeholders. There is no yet consensus on a single individual or set of metrics for evaluating the thermal resilience of buildings. Most of the previous studies only adopted one metrics as the thermal performance indicator, which was only applicable in either hot or cold event instead of both conditions. Metrics that can be used in both hot and cold events, on the other hand, lack of thermal impact grading. Therefore, considering interests of various stakeholders (e.g., building occupants, owners or operators, regulators, public health agencies), we adopt three metrics in this study to thoroughly assess thermal resilience of buildings during extreme temperature events coincident with power outages, from the perspectives of occupant health and survivability, including: (1) the SET degree-hours for both hot and cold events, (2) the Heat Index for hot events, and (3) the Hours of Safety based on indoor air temperature during cold events. As described below, these metrics are used to quantitatively evaluate the thermal resilience of the baseline building conditions, as well as improvements to thermal resilience for the efficiency upgrade scenarios.

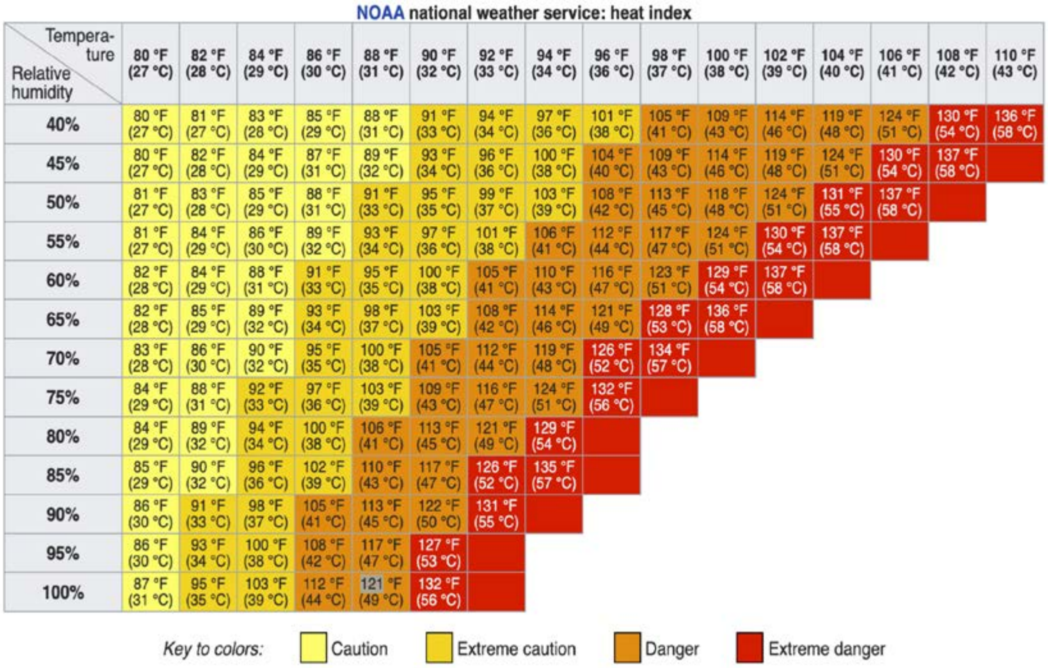
Standard Effective Temperature (SET) is a temperature metric that considers indoor air dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. SET has long been adopted in ASHRAE thermal comfort standard 55. The LEED v4.1 Credit for Passive Survivability and Backup Power During Disruptions defines “livable conditions” as SET between 12.2°C (54°F) and 30°C (86°F). SET can be used to assess thermal survivability in both hot and cold events (Wilson, 2005). To receive LEED credit for residential buildings, the unlivable SET degree-hours below 12.2°C (54°F) or above 30°C (86°F) must not exceed 120 degree(°C)-hours (216 degree(°F)-hours) for a seven-day power outage during an extreme hot or cold event. The SET degree-hours metric is more complex to calculate but considers six thermal comfort parameters and the accumulated severity of the thermal stress during the extreme weather events which are described later in

Section 2.3. The metric is hard to measure directly in indoor environments but can be easily calculated using building simulation tools such as EnergyPlus.

Heat Index (HI) combines air temperature and relative humidity to measure the human-perceived equivalent temperature. It was originally developed for assessing the outdoor thermal environment during hot summer days, but it is also applied to indoor thermal resilience assessment (Sun et al., 2020; LEED v4.1 Passive Survivability Credit). There are four levels of heat stress based on HI (Table 1, Figure 2), including Caution, Extreme Caution, Danger, and Extreme Danger. The HI hours are calculated as the accumulated number of hours when HI falls within a certain hazard level. The metric of Heat Index hours, although ignoring the other four indoor thermal comfort parameters, provides well defined heat hazard and risk levels, as well as the accumulated severity of the thermal stress during heat waves. The metric is used for hot events only. It is easy to measure, as it only requires the indoor air temperature and humidity. It should be noted that the heat index ranges and hazard levels are defined for general population although vulnerable population (e.g., seniors living in ALFs or nursing homes, people with medical conditions) is more sensitive to overheating risk.

Table 1. Heat Index and Heat Stress Level

Heat Index Range	Hazard Category	Heat Syndrome
Below 27 °C (80 °F)	Safe	None
27 to 32 °C (80 to 90 °F)	Caution	Fatigue possible with prolonged exposure and physical activity
32 to 41°C (90 to 105 °F)	Extreme Caution	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and physical activity
41 to 54 °C (105 to 130 °F)	Danger	Sunstroke, heat cramps, or heat exhaustion likely. Heat stroke possible with prolonged exposure and physical activity
Higher than 54 °C (130 °F)	Extreme Danger	Heatstroke or sunstroke imminent



NOAA national weather service: heat index

Temperature / Relative humidity	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution · Extreme caution · Danger · Extreme danger

Figure 2. Heat Index chart and heat stress levels (Source: NOAA/NWS)

Hours of Safety (HOS) is a metric developed by the U.S. Environmental Protection Agency (EPA) and the Rocky Mountain Institute (Ayyagari et al., 2020) as a measure of the duration of time a building is able to maintain safe conditions above a predefined temperature threshold during a cold event (Figure 3). Table 2 shows the various temperature thresholds considering the safety level and population demographics. When indoor air temperature falls below 12.2°C (54°F), there is an increased health risk for vulnerable populations; when indoor air temperature drops below 4.44°C (40°F), there is an increasing risk of hypothermia for all populations (healthy and vulnerable). The metric of Hours of Safety is simple to understand and easy to calculate via simulations or measurements. It aims to serve as a potential resilience score of buildings, in analog to the ENERGY STAR score for representing energy efficiency of buildings. Hours of Safety is particularly useful for cold events as buildings tend to gradually lose heat over the course of the event; for extreme heat events, temperatures might oscillate between safe and unsafe conditions due to diurnal swings.

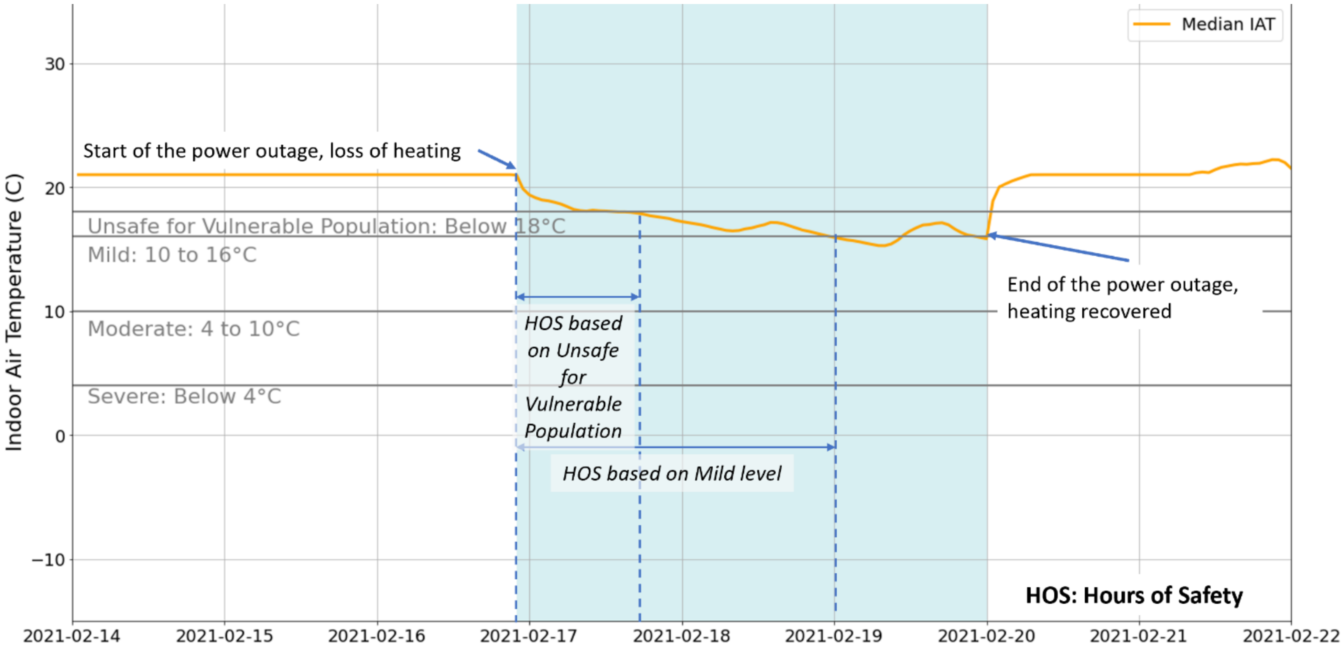


Figure 3. The concept of Hours of Safety

Table 2. Cold stress levels for determining Hours of Safety (Adapted from Ayyagari et al., 2020)

Cold Stress Level	Indoor Air Temperature Range °C (°F)
Safe for All Population	Above 17.78 (64)
Unsafe for Vulnerable Population	Below 17.78 (64)
Mild for Healthy Population	10 to 15.56 (50 to 60)
Moderate for Healthy Population	4.44 to 10 (40 to 50)
Severe for Healthy Population	Below 4.44 (40)

For a building with multiple thermal zones (spaces with different temperatures), such as multi-family buildings or assisted living facilities, it is necessary to collect results for multiple spaces as temperatures are likely to vary by orientation and floor level. For this case study, thermal resilience metrics are calculated for each occupied space, and results can be presented with the worst, median, 5% or 95% tile of spaces, and the aggregation weighted by the number of residents or bedrooms for the whole building.

EnergyPlus (version 9.4 and later) is able to directly calculate and report the SET degree-hours and the Heat Index hours (Luo et al., 2021). The Hours of Safety requires post-processing of the EnergyPlus simulated time series of indoor air temperatures. EnergyPlus version 22.2 and later add a new feature to calculate and report the Hours of Safety metric.

2.3 Extreme weather events

In contrast to the typical year weather data (e.g., typical meteorological year, or TMY) used for annual energy simulations, modeling thermal resilience of buildings requires specific weather data that represents an extreme temperature event. There are several methods used to identify an extreme temperature that consider additional factors than maximum temperature, such as duration, cumulative intensity, and variation from historical averages. A heat wave is a period of abnormally hot weather generally lasting three or more days. In this study, we adopted the method of extreme weather event identification developed by Ouzeau et al. (2016), which was coded by Machard et al. (2020). Adopted by the IEA EBC Annex 80 Resilient Cooling project, Machard's code converts the 30-year hourly weather data into daily mean ambient air temperature data. A heat wave is defined by three temperature thresholds, as shown in Figure 4, as an event lasting for a period of time. This method uses statistical climatology thresholds, which are not restricted by geological region, and Annex 80 adopted this method to detect heatwaves in all ASHRAE climate zones (IEA Annex 80, 2022). The three temperature thresholds were computed as the percentile among the 30-year mean daily temperature distribution and were set to detect occurrence and the start and end dates of extreme temperature events:

- *Tpic* as the threshold of detection (if the daily mean temperature exceeds this threshold, a heat wave's existence is detected).
- *Tdeb* as the threshold of the start and end of the event (once the daily mean temperature reaches this threshold but stays beneath Tpic, the day is identified as either the start date or the end date of the heat wave).
- *Tint* as the threshold of interruption, if the daily mean temperature falls below Tdeb but stays above Tint, the day can be seen as an interruption of the heat wave, so that code users and researchers are allowed to merge (or separate into) two neighboring events if needed.

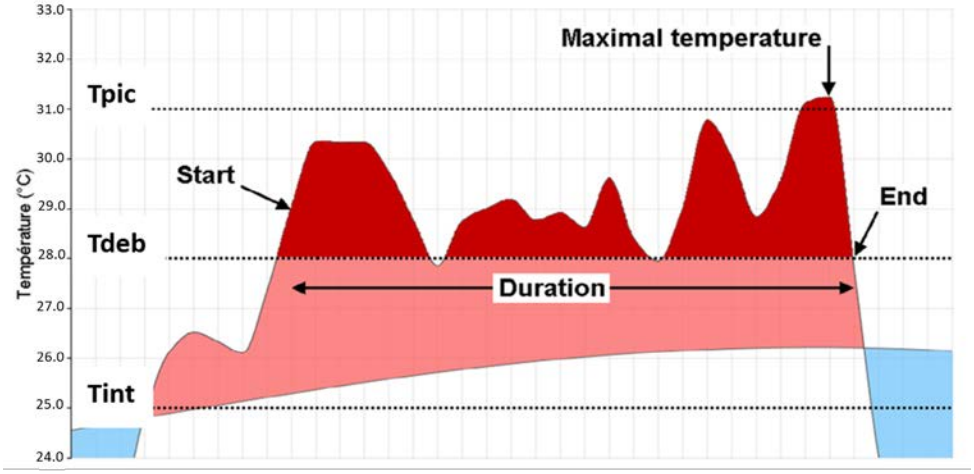


Figure 4. Characterization of a heat wave based on the daily mean temperature indicator (adapted from Ouzeau et al., 2016)

In this study, we merged two neighboring extreme weather events if there was an interruption. We use the three percentiles indicated by Ouzeau et al. (2016) to determine the extreme temperature events: 99.5% for *Tpic,* 97.5% for *Tdeb,* and 95% for *Tint.* In Houston, the three temperature thresholds are determined to be 31.8℃ for *Tpic*, 30.5℃ for *Tdeb*, and 29.9℃ for *Tint.* Two extreme temperature events were selected from the historical 30 years' weather data for this study: (1) a six-day heat wave that occurred from July 26 to 31, 2015, and (2) a three-day cold snap that occurred from February 17 to 19, 2021 during Winter Storm Uri. The ALF suffered a power outage beginning at 10 pm on February 16 and ending February 19th. Figure 5 shows the outdoor air temperature during the two extreme temperature events (the shaded period of the figure).

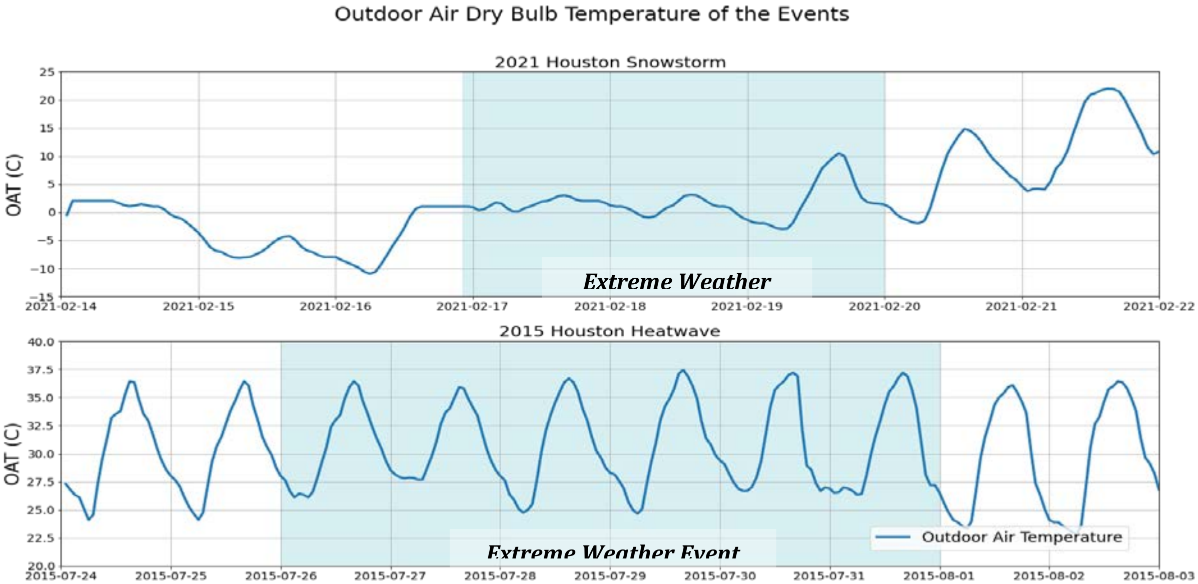


Figure 5. Hourly outdoor air temperature of the two selected extreme temperature events: the three-day cold snap in 2021 (top subfigure) and the six-day heat wave in 2015 (bottom subfigure)

2.4 Resilience mitigation measures

A total of 13 energy efficiency measures were modeled and evaluated in this study to determine their import on the facility's thermal performance. They are common retrofit measures of buildings. It should be noted there are other mitigation measures such as phase change materials which are not considered in the present study due to the high first cost consideration.

Passive Measures

Eight passive measures focusing on the building envelope retrofit were evaluated (Table 3), including adding insulation to exterior walls and roofs, applying a cool coating to walls and roofs, installing interior window shades, installing solar film on windows, sealing the building envelope to reduce air infiltration, and opening windows for natural ventilation when conditions fit. None of these measures require energy or power to function. The envelope package including seven measures was also evaluated to consider their integrated effects on thermal resilience. Table 3 lists key model parameters of the baseline ALF model (based on ASHRAE Standard 90.1-2013) and the older ALF model assumed to be built about 20 years ago (complying with ASHRAE 90.1-1999 requirements), as well as the measures.

Table 3. Passive measures and their key parameters for the ALF

Passive EEMs	Baseline Model Assumptions (ASHRAE 90.1-2013)	EEM Model Assumptions	Older ALF Model Assumptions (ASHRAE 90.1-1999)
Exterior Wall Insulation, U-value in W/m^2K ($Btu/h\text{-}ft^2\text{-}°F$)	0.477 (0.084)	0.284 (0.05)	0.715 (0.126)
Cool Wall Coating (Solar reflectance)	0.3	0.6	0.3
Roof Insulation, U-value in W/m^2K ($Btu/h\text{-}ft^2\text{-}°F$)	0.301 (0.053)	0.153 (0.027)	0.466 (0.082)
Cool Roof Coating (Solar reflectance)	0.3	0.6	0.3
Interior Window Shade, Horizontal blind (solar reflectance)	N/A	0.8	N/A
Window Solar Film	$U = 4.26\ W/m^2K$ ($0.751\ Btu/h\text{-}ft^2\text{-}°F$) SHGC = 0.25 VT = 0.564	$U = 3.73\ W/m^2K$ ($0.657\ Btu/h\text{-}ft^2\text{-}°F$) SHGC = 0.057 VT = 0.42	$U = 6.98\ W/m^2K$ ($1.23\ Btu/h\text{-}ft^2\text{-}°F$) SHGC (non-north) = 0.25 SHGC (north) = 0.61 VT = 0.76
Infiltration Reduction (ach)	0.3	0.25	0.5
Natural Ventilation	N/A	Yes (3 ach)	N/A
Envelope Package (includes the above measures except the natural ventilation)	N/A	Wall Insulation + Cool Wall Coating + Roof Insulation + Cool Roof Coating	N/A

		+ Interior Window Shade+ Solar Window Film + Infiltration Reduction	

Exterior wall and roof insulation reduce the heat transfer between outdoor and indoor environments, thus reducing space heating and cooling loads. Cool roof and cool wall coatings have higher solar reflectance and higher thermal emittance, so the wall and roof can stay cool under the sun and at night by minimizing solar absorption and maximizing longwave radiant heat exchange with surrounding environments.

The interior shade measure was modeled assuming rational use by residents—in summer, the shade is deployed during the day and open during the night to reduce daytime solar heat gain and allow night cooling; in winter, it is the opposite, the shade is open during the day and closed during the night to increase daytime solar heat gain and reduce nighttime heat loss from the bedrooms.

Since the facility was completed recently, in 2018, windows are already double-pane with low-e coating. We applied solar window film to further improve window performance, which has a lower thermal transmittance, lower solar heat gain coefficient (SHGC), and lower visible transmittance (VT).

Infiltration reduction is usually achieved by sealing windows and doors to reduce the amount of unexpected outdoor air into the building, which may lower the space cooling and heating loads.

The natural ventilation measure was modeled assuming the residents open windows when the indoor air temperature is higher than outdoors during heat waves. When natural ventilation was deployed, we assume an air exchange rate of three air changes per hour for bedrooms with operable windows. During the cold event without power, we assume the residents close windows to stay warm.

Active Measures

Five active measures were selected, with detailed parameters listed in Table 4. The measures were: efficient LED lighting, daylighting control, high-efficiency air-conditioning system, ceiling fan, and plug load controller. These technologies require electric power to function.

LED is a highly energy-efficient lighting technology that can consume less energy with a longer product life. As a rapidly spreading technology, it is also very affordable. We adopted the lighting power density at 4.31 watts per square meter (W/m^2) according to ASHRAE report 1651, *Development of Maximum Technically Achievable Energy Targets for Commercial Buildings* (ASHRAE 2016).

The common area direct expansion (DX) cooling coils have a coefficient of performance (COP) of about 3, and we adopted the maximum technically achievable COP of 5.03 based on ASHRAE report 1651. The COP of DX cooling coils were adjusted in EnergyPlus to model this measure. No changes were made to the baseline packaged terminal air-conditioners serving the individual resident suites.

Daylighting control adjusts the amount of lighting power required based on the availability of incoming daylight through fenestration surfaces, thus reducing the electric lighting load. Daylighting control was only applied in common areas in perimeter zones of the building, since individuals should have control over the lighting in their own rooms. The continuous dimming method was used.

The ceiling fan was applied as a low-power active measure to improve comfort levels through increased air circulated. This measure aimed to raise the upper boundary of the occupants' comfort zone by increasing air circulation in the bedroom. Studies show that an air speed of 0.8 to 1.05 meters per second (m/s) could maintain comfort between 28°C and 29.5°C at 50% relative humidity (Burton et al., 1975; McIntyre, 1978; Rohles et al., 1974; Scheatzle et al., 1989). In our study, we assume that indoor air speed increases from the baseline value of 0.137 m/s to 0.8 m/s when the installed ceiling fans operate, and the cooling setpoint can be raised to 28°C when occupied. Ceiling fans draw a modest amount of power. We assume the adoption of DC-driven ceiling fans, which consume about 0.355 W/m^2 (0.033 W/ft^2) of bedroom floor area during normal operation. This is based on the specifications of several affordable ENERGY STAR certified products and the findings from a previous study (Miller D. et al., 2021).

Plug load controllers can automatically turn off power to designated plug loads based on usage schedules and prevent "standby" loads. ASHRAE report 1651 states that plug load controllers can reduce plug load power density by 8.7% maximum.

Table 4. Active measures and their key parameters for the ALF

Active EEMs	Baseline Model	EEM Model	Older ALF ASHRAE 90.1-1999
Lighting Power Density W/m^2 (W/ft^2)	9.47 (0.880)	4.31 (0.401)	17.2 (1.6)
Daylighting Control	N/A	Continuous dimming control in perimeter, common areas	N/A
DX Cooling Coil Efficiency (COP)	3.0	5.03	3.0

Ceiling Fan	N/A	Yes (Air velocity 0.8 m/s)	N/A
Plug Load Controller	N/A	Yes (Reducing the plug loads by 8.7%)	N/A

2.5 Modeling and analysis workflow

The thermal resilience of the ALF was evaluated under two extreme cold and hot weather events coincident with power outages as the worst case scenarios. Figure 6 illustrates the key steps to the modeling and analysis of thermal resilience of the baseline facility.

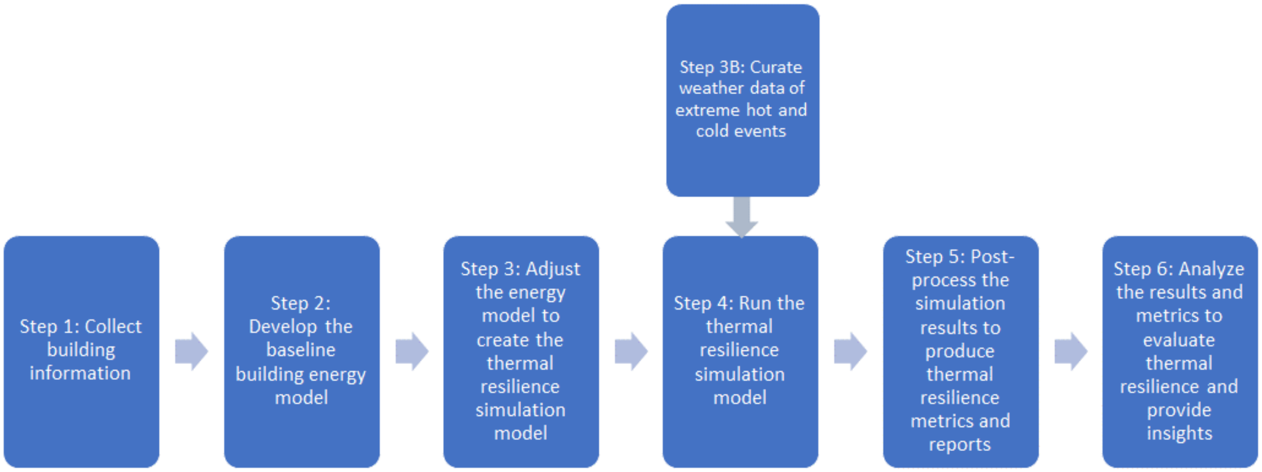


Figure 6. A modeling and analysis workflow for assessing thermal resilience of buildings

Step 1 collects information about the facility (details are described in Section 2.1). Step 2 develops the energy model of the ALF using information collected from Step 1. Step 3 adjusts the baseline energy model to simulate thermal resilience by turning off the energy use systems or components in the building (for details, see Section 2.6). Step 4 runs the modified energy model simulations for the selected extreme temperature events identified in Step 3B. In Step 5, the simulation results go through post-processing using Python scripts to convert hourly temperature performance data into three thermal resilience metrics (described in Section 2.2). Step 6 analyzes the thermal resilience performance of the ALF during the two extreme temperature events without a power supply (for details, see Section 3.1 and Section 3.2).

Building energy models are simulated in EnergyPlus, an open source program that models heating, ventilation, cooling, lighting, water use, renewable energy generation, as well as other building energy flows (Crawley et al., 2001), and is the flagship building simulation engine supported by the United States Department of Energy.

Following the baseline assessment, we run additional simulations using eight selected passive energy efficiency measures. The envelope package, excluding the interior window shades and natural ventilation, were also evaluated to consider its effect on thermal resilience. Since the ALF is a fairly new facility (constructed in 2018), we also modify the ALF baseline model to reflect the characteristics of an older facility built about 20 years ago. Details of the measures are described in Section 2.4. Detailed results and analysis are provided in Sections 3.3, 3.4 and 3.5.

In Section 3.6, we expand the analysis to consider the impacts of the passive energy efficiency upgrades on backup power capacity of the ALF. Assuming the power requirements needed to operate full services during the extreme temperature event, we are able to determine the backup power needs with respect to each efficiency measure upgrade.

2.6 Building energy models and simulation tool

EnergyPlus version 9.6 is used to create the building energy models for the baseline ALF, the older ALF, and each of the mitigation measures, as well as two packages. These models are simulated for the selected two extreme temperature events. The three thermal resilience metrics were calculated from EnergyPlus simulation results for further analysis and evaluation.

Two power scenarios were studied. The completely no power scenario was assumed to be the worst case for studying how the baseline ALF and mitigation measures perform in thermal resilience under extreme temperature conditions. The backup power scenario was used to determine the capacity needs for backup power for maintaining the full services during the grid power outages. The selected cold event in 2021 coincided with an actual power outage which caused significant impacts to the facility and its residents. For the selected hot event in 2015, a power outage during the event was assumed to provide a worst case scenario for thermal resilience analysis.

For the no power scenario, we turned off all energy-consuming equipment and systems (lighting, plug loads, and HVAC), and the entire facility was assumed to be in free-floating mode during the extreme temperature events. For the backup power scenarios, we assumed the facility had on-site backup power to operate to meet the full services during the extreme temperature events, then we determined the backup power needs (in electricity usage kWh and peak electricity demand kW) from EnergyPlus simulation results.

3. Results and Analysis

The simulation results for the two extreme events are presented below. The max, 95th percentile, median, and 5th percentile results are based on temperature performance data from all 97 resident bedrooms.

3.1 Resilience of the baseline ALF under the six-day heat wave without a power supply

Figure 7 compares the hourly SET distribution of all resident bedrooms at different percentiles with the outdoor air temperature during the 2015 heat wave with a power outage for the baseline ALF model. The maximum SET and the 95th percentile SET reached the upper threshold (30°C) for passive survivability in fewer than 12 hours. The median time for a bedroom to reach 30°C SET was 20 hours. Four bedrooms on the second floor had SET exceeding 30°C quickly, within 10 hours—two of them were the rooms at the corner with the largest east-facing window area, making them the earliest rooms to receive the incoming solar radiation after the start of the power outage, and the other two were the rooms with the smallest floor area. Thirty-four bedrooms on the first floor had SET exceeding 30°C after 24 hours since the start of the power outage. It took the longest time, about 44 hours, for the first-floor bedroom facing true north to reach the SET of 30°C.

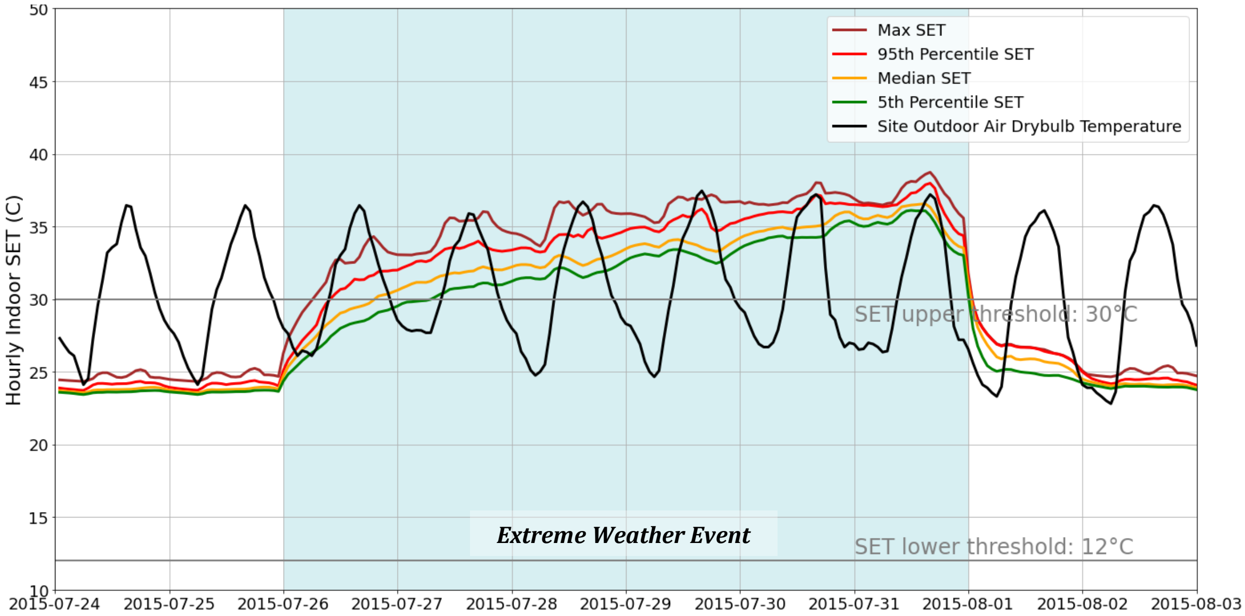


Figure 7. Hourly SET distribution of all resident bedrooms and outdoor air temperature of the baseline ALF model during the 2015 heat wave. The median bedroom SET exceeded the upper passive survivability threshold at 30°C within 24 hours after the start of the power outage, while the maximum bedroom SET quickly exceeded the threshold, within six hours.

LEED Passive Survivability defines the thermal safety using the SET degree-hours. In the cooling scenario, the accumulated SET degree-hours shall not exceed 120 SET degree(°C)-hours above 30°C for residential areas. In the 2015 heat wave, the average time for all resident bedrooms of the baseline model to violate the LEED passive survivability criteria is 76 hours; this translates to 53% of residents needed to be evacuated by a little over three days. Four bedrooms on the second-floor corners with the largest window area exceeded the 120 SET degree(°C)-hours threshold within 48 hours. One bedroom on the first floor with the least exterior window area did not exceed the criteria until 96 hours after the power outage.

Using the heat index as the resilience metric, Figure 8 compares the hourly HI distribution of all bedrooms at different percentiles with the outdoor air temperature during the 2015 heat wave for the baseline model. Ten percent of the bedrooms quickly reached the Caution level within one hour, 59% of the bedrooms reached the Extreme Caution level within eight hours, and 46% of the bedrooms reached the Danger level in less than two days.

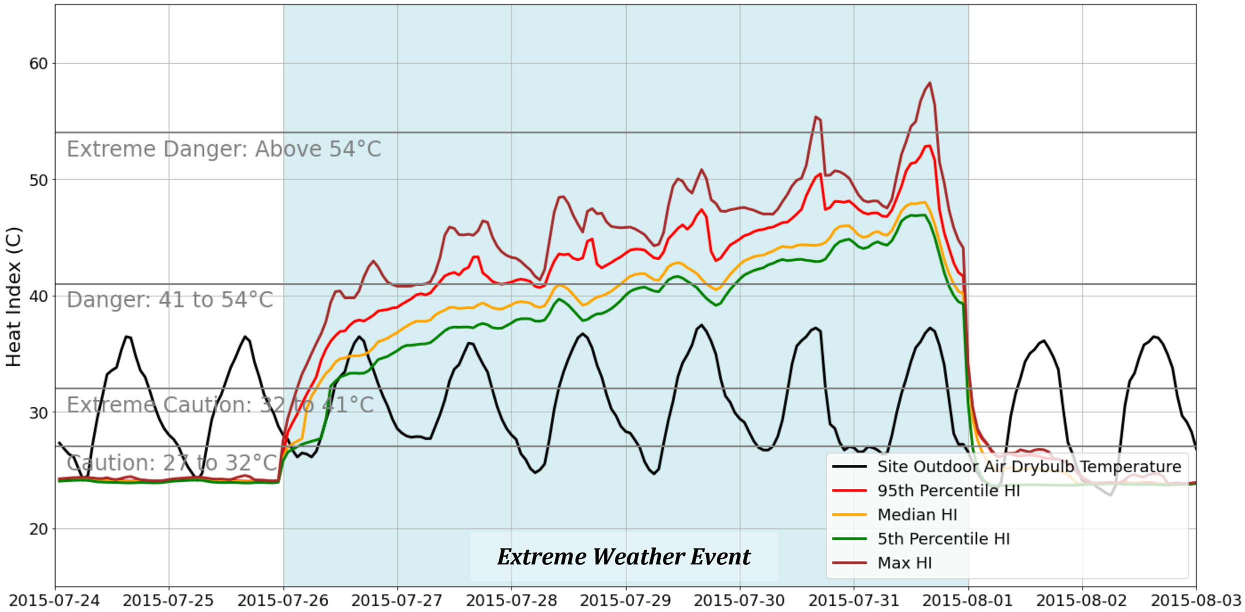


Figure 8. Hourly heat index (HI) distribution among all bedrooms and outdoor air temperature of the baseline model during the 2015 heat wave. The median bedroom HI exceeded the Danger level after 72 hours since the start of the power outage, while the maximum bedroom HI quickly reached the Danger level within 24 hours.

3.2 Resilience of the baseline ALF under the three-day cold snap without a power supply

Figure 9 compares the hourly SET distribution of all resident bedrooms at different percentiles with the outdoor air temperature during the 2021 snowstorm with a power outage for the baseline ALF model. Although the SET began to drop after the start of the blackout, the SET did not decrease dramatically, and none of the bedrooms broke the lower livable SET threshold at 12°C.Therefore, the SET degree-hours of the baseline model during the snowstorm were zero. It is unnecessary to compare the SET degree-hours of the baseline with other measures, as the baseline already performed at a livable standard.

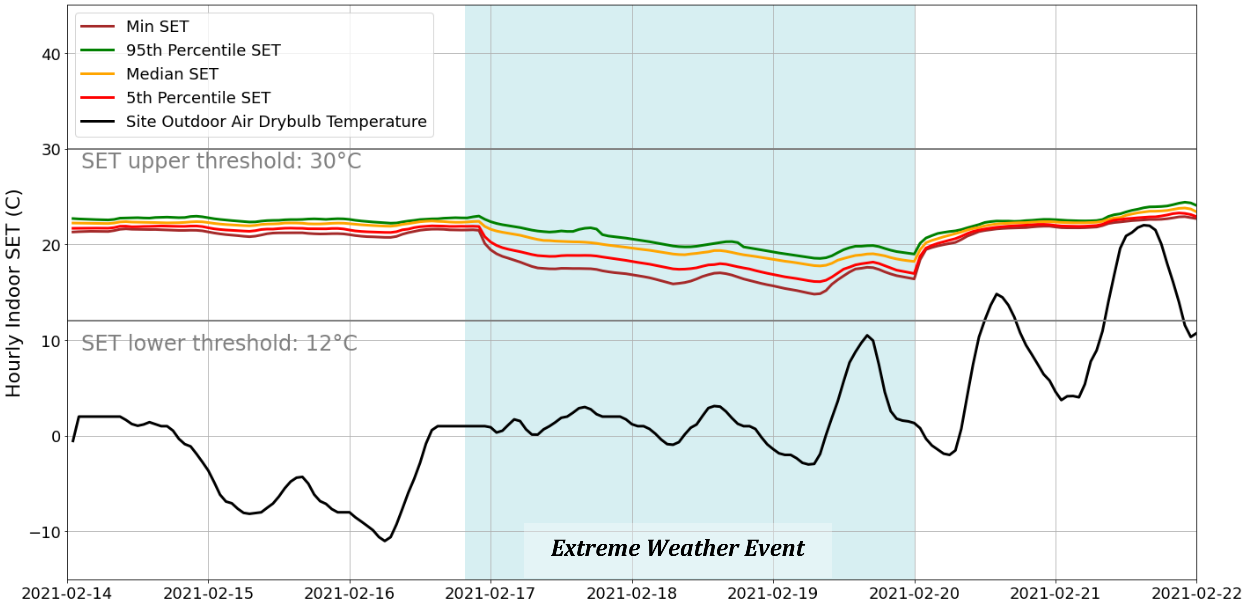


Figure 9. Hourly SET distribution of all resident bedrooms and outdoor air temperature of the baseline ALF model during the 2021 snowstorm. The minimum hourly SET never drops below the lower threshold of passive survivability at 12°C.

Figure 10 shows the time series of indoor air temperature (IAT) distribution of all the bedrooms for the baseline ALF model during the 2021 snowstorm. Unlike the SET, the IAT dropped slightly more dramatically and broke two thresholds of the cold stress levels for determining Hours of Safety: Minimum for Vulnerable Populations and Mild. The minimum IAT never dropped below the Moderate cold stress level of 10°C. The median time for a bedroom to drop the IAT below the Minimum for the Vulnerable Population level was 27 hours, and 60 hours for the Mild level. Six bedrooms on the second floor dropped their IAT below the Minimum for Vulnerable Population level within six hours. Two of these bedrooms, although in the middle of the floor plan, are right next to the spacious public rooms with large exterior walls, and the other four are on the corners of the building, thus having the most exterior window area.

According to the facility manager, the minimum IAT dropped to 16°C around 3 to 4am Wednesday morning, a few hours after the power outage started at 10:30pm Tuesday February 16, 2021. This agreed with the simulation results shown in Figure 10. The indoor air temperature of the facility further dropped to below 15°C in the afternoon of Wednesday when the facility started evacuating the residents.

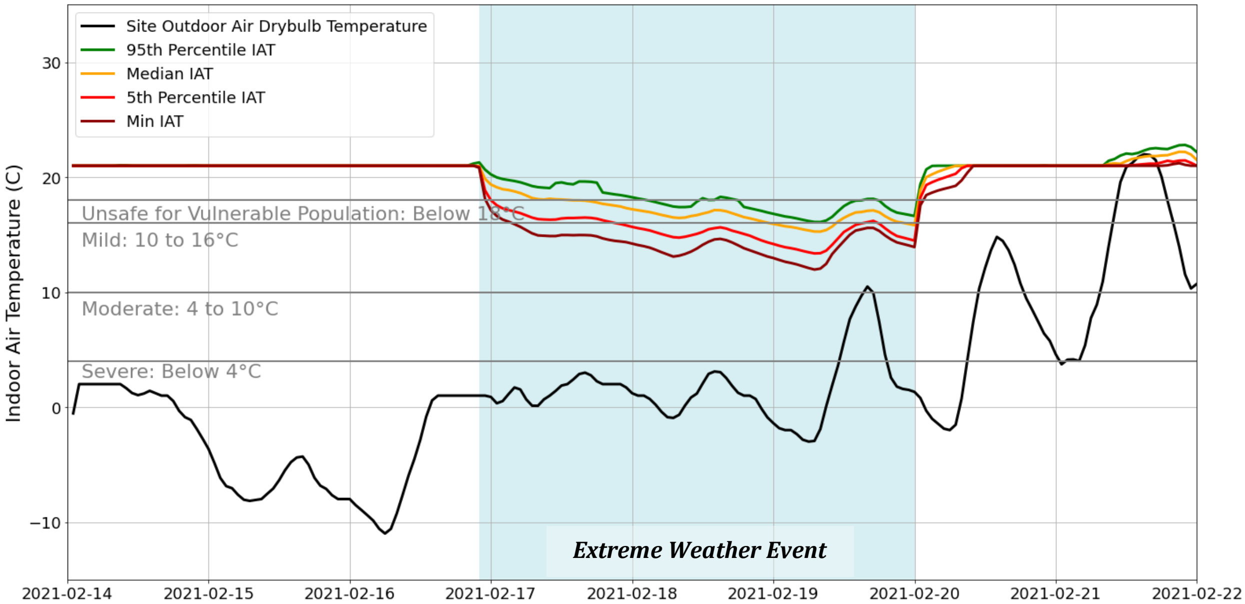


Figure 10. Hourly indoor air temperature (IAT) distribution and outdoor air dry-bulb temperature of the baseline model during the 2021 snowstorm. The median bedroom IAT dropped below the Unsafe for Vulnerable Population level within 12 hours and below the Mild level after 48 hours, while the minimum bedroom IAT dropped below the Unsafe for Vulnerable Population level within two hours and below the Mild level within six hours. Using the Mild level as the threshold of HOS, the baseline HOS was about nine hours.

3.3 Influence of mitigation measures on the resilience of the ALF under the six-day heat wave without a power supply

Figure 11 shows the relative reduction of the average SET degree-hours above 30°C for the passive mitigation measures during the 2015 heat wave with a power outage. Adding window solar film, natural ventilation, and envelope package significantly reduced the average SET degree-hours above 30°C per bedroom by 27%, 62%, and 32%. However, the measure of reducing infiltration showed a substantial, opposite effect by an average 20% increase in the SET degree-hours. Internal window shade was about twice as effective as the wall and roof insulation and coating measures.

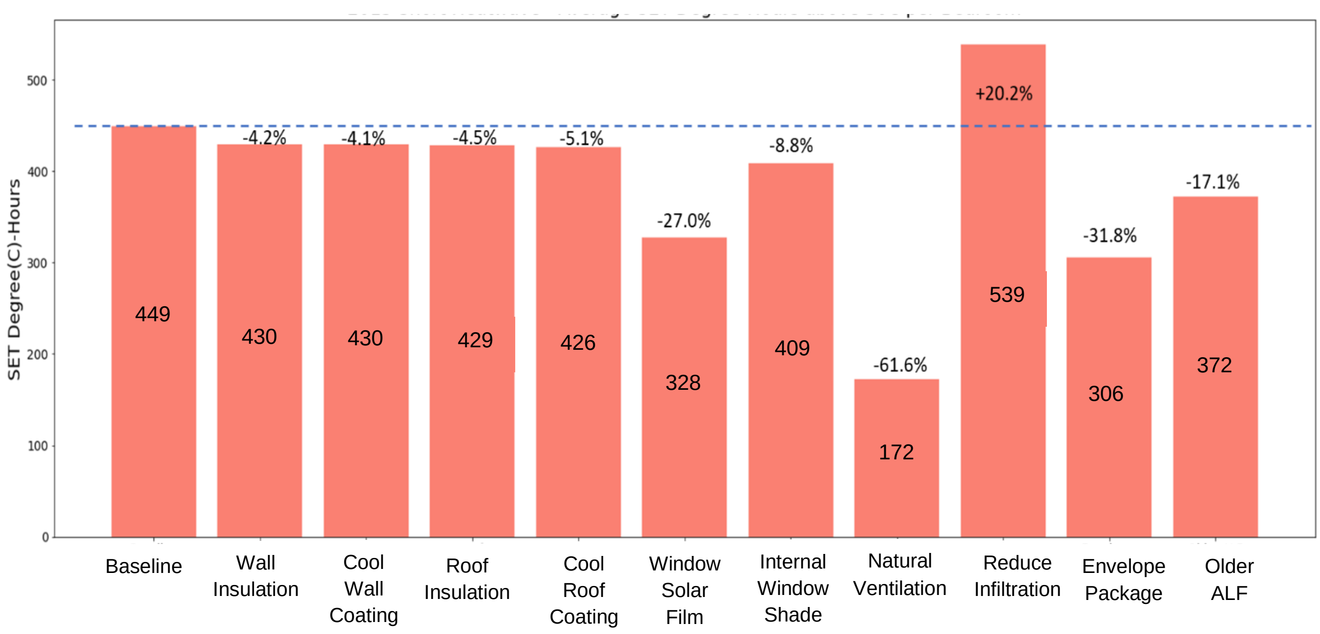


Figure 11. Average SET degree-hours above 30°C of the baseline ALF model, the improved ALF models with passive measures, and the older ALF, during the 2015 heat wave

The older ALF model, which reflects a replicate facility constructed to ASHRAE 90.1-1999 code, outperforms the baseline model. This is due to its lower insulation levels and airtightness of the building envelope, which allows internal heat to escape. The percentage of residents need to be evacuated dropped significantly from 53% in the baseline case to 3% in the older ALF case.

Using the Heat Index hours as the metric, Figure 12 presents the percentage of the HI hours weighted by the number of residents/bedrooms under different thresholds (Caution, Extreme Caution, Danger and Extreme Danger), with the number indicating the total percentage of hours at Danger and Extreme Danger levels for all bedrooms. The results are consistent with the SET degree-hours results.

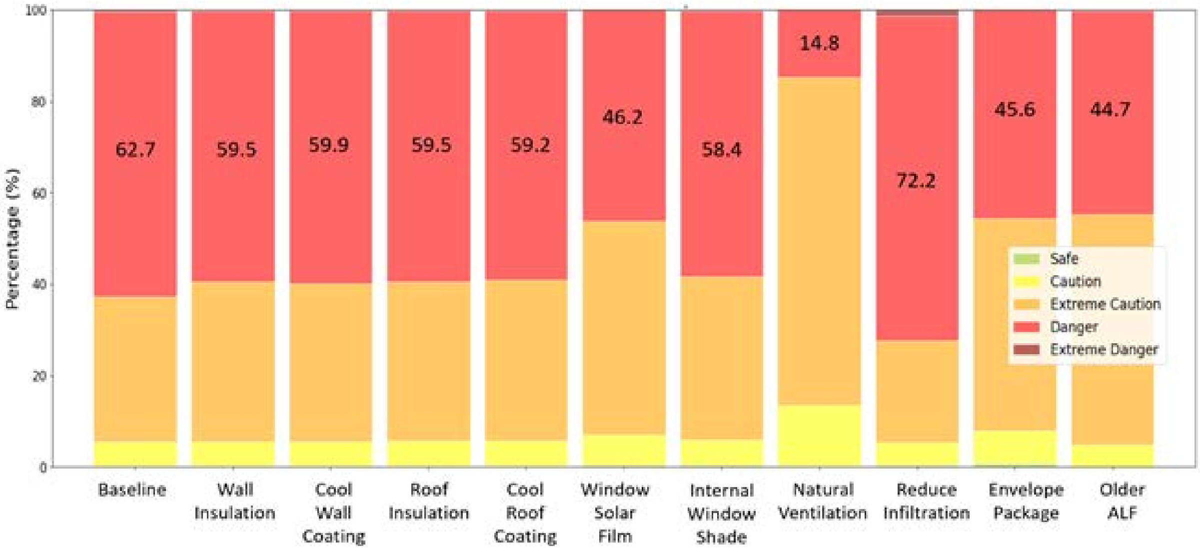


Figure 12. Percentage of aggregated hours for all bedrooms at each HI hazard level of the baseline ALF, the mitigated passive measures, and the older ALFs, during the 2015 heat wave

3.4 Influence of mitigation measures on the resilience of the ALF under the three-day cold snap without a power supply

Figure 13 top subfigure shows the percentage of time when the indoor air temperature (IAT) had impacts on vulnerable and general population respectively. The IAT never dropped to the Moderate cold stress level for the baseline and any passive measures. Since the start of the power outage, about 60% of the time the IAT stayed below the Unsafe for Vulnerable Populations level but above the Mild for Healthy Populations level. Wall and roof insulation both reduced the hours at Mild cold stress level, although the improvement of roof insulation was very limited. Cool wall coating and cool roof coating both slightly increased the hours at the Mild cold stress level. With a more insulated envelope, the envelope package marginally reduced more the Mild cold stress level hours than the infiltration reduction.

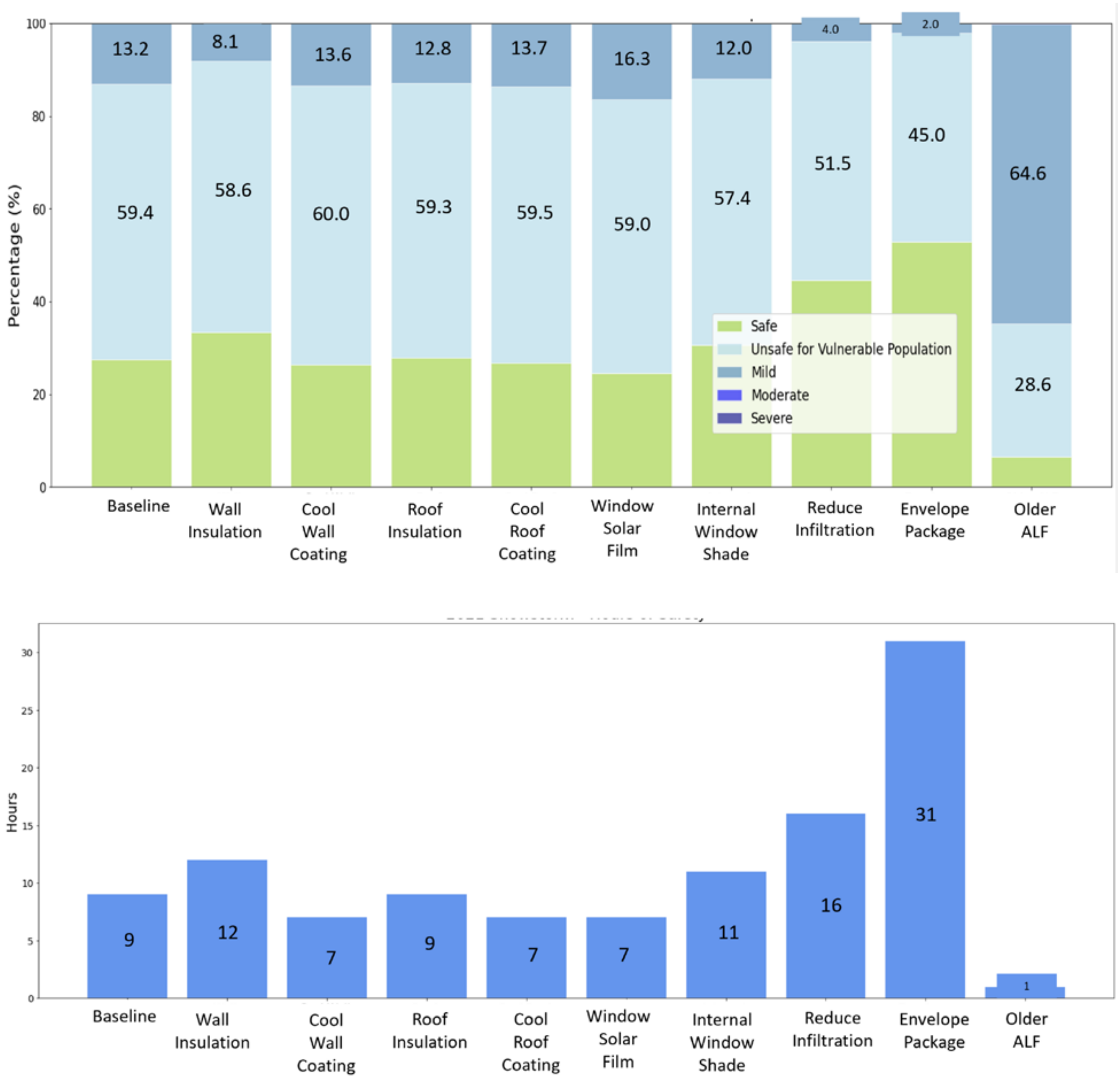


Figure 13. Top: Percentage of aggregated hours for all bedrooms at each cold stress level of the baseline ALF and the mitigated ALFs with passive measures during the 2021 snowstorm; Bottom: HOS of the baseline ALF and mitigated ALFs with passive measures during the 2021 snowstorm

For the cold event, the older ALF performed much worse than the baseline facility. The percentage of safe hours of the older ALF (6.8%) was much lower than that of the baseline (27.4%), implying that more hours were below the level of Unsafe for Vulnerable Populations. Within these unsafe hours, the older ALF had a higher percentage of Mild hours (64.6%) than the baseline (13.2%), indicating the older ALF was not only dangerous for vulnerable populations, but very unsafe for healthy populations as well.

As shown in Figure 13 bottom subfigure using the Mild level (16°C) as the HOS threshold, the baseline HOS was nine hours. We used the Mild level instead of the Unsafe for Vulnerable Population level to differentiate the performance among the baseline and different measures. Otherwise, if the Unsafe for Vulnerable Population level was used, HOS would be one hour for all cases. Cool wall coating, cool roof coating and the window solar film measures decreased HOS because they reduced solar heat gains into the facility. Infiltration reduction can significantly improve HOS from 9 hours to 16 hours, allowing more time for the facility to prepare and respond to the cold event. The envelope package can effectively extend HOS to longer than one day, while the older ALF would only have one hour of safety due to its leaky envelope.

3.5 Influence of mitigation measures on the annual energy use of the ALF with full power

EnergyPlus simulations using the TMY3 weather data of the Houston international airport were run to quantify the impacts of the mitigation measures on the facility's annual energy use. Figure 14 shows the annual site energy use intensity (EUI) of the baseline ALF and improved cases with passive and active mitigation measures. The baseline ALF had an EUI of 159 kWh/m^2 (50.4 kBtu/ft^2). Since the utility bill was not available for the real building, we benchmarked the annual site EUI of our baseline model with the Building Performance Database (bpd.lbl.gov). According to the database, the median annual site EUI of nursing homes in Houston built after 2016 is 170 kWh/m^2 (54 kBtu/ft^2), and the baseline model of this new ALF has an annual site EUI of 159 kWh/m^2 (50.4 kBtu/ft^2), which is in a reasonable range. One building from the database with a similar floor area, about 10,777 m^2 (116,000 ft^2), has an annual site EUI of 139 kWh/m^2 (44 kBtu/ft^2), further confirming the credibility of the baseline model.

Passive measures, in general, have limited impact on EUI, except the measure to reduce infiltration, which is the most effective, with a 4.6% energy savings. The envelope package shows 2.6% annual energy savings. The active measures can achieve 3% to 4% energy savings for the ceiling fan, high efficient DX cooling unit, and plug load controller. The lighting measure can achieve higher savings of 8.6%. When the passive and active measures are combined into a package (labeled EnvelopePackagewithActiveMeasures), it can achieve 16% energy savings compared with the baseline ALF. In contrast, the older ALF consumed 20% more in annual site energy than the baseline ALF.

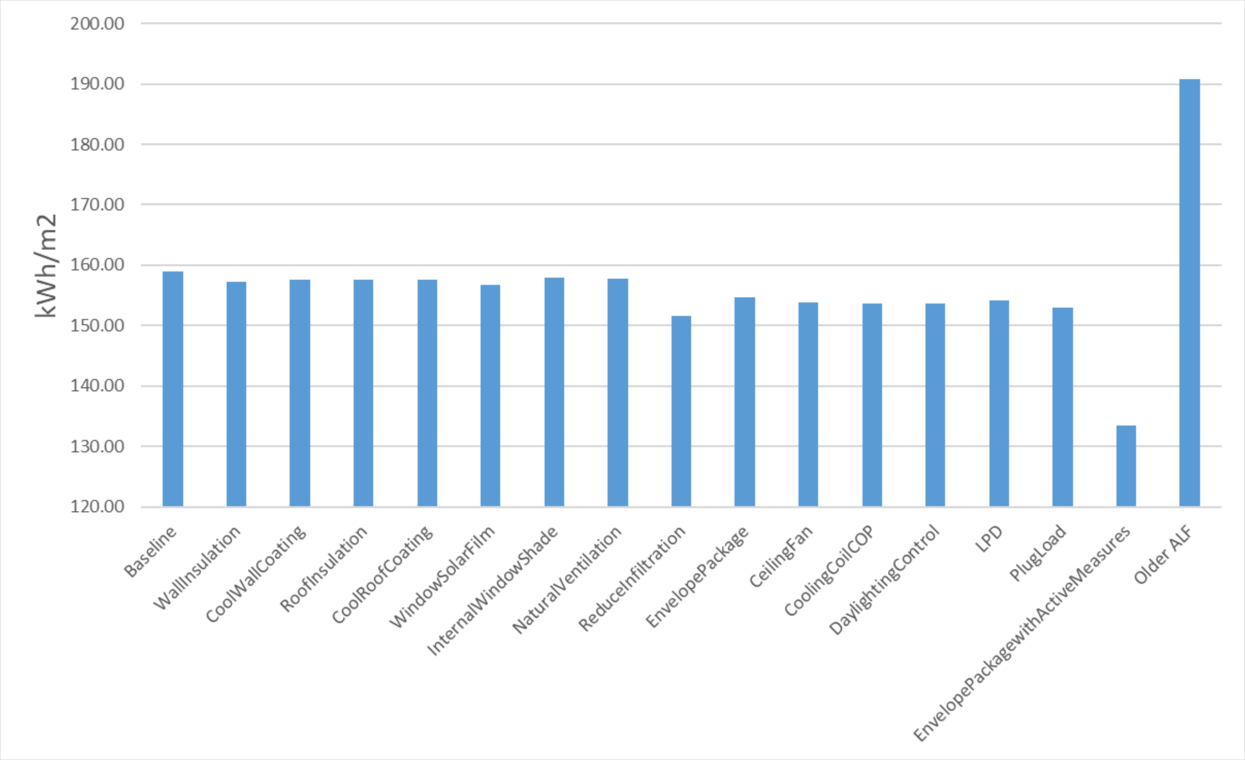


Figure 14. Annual site energy use intensity (EUI) of the baseline ALF, the mitigated ALFs with passive and active measures, and the older ALF

3.6 Influence of mitigation measures on the backup power capacity to provide full services for the three-day cold snap event

Figure 15 shows the simulation results of backup power capacity and peak demand to meet the full services of the ALF during the three-day cold snap period. The backup power system needed to provide 9,828 kWh with a peak demand of 177 kW. Passive measures had a limited impact on the power demand required to meet full energy usage. Three measures, cool roof coating, cool wall coating, and window solar film marginally increase power demand as they are intended to reduce solar heat gains. The complete upgrade package (Envelope Package with Active Measures) was able to reduce energy demand by 19%. In contrast, the older ALF would require a higher backup power capacity, about 18% higher than the baseline ALF. The peak demand of the backup power system for the baseline and other measures showed the same trend.

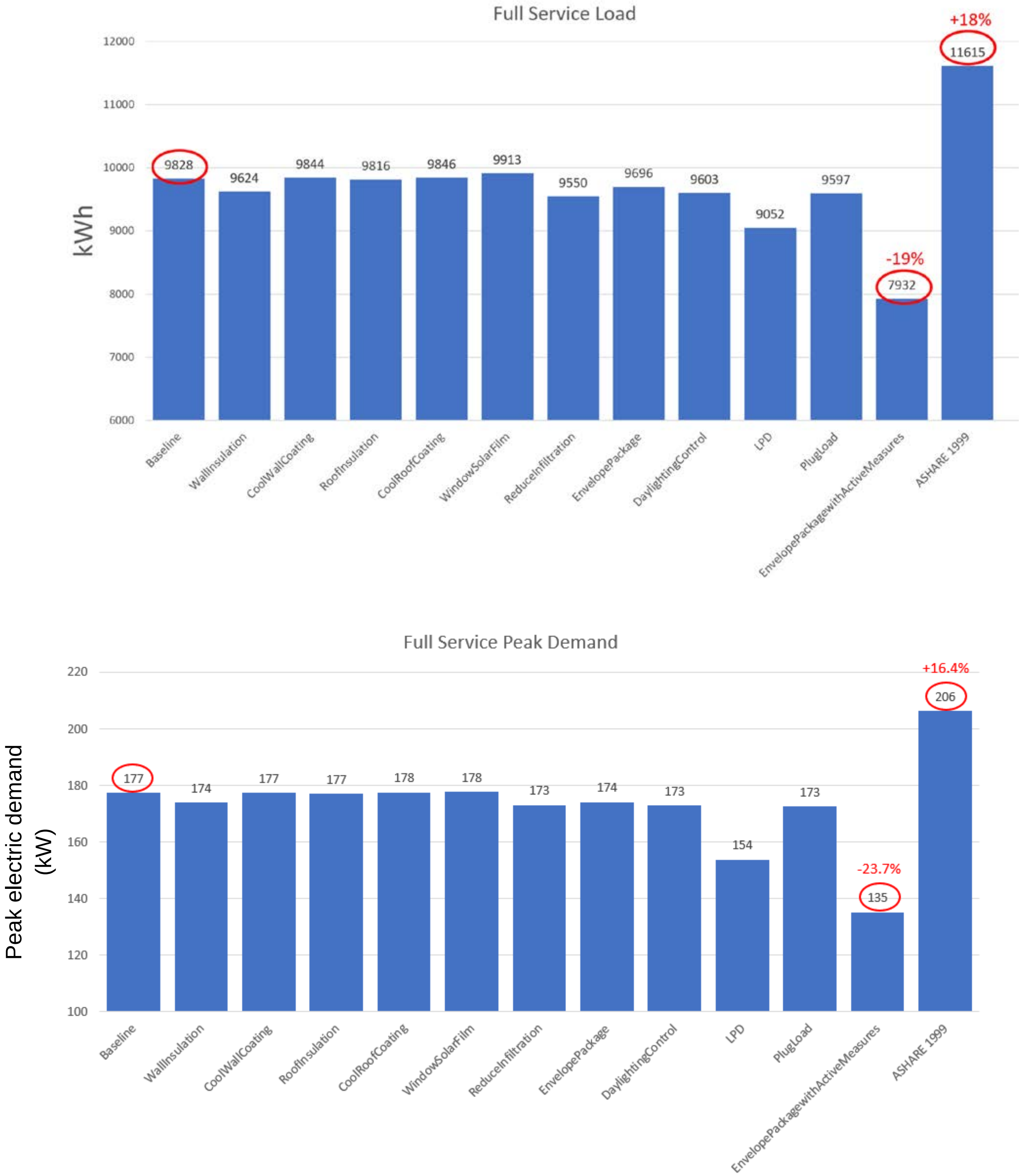


Figure 15. Backup power to provide full service loads for the three-day cold event. Top: backup power capacity in kWh; Bottom: backup power peak demand in kW

On-site power can be provided with various technologies including Solar PV, battery storage, diesel generators, or natural gas generators. One option of clean energy to provide the backup power is using on-site PV panels on the roofs. To provide the full-service capacity for the three-day event, about 3,280 kWh per day and a peak demand of 177 kW would be required. Since the facility has a pitched roof, with the assumption of 50% of the 3,861 m^2 roof area available for PV panels, PV system efficiency of 12%, and five solar hours in Houston, the PV panels could generate a peak power of 463 kW, which meets the peak demand of the baseline ALF. However, the PV panels only produce about 1,620 kWh per day, which is less than half of the daily full-service load. Therefore, PV panels alone are not enough to help the facility survive through the 3-day power outage during the snowstorm. Extra battery storage or fuel-sourced generators are necessary.

4. Discussion

4.1 Summary of findings

4.1.1 Thermal resilience of the baseline facility during the hot and cold events without a power supply

For the six-day heatwave in 2015, it took between two to four days (on average, three days) for the bedrooms to exceed 120 SET degree(°C)-hours, violating the LEED Passive Survivability criteria. This indicates that although the newly built baseline ALF is energy efficient, if not incorporated with natural ventilation, the heat could be trapped indoors, leading to excess heat exposure for residents. Depending on the location, orientation, and window area, there is a wide range in thermal performance across the resident bedrooms. Bedrooms on the second floor oriented to the south present the greatest risk due to solar heat gains through window and roof.

For the three-day cold snap in 2021 without a power supply, the baseline ALF performed relatively well—no bedroom had a SET temperature below 12.2°C (54°F). Only the worst bedroom had a SET below 15.6°C (60°F) for a few hours. The average time for the IAT of a bedroom to drop below the Minimum for Vulnerable Population level was 27 hours, and 60 hours for the Mild level. Bedrooms located at the middle of the bottom floor with no or fewer windows can maintain higher indoor temperatures due to less heat loss from the envelope. Using the Hours of Safety (indoor air temperature above 15.6°C (60°F)) as the metric, the bedrooms had from 9 to 74 hours of safety for residents—showing a wide variation of performance.

The wide varying thermal resilience of all bedrooms indicates that design and operation strategies should be considered with care for the most vulnerable bedrooms. Natural ventilation or low-power equipment (e.g., a portable or ceiling fan) may be essential to avoid deadly heat hazards for residents in more vulnerable bedrooms. Also, residents in those dangerous bedroom conditions could be considered for moving to safer bedrooms.

The overall thermal resilience of the baseline ALF during the hot and cold events without grid power indicates that although passive measures can be effective to improve indoor conditions for residents, they are far from adequate to maintain safe conditions, especially for the vulnerable population in the ALF. Therefore, backup power should be considered, or an emergency plan to quickly move the residents to a safe facility should be in place.

4.1.2 Influences of passive measures on the facility's thermal resilience

The influences of passive measures on the thermal resilience of the baseline ALF is complex, depending on the nature of each individual measure and type of extreme temperature event (cold or hot), as well as the resilience metric and criteria adopted for the evaluation. For the heat wave without power event, natural ventilation is the most effective passive measure to improve thermal resilience. The window film measure is the second most effective measure, while other passive measures have marginal improvements. Reducing air infiltration has a negative impact on thermal resilience, as it prevents heat from escaping during the night, when temperatures are cooler outdoors. For the cold snap event, mitigation measures provide opposite impacts on thermal resilience, particularly for measures that help reduce solar heat gain and infiltration. In addition, other measures that reduce solar heat gain, including the cool wall and cool roof coating, benefit the hot event but worsen the cold event. These results reinforce the need to consider thermal resilience for both extreme heat and cold. The prevalence of such types of events is also an important factor to consider.

Table 5 and Table 6 summarize the relative influences of the mitigation measures (against the baseline settings, negative values indicate improvements) on the thermal resilience of the ALF. The envelope package overall improves thermal resilience in both heat and cold events, as it includes measures that improve both cold and heat resilience (like wall and roof insulations), as well as measures that have contradictory performance (like infiltration reduction, window solar film, and cool wall and roof coating). This allows the envelope package to operate with flexibility in both scenarios. This also implies that passive measures will not work independently, but will be used coordinately to provide well balanced thermal resilience. Interior window shade, as a flexible measure that can be controlled manually, when operated with the correct schedule can prevent heat coming in during the day in heat events, as well as prevent heat escaping at night in cold events. Results in Table 5 and 6 show consistent performance improvements for the hot event using either the HI hours or SET degree-hours metric.

Table 5. Relative difference of HI hours in the Danger and Extreme Danger hazard levels during the six-day heat wave and in the Minimum for Vulnerable Population and Mild hours during the three-day cold snap

	Wall Insulation	Cool Wall Coating	Roof Insulation	Cool Roof Coating	Window Solar Film	Internal Window Shade	Natural Ventilation	Reduce Infiltration	Envelope Package
Heat Wave	-5.1%	-4.5%	-5.1%	-5.7%	-26.4%	-6.9%	-76.4%	+15.2%	-27.2%
Snowstorm	-8.0%	+1.3%	-0.7%	+0.9%	+3.9%	-4.3%	NA	-23.6%	-35.2%

Table 6. Relative difference of SET degree-hours (above 86°F) during the six-day heat wave. The SET degree-hours (below 54°F) during the three-day cold snap is 0.

	Wall Insulation	Cool Wall Coating	Roof Insulation	Cool Roof Coating	Window Solar Film	Internal Window Shade	Natural Ventilation	Reduce Infiltration	Envelope Package
Heat Wave	-4.2%	-4.1%	-4.5%	-5.1%	-27.0%	-8.8%	-61.6%	+20.2%	-31.8%

4.1.3 Energy efficiency measures reduce capacity of backup power system

The energy efficiency package, including both the passive envelope measures and the active efficient lighting and plug loads control measures, can reduce the needed capacity of backup power of the baseline ALF by 19%, to meet the full loads during the grid power outages. In other words, with the same backup power capacity, energy efficiency measures enable the ALF to operate longer safely during grid power outages.

4.1.4 An older facility would perform much worse during cold events and require a larger backup power system

The older ALF performs much worse than the baseline ALF during the extreme cold event, due to a less insulated and leakier envelope. The older ALF also increases indoor heat exposure faster than the baseline ALF during the extreme hot event; however, the older ALF performs better than the baseline ALF after the first day of the hot event because the baseline ALF traps solar heat gain and the well-insulated and airtight envelope reduce the heat release from indoors to outdoors. The older ALF consumes 20% more annual site energy, has a 16% higher peak demand than the baseline ALF, and requires 18% more backup power capacity to meet the full loads for the three-day cold snap event. In general, the older ALF can benefit from retrofits with both passive and active measures to improve thermal resilience and reduce energy use and peak demand. The active management of interior window shades and operable windows to enable natural ventilation are the two measures most effective in improving resilience.

4.2 Policy implications

While the energy efficiency requirements of newer building energy codes (e.g., well insulated walls, roofs, windows, and airtightness) have positive influences on improving the thermal resilience of occupants during extreme cold temperature events with power outages, the influences on the thermal resilience under extreme hot temperature events without power can be quite opposite. This is because a highly insulated and airtight building envelope traps solar heat gain and prevents nighttime cooling, leading to a higher temperature indoors than outdoors. Such a situation can only be mitigated with natural ventilation—indicating that natural ventilation or low-power mechanical ventilation is essential to help reduce the extreme temperature hazard for residents during hot summer days with power outages.

Current building energy codes (e.g., ASHRAE standard 90.1 for non-residential buildings) do not mandate minimal requirements on space cooling or heating to maintain safe indoor temperature conditions for occupants. The LEED green building certification system v4.1 has credits for passive survivability to encourage resilient design principles. In January 2022, U.S. Congressman Earl Blumenauer introduced the Climate Risk and Emergency Support in Livable Inclusive and Equitable Neighborhoods and Communities Everywhere (RESILIENCE) Act, a bold legislation to strengthen the Federal Emergency Management Agency's (FEMA) approach to climate disasters. The Climate RESILIENCE Act improves FEMA's disaster definition to include extreme temperature events, like heat waves and freezes.

Certain energy efficiency measures, such as making a building envelope airtight, may have conflicting influences on a building's thermal resilience—good for reducing heat loss from buildings during cold weather but bad for preventing heat loss from buildings during hot weather without power when the indoor air temperature is higher than that outdoors. Also, some passive measures may not show energy savings benefit, but they are critical to improve thermal resilience during extreme temperature events. Benefits of resilience mitigation measures should be evaluated across seasons and under various extreme hot and cold weather conditions. Low-cost and behavioral related measures such as natural ventilation should be encouraged (via awareness, behavior change, and training) and enabled (with operable windows) in the building design and operations.

Energy efficiency measures also reduce the size or capability of backup power equipment. This benefit should be incorporated in the benefit-cost analysis for energy efficient design or retrofit. Passive measures can improve thermal resilience of buildings but may not be adequate to fully maintain safe conditions for residents, especially during extended power outages under extreme hot or cold weather, which requires backup power for running HVAC systems to provide critical cooling or heating service.

Assisted living facilities are not currently required to have backup power. In Texas, assisted living facilities are required to have emergency plans but not on-site power generators. In California, the legal standard on backup power for nursing homes is limited. A decades-old regulation (State of California *Code of Regulations*, 22 CCR §72641) requires skilled nursing facilities to have backup power available for only six hours, and even then, only for exceedingly limited functions. Many states are discussing strengthening requirements of backup power for assisted living facilities and nursing homes, where residents comprise a vulnerable population with high risk of exposure to extreme temperature events when there is a power outage. The studied facility is considering installation of backup power to improve thermal resilience in future.

4.3 Limitations

This study has limitations. It is a simulation-based study using EnergyPlus models. Although the facility manager provided valuable information about the facility through an interview, necessary assumptions and simplifications were made in the building modeling and analysis. The simulated results were not calibrated due to the lack of utility bill data. While the simulated results are case specific, as they can vary due to the actual ALF design and operations (as well as the actual extreme weather conditions), the findings from the study are for general reference. The three-day cold event was based on the actual power outage of the ALF during the 2021 Texas snowstorm, while the six-day hot event in 2015 was selected from the historical extreme high temperature events. Therefore, readers should be cautious when trying to directly compare both events and the influences of mitigation measures on thermal resilience of the ALF during both events.

Infiltration was assumed to be constant and natural ventilation was activated when indoor air temperature is higher than the outdoor during the heat waves. Inter-zone airflow was ignored due to the consideration of privacy and acoustic concerns of the individual resident suites. These assumptions can be refined in future studies to more accurately account for the actual infiltration, natural ventilation and inter-zone airflow using methods such as those developed by Ng et al. (2014).

4.4 Future work

Thermal resilience of buildings is a multidisciplinary research topic touching upon building science, building technologies and design, climate science, occupant thermal comfort and health, building energy codes, and policy. Future research is needed to: (1) study and compare thermal resilience of ALFs in other climate zones and under future climate scenarios, to provide robust assessments and recommendations of mitigation measures, (2) provide recommendations on thermal resilience of ALFs to stakeholders and organizations that develop design and operation guidelines for ALFs, and (3) implement the mitigation measures in practice and measure their actual performance. Future research can also investigate how residents and facility operators may or should behave differently and the associated impacts on thermal resilience during extreme weather events with power outages.

Individual measures may not be cost effective. However, multiple measures may be effective when bundled together for implementation (from perspectives of costs and effort) at particular decision points, e.g., retrofitting the facility for improving indoor air quality (IAQ) or COVID-19 mitigation, energy retrofits to reduce carbon emissions, PV installation, changes to reduce insurance premiums, or installation of broadband internet connections. Adding cost effectiveness analysis of the mitigation measures can be helpful to decision makers. Transferring the quantitative thermal resilience metrics to benefits or losses of occupant health, productivity and well-being is another research topic linked to a framework of total benefit-cost analysis to inform decision making.

Further studies can also improve and consolidate current thermal resilience metrics for simplicity and standardization that can benefit the adoption of resilient design in policies and regulations. Three thermal resilience metrics were selected in this study to holistically assess the facility's risk of resident's exposure to extreme indoor thermal environment. SET degree-hours is used in the LEED Passive Survivability design credits that cover both the hot and cold events and can provide an overall evaluation of mitigation measures (e.g., envelope insulation, infiltration) that can show conflicting impacts on the built environment during the hot summer season and the cold winter season. The SET considers all the six major factors influencing thermal comfort of occupants and can be used to evaluate mitigation measures (e.g., interior window shades) that change indoor mean surface radiant temperatures or indoor air velocity due to the use of ceiling fans. However, there are questions on whether the adopted temperature thresholds (86℉ for hot events and 54℉ or cold events) can represent the occupant thermal risk under extreme cases. The heat index, adopted by US NOAA, defines clear heat hazard levels but only covers the hot events and does not consider influences of thermal parameters such as indoor air velocity, which is a key factor in evaluating the cooling effect of fans during summer. The heat index does not consider the accumulative hazard impacts (e.g., the number of hours an occupant exposes to the Danger hazard level). Neither the SET degree-hours nor the heat index uses different thresholds to represent the thermal vulnerability of different populations (seniors or people with medical conditions would be more vulnerable to extreme high or low temperatures than the healthy population). The Hours-of-Safety, developed by RMI and US EPA, does use different thresholds for the healthy and vulnerable populations but it only covers the cold events so far. It is designed to serve as the resilience score of buildings but it is hard to use to evaluate the thermal hazard and mortality of occupants which usually happens after the safe hours.

Benefits of backup power system for improving thermal resilience of buildings can be further studied. Determining critical loads (e.g., HVAC loads, refrigeration of essential medicine, emergency lighting, and charging of communication devices) in buildings to meet during extreme situations, comparing various backup power systems (e.g., PV + storage, on-site power generation) for economic and environmental benefits, and reasonably sizing the backup power system can support facility managers in planning and implementing a backup power system.

5. Conclusions

This paper presents a modeling and analysis framework using building performance simulation and three complementary metrics to assess thermal resilience performance of an assisted living facility located in the greater Houston area under both the extreme cold and hot weather events coincidently with power outages.

Although the facility was newly built, it still suffers from extreme indoor temperatures during the extreme hot and cold events with power outages. Passive envelope measures can improve thermal resilience of the facility; however, backup power is needed to run HVAC systems to provide thermally safe conditions for residents. Some envelope measures, such as making the envelope airtight, improves thermal resilience in cold events but makes it worse during hot events if windows cannot be opened for natural ventilation cooling. Natural ventilation can be an effective measure to mitigate summer indoor overheating, especially when indoor temperature becomes pretty high (higher than outdoor air temperature) during power outages. Energy efficiency measures can reduce the backup power capacity for meeting the full services of the facility during the power outages; however, this benefit is usually not accounted for in valuing energy efficiency.

Passive and active mitigation measures to improve thermal resilience of buildings may influence energy use, utility cost, and indoor air quality (e.g., an airtight envelope helps reduce infiltration during wildfire events when outdoor air is polluted) of the buildings. It is recommended that co-benefits of energy efficiency and thermal resilience should be considered in a holistic way to evaluate building technologies and design features which cover both the extreme cold and hot weather events and for the worst case with power outages. Requirements on thermal resilient building design should be defined in building energy codes or related policy; this is especially critical as globally buildings are transitioning towards carbon neutrality, and ensuring they are climate resilient is a timely necessity.

The modeling and analysis framework developed in this work can be adopted for studies to improve thermal resilience of other types of buildings, either residential or commercial, in various climates during extreme weather events with power outages. Although measure evaluation is based on simulation results and can benefit from field validation, it can inform cities, communities, and utilities in developing effective and targeted strategies to ensure thermal resilience for residents, especially the vulnerable populations during increasingly frequent extreme hot or cold weather events.

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References

ASHRAE. 2016. 1651-RP: Development of Maximum Technically Achievable Energy Targets for Commercial Buildings.

Athienitis, A., L. Wang, H. Ge, and J. Bambara. 2020. "Design and Operation of Resilient and Flexible Building." In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

Attia, S., R. Levinson, E. Ndongo, P. Holzer, O.B. Kazanci, S. Homaei, C. Zhang, et al. 2021. "Resilient Cooling of Buildings to Protect against Heat Waves and Power Outages: Key Concepts and Definition." *Energy and Buildings* 239: 110869. https://doi.org/10.1016/j.enbuild.2021.110869.

Ayyagari, S., M. Gartman, J. Corvidae. 2020. Hours of safety in cold weather: A framework for considering resilience in building envelope design and construction. Insight brief, Rocky Moutain Institute.

Baniassadi, A., et al. 2019. "Passive survivability of buildings under changing urban climates across eight US cities." Environmental Research Letters 14.7: 074028.

Baniassadi, A., et al. 2022. " Co-benefits of energy efficiency in residential buildings." Energy 238(1):121768.

Belova, A., Goldsmith, L., Greenwell, M. 2021. Future Heat Waves and Heat-Related Deaths Projected to Increase in the Pacific Northwest. ICF.

Burton, R., Robeson, A., & Nevins, R. 1975. The effect of temperature on preferred air velocity for sedentary subjects dressed in shorts. ASHRAE Transactions, 81(2):157–158.

Busby, J.W., et al. 2021. "Cascading risks: Understanding the 2021 winter blackout in Texas." Energy Research & Social Science 77: 102106.

City of Austin and Travis County. “2021 Winter Storm Uri AAR Findings Report,” 2021.

Crawley, D.B., L.K. Lawrie, F.C. Winkelmann, W.F. Buhl, Y.J. Huang, C.O. Pedersen, et al. 2001. EnergyPlus: creating a new-generation building energy simulation program, Energy Build. 33:319–331, https://doi.org/10.1016/ S0378-7788(00)00114-6.

Dahl, K., R. Licker, J. T. Abatzoglou, and J. Declet-Barreto. 2019. Increased frequency of and population exposure to extreme heat index days in the United States during the 21st century. Environmental Research Communications 1 (7), 075002, https://doi.org/10.1088/2515-7620/ab27cf.

Despart, Z. et al. “Analysis Reveals Nearly 200 Died in Texas Cold Storm and Blackouts, Almost Double the Official Count.” Houston Chronicle, Houston Chronicle, April 2. 2021. https://www.houstonchronicle.com/news/houston-texas/houston/article/texas-cold-storm-200-died-analysis-winter-freeze-16070470.php#:~:text=The%20deaths%20of%20nearly%20200,in%20Texas%20this%20past%20century.

Field, C.B., et al., eds. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press.

Gamero-Salinas, J., Aurora Monge-Barrio, Nirmal Kishnani, Jesús López-Fidalgo, and Ana Sánchez-Ostiz. 2021. “Passive Cooling Design Strategies as Adaptation Measures for Lowering the Indoor Overheating Risk in Tropical Climates.” *Energy and Buildings* 252: 111417. https://doi.org/10.1016/j.enbuild.2021.111417.

Gupta, R., A. Howard, M. Davies, A. Mavrogianni, I. Tsoulou, N. Jain, E. Oikonomou, and P. Wilkinson. 2021. “Monitoring and Modelling the Risk of Summertime Overheating and Passive Solutions to Avoid Active Cooling in London Care Homes.” *Energy and Buildings* 252: 111418. https://doi.org/10.1016/j.enbuild.2021.111418.

Hachem-Vermette, C. 2020. “Design Strategies for Climate Resilient Neighborhoods.” In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

Homaei, S., and Hamdy, M. 2021. “Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labeling metric”. Building and Environment, 201, 108022.

Howe, P.D. 2021. “Extreme Weather Experience and Climate Change Opinion.” *Current Opinion in Behavioral Sciences* 42: 127–31. https://doi.org/10.1016/j.cobeha.2021.05.005.

International Energy Agency Annex 80 – Resilient Cooling. 2022. Webinar 2: Future Weather Data and Heatwaves. https://www.aivc.org/sites/default/files/AllSlides_10.pdf

International Energy Agency and Organisation for Economic Co-operation and Development (IEA and OECD). 2018. The Future of Cooling: Opportunities for energy-efficient air conditioning. https://www.oecd.org/about/publishing/TheFutureofCooling2018Corrigendumpages.pdf

Ji, L., Shu, C., Laouadi, A., Gaur, A., Lacasse, M., Wang, L.et al. 2022. "Quantifying Building and Zone Level Thermal Resilience Against Summertime Heat Events." COBEE 2022.

Kennedy, C., and A. Pape_Salmon. 2020. “Jurisdictional Responsibility for Improving the Resilience of Buildings to Climate-Related Power Outages.” In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

Kesik, T., L. O’Brien, Amy Oliver, Yan Ferron, and William Harvey. 2020. “The Challenges of Developing Thermal Resilience Policies, Protocols and Procedures for Buildings.” In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

Kurtz J, Saur G, Sprik S, and Ainscough C. 2014. Backup Power Cost of Ownership Analysis and Incumbent Technology Comparison, NREL.

Larsen, P.H., et al. 2018. "Projecting future costs to US electric utility customers from power interruptions." Energy 147: 1256-1277.

Lawrence, C., 2021. Data analysis estimates 700 deaths in Texas from Winter Storm Uri. 31 May 2021. https://www.wsws.org/en/articles/2021/06/01/texa-j01.html

Liu, J.Z., C. Li, and M. Touchie. 2020. “Passive Strategies to Improve Multi-Unit Residential Buildings Thermal Comfort Resilience in Future Climate Scenarios.” In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

Luo, X., T. Hong, and K. Sun. 2021. Simulating thermal resilience of buildings and their influence by urban microclimate using EnergyPlus. IBPSA Building Simulation Conference.

Malik, A., C. Bongers, B. McBain, O. Rey-Lescure, R. de Dear, A. Capon, M. Lenzen, and O. Jay. 2022. “The Potential for Indoor Fans to Change Air Conditioning Use While Maintaining Human Thermal Comfort during Hot Weather: An Analysis of Energy Demand and Associated Greenhouse Gas Emissions.” *The Lancet Planetary Health* 6(4):E301–E309. https://doi.org/10.1016/S2542-5196(22)00042-0.

McIntyre, D. A. 1978. Preferred air speeds for comfort in warm conditions. ASHRAE Transaction, 84(1):264–277. http://ci.nii.ac.jp/naid/10020708104/en/

Melius, J., R. Margolis, and S. Ong. 2013. “Estimating Rooftop Suitability for PV: A Review of Methods, Patents, and Validation Techniques,” https://doi.org/10.2172/1117057.

Miller, D., Raftery, P., Nakajima, M., Salo, S., Graham, L. T., Peffer, T., Delgado, M., Zhang, H., Brager, G., Douglass-Jaimes, D., Paliaga, G., Cohn, S., Greene, M., & Brooks, A. 2021. Cooling energy savings and occupant feedback in a two year retrofit evaluation of 99 automated ceiling fans staged with air conditioning. Energy and Buildings, 251:111319. https://doi.org/10.1016/j.enbuild.2021.111319

Miller, W., Machard, A., Bozonnet, E., Yoon, N., Qi, D., Zhang, C. et al. 2021. “Conceptualising a resilient cooling system: A socio-technical approach.” City and Environment Interactions, 11:100065.Ng, L., Emmerich, S., Persily, A.K., 2014. “An improved method of modeling infiltration in commercial building energy models.” NIST Technical Note 1829, April 2014. http://dx.doi.org/10.6028/NIST.TN.1829

NOAA. “2020 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context. Climate.Gov.” Accessed May 3, 2022. https://www.climate.gov/disasters2020.

NOAA. “2021 U.S. Billion-Dollar Weather and Climate Disasters in Historical Context. Climate.Gov.” Accessed May 3, 2022. https://www.climate.gov/news-features/blogs/beyond-data/2021-us-billion-dollar-weather-and-climate-disasters-historical.

O’Brien, L., and T. Kesik. 2020. “A New Housing Stress Test: Codifying Thermal Resilience of Buildings.” In *Proceedings, Montreal Symposium*. Montreal, QC, Canada.

“Older Adults and Extreme Cold,” December 3, 2021. https://www.cdc.gov/aging/emergency-preparedness/older-adults-extreme-cold/index.html.

Ouzeau, G., J.-M. Soubeyroux, M. Schneider, R. Vautard, and S. Planton. 2016. “Heat Waves Analysis over France in Present and Future Climate: Application of a New Method on the EURO-CORDEX Ensemble.” *Climate Services* 4:1–12. https://doi.org/10.1016/j.cliser.2016.09.002.

Rajput, M., G. Augenbroe, B. Stone, M. Georgescu, A. Broadbent, S. Krayenhoff, and E. Mallen. 2022. “Heat Exposure during a Power Outage: A Simulation Study of Residences across the Metro Phoenix Area.” *Energy and Buildings* 259:111605. https://doi.org/10.1016/j.enbuild.2021.111605.

Ramasamy V, Feldman D, Desai J, Margolis R. 2021. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021. NREL.

Reiner, M., Franconi, E., Hong, T., Hotchkiss, E. 2022. Trials and Tribulations of Valuing Building Energy Resilience. 2022 ACEEE Summer Study on Building Energy Efficiency. https://aceee2022.conferencespot.org/event-data/pdf/catalyst_activity_32658/catalyst_activity_paper_20220810191654705_ca663b64_3f62_4fe8_98c8_939becbeb99c

Reisner, N., Fink, S. and Yee, V. 2017. Eight Dead from Sweltering Nursing Home as Florida Struggles After Irma. The New York Times. Sept. 13, 2017. https://www.nytimes.com/2017/09/13/us/nursing-home-deaths-florida.html

Rohles, F. H., Woods, J. E., Nevins, R. G. 1974. The effects of air movement and temperature on the thermal sensations of sedentary man. ASHRAE Transactions, 80(1):101–119.

Samuelson, H., A. Baniassadi, A. Lin, P. L. González, T. Brawley, and T. Narula. 2020. “Housing as a Critical Determinant of Heat Vulnerability and Health.” *Science of The Total Environment* 720:137296. https://doi.org/10.1016/j.scitotenv.2020.137296.

Sengupta, A., Steeman. M., and Breesch. H. 2020. "Analysis of resilience of ventilative cooling technologies in a case study building." 1st International Conference on Climate Resilient Built Environment-iCRBE. Vol. 1. No. 1.

Scheatzle, D.G., Wu, H., & Yellott, J. 1989. Extending the summer comfort envelope with ceiling fans in hot, arid climates. ASHRAE Transactions, 95(1):269–280.

Shield, S.A., S.M. Quiring, J.V. Pino, and K. Buckstaff. 2021. “Major Impacts of Weather Events on the Electrical Power Delivery System in the United States.” *Energy* 218:119434. https://doi.org/10.1016/j.energy.2020.119434.

State of California. *California Code of Regulations, (Vol. 30), Title 22, Social Security (Part 3)*. Accessed May 12, 2022. http://archive.org/details/gov.ca.ccr.22.3.

Stone, B., E. Mallen, M. Rajput, A. Broadbent, E.S. Krayenhoff, G. Augenbroe, and M. Georgescu. 2021. “Climate Change and Infrastructure Risk: Indoor Heat Exposure during a Concurrent Heat Wave and Blackout Event in Phoenix, Arizona.” *Urban Climate* 36:100787. https://doi.org/10.1016/j.uclim.2021.100787.

Stone, B., E. Mallen, M. Rajput, C.J. Gronlund, A.M. Broadbent, E. S. Krayenhoff, G. Augenbroe, M. S. O’Neill, and M. Georgescu. 2021. “Compound Climate and Infrastructure Events: How Electrical Grid Failure Alters Heat Wave Risk.” *Environmental Science & Technology* 55 (10): 6957–64. https://doi.org/10.1021/acs.est.1c00024.

Sun, K., Specian, M., and Hong, T. 2020. “Nexus of Thermal Resilience and Energy Efficiency in Buildings: A Case Study of a Nursing Home.” *Building and Environment* 177: 106842. https://doi.org/10.1016/j.buildenv.2020.106842.

The Administration for Community Living, and U.S. Department of Health and Human Services. “2020 Profile of Older Americans,” n.d. https://acl.gov/sites/default/files/Aging%20and%20Disability%20in%20America/2020ProfileOlderAmericans.Final_.pdf.

UNEP (United Nation Environment Programme). 2021. A Practical Guide to Climate-resilient Buildings & Communities. https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/36405/Adapbuild.pdf.

U.S. Green Building Council. “Passive Survivability and Back-up Power During Disruptions” Accessed May 3, 2022. https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-data-48.

USGCRP. 2018. “Fourth National Climate Assessment.” U.S. Global Change Research Program, Washington, DC. https://nca2018.globalchange.gov.

khou.com. “Winter Storm Forced Evacuations at 33 Long-Term Care Facilities,” February 10, 2021. https://www.khou.com/article/news/investigations/winter-storm-evacuations-long-term-care-facilities-houston/285-c02a7c05-d9da-4faf-aa93-8933ba4498b7.

van Hooff, Twan, et al. 2016. "Analysis of the predicted effect of passive climate adaptation measures on energy demand for cooling and heating in a residential building." Energy 94: 811-820.

Wilson, A. 2005. Passive Survivability. Building Green. https://www.buildinggreen.com/op-ed/passive-survivability

Wuebbles, D.J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock (eds.). 2017. U.S. Global Change Research Program, “Temperature Changes in the United

States," chapter 6 in Climate Science Special Report, Fourth National Climate Assessment, Volume I, (Washington, DC).

Zhang, C., O.B. Kazanci, R. Levinson, P. Heiselberg, B.W. Olesen, G. Chiesa, B. Sodagar, et al. 2021. "Resilient Cooling Strategies – A Critical Review and Qualitative Assessment." *Energy and Buildings* 251: 111312. https://doi.org/10.1016/j.enbuild.2021.111312.

Acronyms

ALF	Assisted Living Facility
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTO	Building Technologies Office, U.S. Department of Energy
DC	Direct Current
DX	Direct Expansion Cooling
EEM	Energy Efficiency Measures
EUI	Energy Use Intensity
FEMA	Federal Emergency Management Agency
HI	Heat Index
HOS	Hours of Safety
HVAC	Heating, Ventilation, Air-Conditioning
HVI	Heat Vulnerability Index
IAQ	Indoor Air Quality
IAT	Indoor Air Temperature
IEA EBC	International Energy Agency’s Energy in Buildings and Communities Programme
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
SET	Standard Effective Temperature
TMY	Typical Meteorological Year
USGBC	United States Green Building Council