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Abstract

Extreme weather events become more frequent and severe due to climate change. Although energy efficiency technologies can influence thermal resilience of buildings, they are traditionally studied separately, and their interconnections are rarely quantified. This study developed a methodology of modeling and analysis to provide insights into the nexus of thermal resilience and energy efficiency of buildings. We conducted a case study of a real nursing home in Florida, where 12 patients died during Hurricane Irma in 2017 due to HVAC system power loss, to understand and quantify how passive and active energy efficiency measures (EEMs) can improve thermal resilience to reduce heat-exposure risk of patients. Results show that passive measures of opening windows and doors for natural ventilation, as well as miscellaneous load reduction, are very effective in eliminating the extreme dangerous occasions. However, to maintain safe conditions, active measures such as on-site power generators and thermal storage are also needed. The nursing home was further studied by changing its location to two other cities: San Francisco (mild climate) and Chicago (cold winter and hot summer). Results revealed that the EEMs' impacts on thermal resilience vary significantly by climate and building characteristics. The study also estimated the costs of EEMs to help stakeholders prioritize the measures. Passive measures that may not save energy may greatly improve thermal resilience, and thus should be considered in building design or retrofit. Findings from this study indicate energy efficiency technologies should be evaluated not only by their energy savings performance but also by their influence on a building's resilience to extreme weather events.

Keywords: energy efficiency, resilience, extreme heat, heat index, buildings, occupant health

1. Introduction

Extreme heat is one of the leading causes of weather-related deaths globally, and the leading cause in the United States [1,2]. The impacts are felt in the developed world as well as in the developing world, in both warmer and cooler climate regions. The death toll from extreme heat events in recent decades has been significant. A 2003 European heatwave is estimated to have caused more than 72,000 deaths [3], while another in 2006 claimed an additional 4,495 lives [4]. A Russian heatwave in 2010 was responsible for up to 56,000 deaths [5], while a 1995 Chicago heatwave led to more than 600 casualties and 3,300 emergency room visits [6]. Other heatwaves in India/Pakistan in 2015, 2003, 2002, and 1998 [7–10], the United States in 1980 [11], and Greece in 1987 [12] each claimed more than 1,000 lives each. The impacts of heat stroke and other heat-related illnesses are particularly dangerous for marginalized and vulnerable populations, including very young children, the elderly, and those in poor health [13].

Climate change has exacerbated the frequency, duration, and intensity of extreme heat events [14]. Since the 1960s the number of heatwaves in American cities has tripled, from an average of about two per year to more than six per year. Over that same period, the length of the heatwave season has increased by 45 days [15]. It is projected that the number of days with a heat index exceeding 100°F (37.8°C) and 105°F (40.6°C) will double and triple, respectively, relative to a 1971–2000 baseline under multiple emissions scenarios [16]. Already upward of 600 Americans die each year due to extreme heat [17,18]. Climate change is projected to increase these negative long-term health impacts on multiple scales. In hot years the number of heat-related deaths in New York City could climb to thousands per year [19,20]. The number of premature heat-related deaths in Britain is expected to more than triple, to over 7,000 by mid-century [21]. And if current levels of carbon dioxide emissions continue unabated, it is estimated that the United States will experience tens of thousands of additional premature deaths by the end of the century [22–24].

The heat risks presented by buildings' indoor environments often exceed those of outdoor environments. About 120 people die in New York City each year due to extreme heat, and approximately 80% of those deaths occur in people's own homes [25]. While indoor air conditioning (AC) is highly effective at reducing these risks, there are many areas where AC is either unavailable or unaffordable. These include regions like San Francisco and much of Europe, where by virtue of their historically temperate climates air conditioning has generally not been necessary [26]. Yet even when AC systems are present, they can be rendered inoperable due to a mechanical failure or power outage [27,28]. If a building is further compromised by excessive heat-generating loads or an inability to ventilate hot indoor air to a cooler outdoor environment, the probability of adverse health impacts will increase. The problem can be exacerbated in an absolute sense by increasing nighttime temperatures [29,30] and the urban heat island effect, which keeps urban temperatures several degrees warmer than surrounding areas [31–33].

In addition, power system reliability appears to be trending in a negative direction. In recent years the duration and frequency of power outages for major U.S. utilities has increased by about 2% per year [34]. The number of weather-related outages in the U.S. has increased significantly since the early 1990s, from about 20% to 70% of all outages [35]. Moreover, the total duration of weather-related outages is typically longer than non-weather-related events [36,37]. Backup power, often in the form of stand-alone diesel generators, offers a hedge again these impacts but brings its own challenges. Generators are dependent on fossil-based fuel that can spoil in a year and replenishment is not always possible following a disaster. They also need to be serviced annually, can be difficult to operate, and offer little additional value under normal conditions.

One potential solution that warrants additional attention is behind-the-meter energy efficiency. It has been proven worldwide that building energy performance is significantly influenced by climate change [38–43], especially on peak demand at extreme scenarios [44–47]. The grid reliability will be challenged by climate change as well [48]. It is crucial that improving building energy efficiency and improving building resilience should be considered together. In fact, energy efficiency in buildings has well-established benefits, including driving economic growth, reducing energy costs and greenhouse gas emissions [49–51], decarbonizing the grid [52–54], and improving indoor air quality, health, and productivity [55–59]. However, the benefits that energy efficiency provide for resilience are less well explored, understood, and valued.

The concepts of resilience and energy efficiency have been considered in tandem before, most notably through the *passive survivability* framework [60]. It was observed following Hurricane Katrina that buildings that lost power but had passive architectural elements like window shadings, wraparound porches and ceilings that allowed thermal stratification of air, and designs that naturally channel cool breezes were better able to maintain livable conditions when electricity was lost. The LEED green buildings rating system has subsequently allowed Passive House certification to serve as a compliance pathway to earn its Resilient Design Pilot Credits [61,62]. Passive survivability is closely linked to the idea of *shelter-in-place*, or the ability to remain in one’s residence rather than evacuating following a disaster. One study found that highly efficient buildings in New York City extended the duration that residents could shelter-in-place following a blackout during a heatwave for up to several days as compared to typical buildings [63].

The connection between energy efficient and disaster-resistant design has been identified, as opportunities to better integrate efficiency and resilience prior to disasters and during post-disaster rebuilds [64–66]. Methods to finance these projects through various market and policy mechanisms have also been studied [67]. The National Institute of Building Science has estimated the levels of cost of the strategies to improve resilience, but only a very small portion of the investigated strategies are energy efficiency measures [68]. Others have explored the merits of individual passive cooling technologies like reflective coatings, earth-to-air heat exchangers, green roofs, cool roofs, and window blinds, as well as design elements like building orientation, structural density, and local topography [69–71]. Previous research has shown that energy efficiency may affect resilience when a building either has access to some form of (potentially limited) generation or must operate without power. In the former case, efficiency renders power generation more valuable by enabling building components to deliver critical services with less energy [72–75]. In addition, it may indirectly benefit other customers through reductions of net load on the grid. If a building has to operate without power, it must rely on passive measures to retain cool air, reduce internal heat gains, and reject excess heat to outdoors. Energy efficiency has been recognized as a tool to improve energy system reliability [74] and as a means of achieving energy security [76]. Mirhosseini et al. discussed the relationship between sustainability and resilience, and proposed a framework to describe the synergies between several resilience and sustainability building certification programs [77]. The New York City provides higher-level guidance on how to adjust a facility's design to account for increasing temperatures and to reduce the facility's contribution to the Urban Heat Island effect, including design based on forward-looking climate data and strategies like passive cooling, natural ventilation and backup systems to reduce heat impact [78]. The Enterprise Green Communities highlighted several energy efficiency measures, such as envelope efficiency, window shading and distributed heating and cooling system, as strategies to improve a facility's ability to adapt to changing climate conditions [79]. However, the above research has focused more on qualitative analysis rather than quantitative evaluation.

Katal et al. performed a case study on an urban area to evaluate the building and city resilience against the extreme events, using a urban platform they developed. A rudimentary retrofit analysis was also conducted to evaluate the added level of resilience [80]. This is a great research that developed a useful tool for evaluating energy efficiency and resilience on urban scale. However, only one energy efficiency measure was investigated and the evaluation of resilience was only limited to a single perspective of indoor temperature. More comprehensive and in-depth analysis on the nexus of energy efficiency and resilience is strongly needed.

While all these efforts offer a solid foundation, deeper dives that identify how energy efficiency characteristics map to resilience goals are less well-represented in the literature [81,82]. This is despite the fact that efficiency measures that yield similar energy savings under normal conditions can have markedly different resilience outcomes under adverse conditions. More comprehensive and quantitative analysis on the impact of energy efficiency on resilience is crucial for a deeper understanding of their nexus, and more practically, can facilitate the integrated design considering both energy efficiency and resilience in the future by the building industry. This is the gap to be addressed, and the focus of the paper.

In this paper, we introduced an in-depth case study of a Hollywood, Florida, nursing home where the main air conditioning system lost power for three days due to the impact of Hurricane Irma in 2017. 12 patients died because of excess indoor temperature. As the healthcare organizations in the U.S. spent more than $6.5 billion on energy each year and the industry continues to be one of the fastest growing in the economy [83], a lot of efforts have been spent on developing and implementing strategies to improve the energy efficiency and reduce the energy intensity of healthcare buildings [84–88]. On the other hand, the resilience of the healthcare facilities is particularly important against the potential impacts from extreme weather events like tornadoes, hurricanes, and floods [89]. The healthcare community and building industry have been actively exploring strategies and technologies to enhance the resilience of healthcare facilities [89–92]. Nonetheless, little has been done to build a bridge between energy efficiency and resilience for healthcare facilities. Research needs to be done to explore the connection and estimate the value of energy efficiency on resilience. In this study, *resilience* refers to the ability of a building to prepare for, withstand, recover rapidly from, and adapt to major disruptions due to extreme weather conditions, i.e., thermal or heat resilience.

In this study, we aim to answer the following questions:

(1) How does improvement of energy performance of buildings through energy efficiency measures influence a building's heat resilience? What is the methodology to quantify their nexus?
(2) Which passive energy efficiency measures offer the greatest resilience benefit, and at what cost? On what occasions should they be recommended?
(3) How effective are active energy efficiency measures in improving resilience, and at what cost? On what occasions should they be recommended?
(4) What current building energy efficiency codes and standards can be improved to integrate the consideration of energy efficiency and thermal resilience of buildings?

The remaining of the paper is organized as follows. In Section 2 we describe our methodology, which involved using publicly available data from real buildings that "failed" during a weather-related power outage to generate EnergyPlus building simulations to assess the impact of various efficiency measures on a building's thermal conditions. Part of this assessment will necessarily involve establishing resilience indicators. Holmes et al. [93] conducted a detailed examination of several indoor heat stress metrics, some of which we adopted in the analysis that follows. In Section 3 we provide an in-depth case study of a Hollywood, Florida, nursing home that lost power for three days following the loss of its main air conditioning system due to the impacts of Hurricane Irma in 2017. We outline our model development and calibration, outline the efficiency measures tested, and discuss the impact of the climate zone in which the building is located. We present our findings in Section 4, which includes an investigation of what would happen if the nursing home had been transplanted to either Chicago or San Francisco during recent heatwaves. Section 5 improves upon these results by introducing cost comparisons for individual and packages of energy efficiency measures. We discuss these results in Section 6 and offer conclusions in Section 7.

2. Methodology

2.1. Overview

The purpose of this study was to better understand how energy efficiency measures impact the resilience of buildings quantitatively under extreme heat conditions, and at what up-front cost. We conducted an analysis with a case study of a Florida nursing home in which 12 residents lost their lives after Hurricane Irma knocked out the power supply to the building's primary heating, ventilation, and air conditioning (HVAC) system. This is a representative case of hurricane causing an extreme heat disaster, which requires further attention as such hybrid disasters are becoming more frequent and severe due to the global climate change [94]. Moreover, major residents of nursing homes are elderly people; the number of which (ages 65 and older) is projected to double from 52 million in 2018 to 95 million by 2060, and their share of the total population will rise from 16 percent to 23 percent, according to the U.S. census [95]. This offered a representative case study since vulnerable populations such as the elderly are affected the most during disasters as such. For example, during the 2003 European heatwave, the majority of the 70,000 deaths were among the older people who were living in non-air conditioned retirement homes [3,96].

While dynamic thermal simulation and socio-technical system approaches can both be used to evaluate building performance [97–99], dynamic thermal simulation was adopted in this study as it focuses on the quantitative analysis from the technology perspective. We used EnergyPlus as the modeling tool to simulate the indoor thermal environment under various scenarios of building energy efficiency improvement. EnergyPlus is an open source program that models heating, ventilation, cooling, lighting, water use, renewable energy generation, and other building energy flows [100] and is the flagship building simulation engine supported by the United States Department of Energy (DOE).

Figure 1 illustrates the overall methodology and workflow of the case study: First, we collected information about the nursing home in Florida, USA, including year built, historical weather data, detailed floor plans, retrofit history, and internal heat loads. Based on the collected information, we developed an energy model of the nursing home in EnergyPlus and calibrated the model with available data; in this way, we were able to “replay” and analyze what actually happened in the building during the incident. We then applied multiple passive and active energy efficiency measures (EEMs) to the baseline energy model, and simulate their impact on the indoor thermal environment during the incident. Finally, we performed cost estimation on these selected EEMs, aiming to provide decision makers with both resilience and financial perspectives to help evaluate retrofit investment more comprehensively. Details are introduced in Section 3.

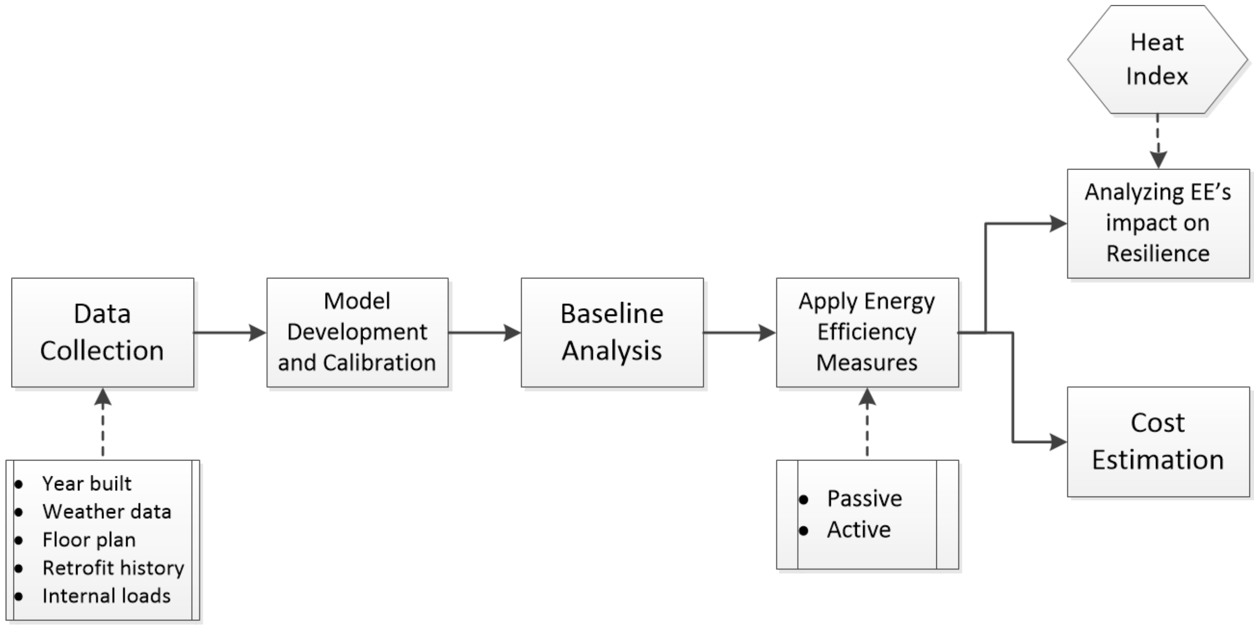


Figure 1. Overall Methodology and Workflow

2.2. Resilience metrics

2.2.1. Review of resilience metrics

Various metrics have been used to evaluate thermal resilience of buildings, which reflect the impacts of extreme events on human health. National and international meteorological and health related organizations and research institutes have had discussions about the metrics used to assess heat stress and thermal resilience [101–105]. Broadly, there are two types of metrics: simplified biometeorological indices and heat-budget models.

The simplified biometeorological indices are based on air temperature or a combination of air temperature and a measure of humidity, sometimes with consideration of how long the thresholds are exceeded. They are easy to calculate and forecast, have relatively higher forecast accuracy due to fewer input variables compared with complex indices, and are more easily understood by the general public and other stakeholders [103]. Typical simplified indices include heat index [106], humidex [107], wet bulb globe temperature (WBGT) [108], and net effective temperature [109]. Another two simplified metrics that have been developed recently are Passive Survivability-Winter (PSW) and Passive Survivability-Summer (PSS) [105]. They were initially derived for building designers to evaluate the resilience level of different design solutions, but were also used to evaluate retrofit measures [80]. One limitation of PSW and PSS is that they only consider temperature, which is relatively less comprehensive for evaluating thermal resilience.

Complex indices such as heat-budget models include the all-important meteorological and physiological parameters needed to better describe the physiological heat load: air temperature, water vapor pressure, wind velocity, and short- and long-wave radiant fluxes [103]. Heat exchange between the human body and the thermal environment can be described in the form of the energy balance or heat-budget equation. The thermal comfort of an individual is the result of a response to the balance between heat gains and losses. This is often expressed in the form of the human energy balance as described by heat-budget models. Typical heat-budget models include predicted mean vote (PMV) [110,111], standard effective temperature (SET*) [111,112], perceived temperature (PT) [113], physiological equivalent temperature (PET) [114], and universal thermal climate index (UTCI) [115]. While PMV and SET* are widely adopted as thermal comfort assessment criteria by ASHRAE Standard 55 [111], they are more suitable for evaluating the comfort level of occupants in conditioned zones, rather than the survivability of occupants under extreme conditions. Therefore, they are not used as the assessment criteria for heat resilience in this study.

2.2.2. Heat index

Heat index is widely used in the United States. The Occupational Safety and Health Administration (OSHA) uses heat index (HI) as an indicator to assess heat stress [104]. It is relatively easy to calculate and was adopted by the U.S. National Weather Service in 1979 to evaluate heat safety quantitatively [116]. Therefore, we selected heat index as the resilience performance metric to evaluate the human health risk under high temperature and humidity conditions. Table 4 and Table 5 in the Appendix define the four levels of heat hazards and their associated heat index ranges. All these characteristics make heat index a very suitable metric to be applied to quantitative analysis of extreme events.

The heat index, also known as the apparent temperature, is what the temperature feels like to the human body when relative humidity is combined with the air temperature. It posits a human-perceived equivalent temperature in shaded areas [116,117]. The human body normally cools itself by perspiration, or sweating. Due to the close relationship between perspiration and relative humidity, heat index is able to capture the human body's comfort more comprehensively than relying on temperature alone. The National Weather Service formulated the heat index based on the range of warm-season conditions we typically see on Earth. Formula (1) below approximates the heat index in degrees Celsius, to within 0.7°C. It is the result of a multivariate fit (temperature equal to or greater than 26.7°C and relative humidity equal to or greater than 40%) to a model of the human body [106,118]. This equation reproduces the values in Table 4 from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (except the values at 32.2°C and 45%/70% relative humidity vary unrounded by less than ±0.5°C, respectively) [116]. As shown in Table 5 (in Appendix), heat indices of or more than 39.4°C can lead to dangerous heat disorders with prolonged exposure and/or physical activity in the heat.

$$Heat\ Index = c_1 + c_2T + c_3R + c_4TR + c_5T^2 + c_6R^2 + c_7T^2R + c_8TR^2 + c_9T^2R^2 \qquad (1)$$

$T\ -\ air\ temperature\ (^0C)$

$RH\ -\ relative\ humidity\ (\%)$

c1 = -8.78469475556, c2 = 1.61139411, c3 = 2.33854883889,

c4 = -0.14611605,	c5 = -0.012308094,	c6 = -0.0164248277778,
c7 = 0.002211732,	c8 = 0.00072546,	c9 = -0.000003582

Heat index is generally used to evaluate heat stress on humans in an outdoor environment by, for example, NOAA, the World Health Organization (WHO), and the Occupational Safety and Health Administration [101,104,119,120]. However, as heat index was devised for shady, light wind conditions, which are very similar to the indoor environment, it was also used for the evaluation of indoor environment in previous research [102,121]. Considering its simple calculation and broad application, heat index and its classification on heat safety was adopted in this study as the metric to use to quantify the impact of building energy efficiency on heat resilience.

3. Case Study

To assess the relationship between resilience and energy efficiency in buildings, we conducted a case study of the Rehabilitation Center at Hollywood Hills. This two-story nursing home in Hollywood, Florida, USA, lost access to its HVAC system after a tree branch hit a transformer and dislodged a fuse during Hurricane Irma in 2017. After a three-day outage, 12 residents lost their lives due to extreme heat. According to government reports on the accident [122], the indoor temperature on the second floor was up to 99°F (37.2°C) during the incident, which was the major reason leading to deaths. We collected information about the nursing home, developed the building energy model in EnergyPlus, and calibrated the model with the available data. In this way, we “replayed” what actually happened in the nursing home during the incident. Then we applied multiple passive and active energy conservation measures to the model, and simulated their impact on the indoor thermal environment during the incident. Lastly, we estimated the costs of EEMs to provide more comprehensive information for decision makers on evaluating retrofit investment. Through this case study, we will better understand the extent to which energy efficiency improvements in buildings affect occupants’ resilience to heat.

3.1. Data Collection

Since the tragedy happened in 2017, the nursing home has been closed, and its license has been suspended. In this case, we collected information mostly through online resources, as shown in Table 1. Note that we obtained the building’s permit documents from the Building Division of the City of Hollywood, Florida, which provided much detailed information about the building, including detailed floor plans, envelope materials, and renovation history. Table 2 lists four major renovations, which had significant impacts on the building performance and were used for the input assumptions of the model.

The two-story nursing home was built in 1978, with a total area of 5,406 m^2. The building is equipped with a central air-conditioning system, using fan coil units for the patient rooms and variable air volume (VAV) terminals for the common area. As the building was built in the United States and it is mandatory to comply with building codes and standards at the year of construction, we assume that the efficiencies and properties originally comply with the appropriate ASHRAE standard 90.1-1989, while those of the renovated elements were updated with available newer ASHRAE standards, accordingly. For example, windows were replaced in 2001, so the window properties would comply with ASHRAE 90.1-2001; the roof was replaced in 2011, so the roof properties would comply with ASHRAE 90.1-2010.

The nursing home lost access to its primary AC system around 3:50 pm on September 10, 2017. The outage lasted more than two and a half days, until about 6:00 am on September 13, 2017. According to the facility records, there were ten rented portable air conditioners (ACs) and fans on site. Five portable ACs were placed on the first floor and four on the second floor, with one malfunctioning unit left. Additionally, portable fans were used in each resident unit, and large industrial fans were used in the hallways. The indoor temperature of the second floor soared to 99°F (37.2°C), which is the key information we used for model calibration.

Actual local weather data in 2017 was purchased from White Box Technologies, a private company specialized in weather data for energy calculations. They collected the measured weather data from the nearest weather station, Fort Lauderdale-Hollywood International Airport, which is about 6km from the nursing home. Figure 20 (in Appendix) illustrates the locations of the nursing home as well as the weather station. The collected actual weather data was applied to the building energy modeling in the following sections.

Table 1. Data sources and collected data types

Data Sources	**Collected Data Types**
City of Hollywood, Building Division	Detailed floor plan, building permit (i.e., retrofit history)
Property Shark Website	Year built, floor area, number of floors
Government report and news	Occupant number and distribution, monitored peak indoor temperature, timeline of the incident, portable AC, portable fans
Google Map Street View	HVAC system type, interior blinds
Nearest weather station, data compiled by White Box Technologies	Historical weather data

Table 2. Renovation history

Year	Renovation
2001	Window replacement
2011	Re-roof
2012	Central AC replacement
2016	Cooling tower replacement

3.2. Model Development

Based on the collected information, a baseline model of the nursing home was developed using DesignBuilder and EnergyPlus. DesignBuilder is one of the most popular graphical user interfaces of EnergyPlus, and was mainly used to develop the model geometry in this study. Figure 2 illustrates the 3D model that was built in DesignBuilder. The geometry, including detailed zoning, was drawn upon the floor plans in the building permit documents shared by the Building Division of the City of Hollywood.

As mentioned in Section 3.1, all the original input assumptions were based on the ASHRAE standard 90.1-1989 Climate Zone One [123], including envelope properties, internal loads, system efficiencies, and infiltration rate. With several major renovations, the performance of window, roof, and HVAC system were upgraded to the ASHRAE standard of the renovation years accordingly. Portable ACs were also added to the model and were set to run at full capacity throughout the incident.

The nursing home functions as a hospital. Figure 3 illustrates the two floor plans highlighting the locations of all the patient rooms with different number of people. All the other areas are public function spaces including intensive care unit (ICU), exam rooms, therapy rooms, kitchen, dining rooms, lounges, offices, conference rooms, corridors, stairs, retail, storage rooms, and a mechanical room. There are four one-patient rooms, 53 two-patient rooms, 25 three-patient rooms, and seven four-patient rooms in the building. Forty of the patient rooms were on the first floor and 49 on the second floor. All schedules of these space types come from the hospital and small hotel types in the DOE prototype model set [124], based on availability.

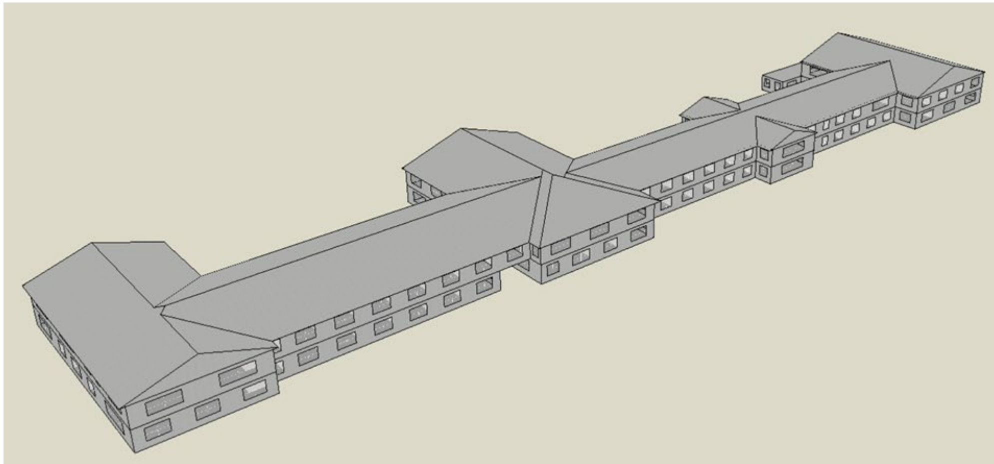


Figure 2. 3D model of the nursing home in DesignBuilder

Figure 3. Detailed floor plans of the first (upper) and second (lower) floors

3.3. Model Calibration

As the facility has been closed since the incident happened in 2017, it was challenging to get historical energy consumption data for calibration purposes. In this case, we adopted available information from public sources for calibration instead of using energy use data. According to the investigation report by the Agency for Health Care Administration [122], the indoor temperature on the second floor rose to 99°F (37.2°C) during the incident, which serves as the "true answer" for calibration. We performed the building energy model calibration through the following steps:

1) Calibrate HVAC system settings based on building design document;
2) Calibrate occupant density based on the investigation reports issued by government;

3) Update the efficiencies of envelope and HVAC system based on building retrofit history from the building permit records;
4) Add portable AC and portable fans according to the investigation reports issued by government;
5) Adjust several other parameters with higher uncertainty and larger impact on energy use, including plug load density, schedules, and infiltration rate.

Figure 4 illustrates the indoor temperature of a hotspot patient room on the second floor and the outdoor air temperature during the incident. The peak temperature is 99.2°F (37.3°C), which proves at a certain level that the baseline model reflects the real situation of the nursing home during the incident.

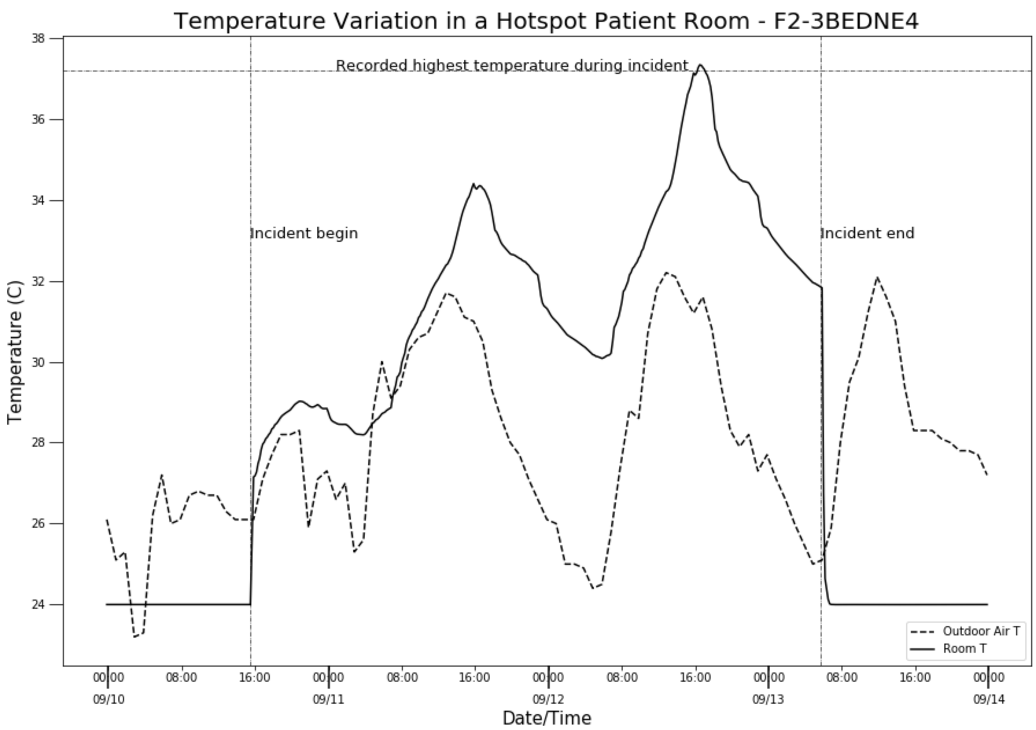


Figure 4. Temperature variation in a hotspot patient room during the incident

3.4. Energy Efficiency Measures

To investigate whether improving building energy efficiency can improve the heat resilience in this nursing home case, we applied multiple passive and active EEMs to the baseline model and evaluated the impact quantitatively. These EEMs were selected from the perspective of their potential influences on both the energy performance and heat resilience of buildings. They were not selected purely based on the potential energy savings.

An EEM is categorized to be a passive measure if it still works when the power is off. On the contrary, EEMs that require full or partial power supply are considered to be active measures. The measures selected are summarized in Table 3 and described in this section.

Table 3. Summary of investigated energy efficiency measures

Category	Measure Name
Passive	- Shield windows with aluminum foil - Shield the roof with aluminum foil - Apply cool roof coating - Seal windows and doors to reduce infiltration - Add insulation to exterior walls and roofs - Replace with low-emissivity (low-e) windows - Exterior overhang shading - Natural ventilation - Reduce/Turn Off Light and Miscellaneous Electric Loads (MELs)
Active	- Install onsite power generation, e.g., solar photovoltaic, to provide a 50% power supply to the HVAC system - Add thermal storage
Packages	- Low/no cost oriented - Operation oriented - Design oriented

3.4.1. Passive measures

This study considered four types of passive measures: envelope, shading, natural ventilation, and reduced light and plug load. Reducing light and plug load is categorized as a passive measure because it still works when the HVAC system is powered off, which was the case in this study.

(1) Envelope

The following measures were included in this envelope category:

- Shield windows with aluminum foil

Aluminum foil has about 98% solar reflectance, so it barely absorbs any solar heat from the sun. Since solar heat gain is one of the main heat sources for windows, applying aluminum foil on a window is expected to reduce solar heat gain significantly. This is an extreme case of improving window performance.

- Shield the roof with aluminum foil

As is true with the windows, the solar heat gain through the roof is also considerable, especially for low-rise buildings. However, note that aluminum foil will also cut down radiant heat emission from the roof to the ambient (especially the sky) due to its very low thermal emissivity. This counter effect can be higher on the roof than on a window, as the roof temperature is usually much higher than the window temperature during the night.

- Apply cool roof coating

Different from aluminum foil, a cool roof has both high solar reflectance and high thermal emittance. Therefore, cool roofs can stay cool in the sun and at night by minimizing solar absorption and maximizing thermal emission [125,126].

- Seal windows and doors to reduce infiltration

For conditioned buildings, reinforcing air sealing can reduce the amount of unexpected outdoor air into the building, thus generally reducing the HVAC system's cooling and heating load.

- Add insulation to exterior walls and roofs

Adding insulation can cut down heat transfer from the outdoor environment to the interior spaces, which will reduce the HVAC system's cooling and heating load.

- Replace with low-emissivity (low-e) windows

This is another measure used to improve window performance; it is more common and less extreme than the aluminum foil measure.

(2) Shading

Exterior shading is added via an overhang to the windows.

(3) Natural ventilation

Natural ventilation is a key measure to get free cooling when the outdoor air temperature is lower than the indoor air temperature. The windows were assumed to remain closed during the incident, based on two considerations: (1) There were nine portable ACs set up and running after the central HVAC system was down. People are often instructed to close the windows to avoid cooling leakage when the AC is on [127]; and (2) For security purposes, windows may be locked to avoid suicide [128,129].

(4) Reduce/Turn Off Light and Miscellaneous Electric Loads (MELs)

While the HVAC system was powered off, other systems were operating normally, including lights and MELs. Lighting can be turned off when daylight is available, while MEL usage can be reduced to a minimal requirement, e.g., critical medical equipment to maintain patient health.

3.4.2. Active measures

This study considered two active measures:

(1) Install onsite power generation, e.g., solar photovoltaic, to provide a 50% power supply to the HVAC system.

Assuming that onsite power generation, e.g., from solar photovoltaics, were added to the building to provide 50% of power supply, the HVAC system could then be operated to provide cooling with reduced capacity. However, there are preconditions for this measure. If the chiller is down and needs to be restarted, it should be equipped with a variable speed starter to allow starting under a lower inrush current. If the chiller is not down and keeps running, the chiller should be equipped with variable frequency drives to guarantee normal operation under partial power supply.

(2) Add thermal storage. Three capacity options were investigated: 8, 12, and 24 hours of cooling supply.

A chilled water tank, one of the most common thermal storage technologies, was added to the HVAC system. There is a precondition for this measure. Since chilled water tank discharge is generally on the secondary loop of the HVAC system and only requires the chilled water pump to supply stored chilled water to the terminals, only a minimal power supply is needed to keep the chilled water pump and terminal fans running. Three options were investigated: 8, 12, and 24 hours of full cooling capacity supply. Full cooling capacity refers to the chiller capacity.

3.4.3. Packages

Integrated packages on the passive side were also evaluated, to explore the maximum potential on a completely passive status. Three packages were investigated based on different selection criteria:

(1) Low/no cost, which can minimize the investment cost: Natural Ventilation + Reduce MELs (Miscellaneous Electric Loads, i.e., light and plug load) + aluminum (Al) foil window + Al foil roof
(2) Operation oriented, which can minimize the interruption of building operation due to major retrofits: Natural Ventilation + Reduce MELs
(3) Design oriented, which focuses on the envelope and could be an early stage preventive intervention: Add insulation + Cool Roof + Overhang shading + Low-e window

3.5. Influences of Climate Zones

This tragedy happened in Hollywood, Florida, which is in ASHRAE climate zone 1A, where the weather is hot and humid. The buildings' performance, especially envelope properties, should comply with the building codes of that specific climate zone. However, what if the building was built in other climates? Would it react the same way as it did in Florida? Would the above EEMs have the same impact on resilience? What different strategies people should take to improve the resilience?

Under these considerations, we “moved” the nursing home from Florida to two other typical U.S. climates: San Francisco (SF) for a mild climate and Chicago for a hot-summer and cold-winter climate. The original baseline model was modified to reflect local building codes, including the efficiency upgrades from major renovations. Moreover, we adopted local disasters instead of the Florida hurricane. The 2017 SF heatwave and the 2012 Chicago heatwave were selected, and the measured historical weather data of the corresponding years in these two cities were used in the EnergyPlus simulations. The weather data was purchased from White Box Technologies which were collected from local weather stations. The SF heatwave lasted four days, from August 31 to September 3, which is the same length as the original Florida incident, while the

Chicago heatwave lasted five days, from July 3 to July 7. So the time span remained the same for the SF case but was extended one day for the Chicago case. We assumed the same problem happened in the building, i.e., the HVAC system lost power.

4. Results and Analysis

4.1. Baseline

From the calibrated baseline model, we simulated the indoor environment and calculated the heat index for all the patient rooms throughout the incident, as shown in Figure 5. The figure is segmented into five zones, according to the heat hazard classification in Table 5, with heat index below 80°F (27°C) being considered as safe. In this box plot, the upper and lower boundaries of each whisker represent the maximum and minimum heat index of all the patient rooms at this particular time. The upper and lower edges of each box represent the third and first quartiles. The band inside the box represents the median value. The heat index started to ramp up from the moment the HVAC system was cut off, and peaked at 120°F (49°C) on the late night of the third day. Right on the early morning of the next day, life failures started to happen, which implies the severe consequences of extreme heat in the indoor environment.

Note that the heat index range was also increasing as the incident developed. In the beginning, all rooms were conditioned at the same temperature. When the HVAC stopped working, the temperature of different patient rooms started to deviate due to different locations and internal heat gain. The second floor, especially, heated faster due to the stack effect and extra heat gain from the roof. This explains why the second floor became warmer and more deaths happened on the second floor. The internal heat gain also varied considerably with different occupant density in patient rooms, e.g., there were one-patient rooms, two-patient rooms, three-patient rooms, and four-patient rooms in the building.

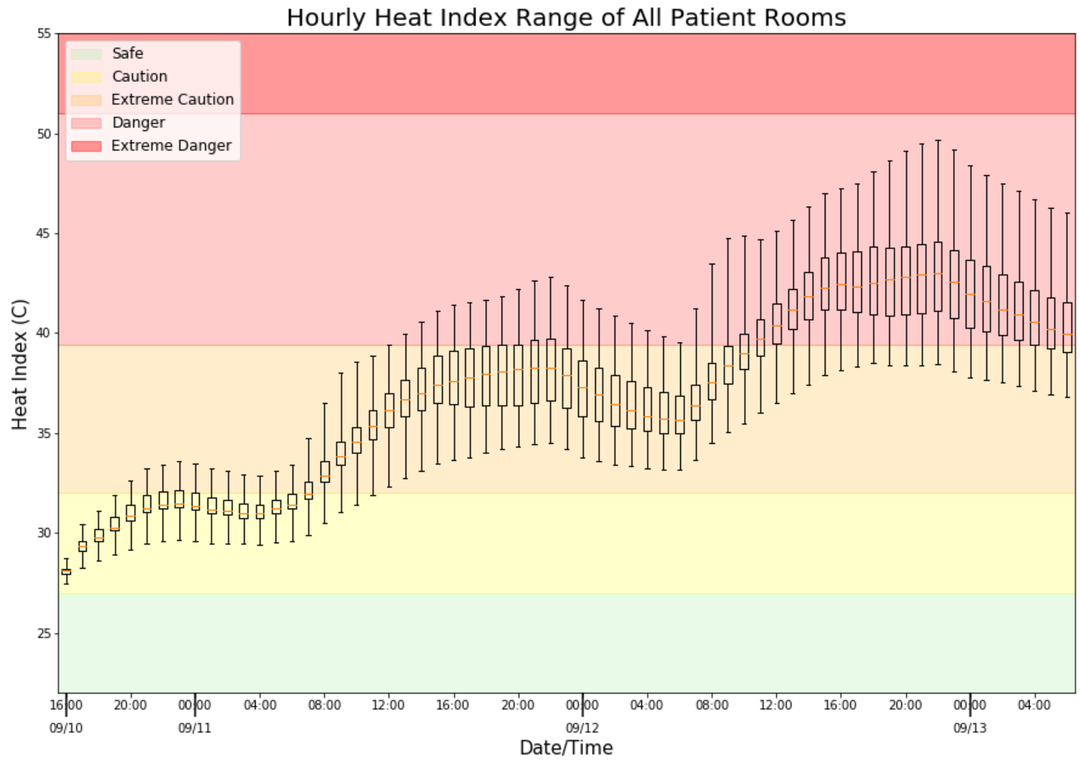


Figure 5. Hourly heat index box plot of all patient rooms

4.2. EEM Impact on Resilience

4.2.1. Passive measures

Figure 6 illustrates the heat index occurrence distributions of the baseline and the passive measures. An *occurrence* is defined as a level of heat index that happened at one time step in one patient room. To be more specific, there are 89 patient rooms in the building, and we simulated indoor temperatures once every 10 minutes (time step) for a total of 62 hours. We therefore had $89 \times 62 \times 60/10$ room-time steps, which we stacked up. Therefore, occurrence distribution is the overall temporal and spatial percentage (i.e., room-time steps percentage) on each level of heat index. Take the baseline as an example: the room-time steps at the "Caution" level accounts for about 22% of all room-time steps.

The occurrence percentage of levels "Danger" and beyond (i.e., Danger and Extreme Danger), named "Danger+", was adopted as the indicator to quantify the resilience improvement. Among all the single passive measures, natural ventilation performed the best, reducing "Danger+" from 32.3% to 1.2%. This is because the indoor temperature exceeded the outdoor temperature a majority of the time, as shown in Figure 4. Natural ventilation can bring in a large amount of free cooling. We assumed the windows remained closed during the incident based on considerations elaborated in Section 3.4.1(3). Natural ventilation was followed by reducing lighting and MELs, which reduced "Danger+" to 6.5%. Our current assumption is relatively conservative, so potentially this measure could improve even more if implemented more aggressively.

It is noted that the improvement for all window measures, including shielding windows with aluminum foil, adding overhang shading, and replacing existing windows with low-e windows, were limited. Aluminum foil is the extreme case of improving window performance, but it still achieved only 25.2% “Danger+.” This is because the nursing home is located in Hollywood, Florida, which is in ASHRAE climate zone 1A. The building code for window performance is already very stringent, especially with a 0.25 solar heat gain coefficient (SHGC), which leaves limited room for improvement.

The only passive measure counters resilience is reducing infiltration. For conditioned buildings in general, reducing infiltration can help cut down unexpected heat gain from outside air, which saves energy for the HVAC system. However, in the nursing home case where the outdoor environment was actually cooler than the indoor environment, reducing infiltration ends up being harmful for resilience, as it functions in the opposite way that natural ventilation does. Therefore, while reducing infiltration can be an effective EEM, it can reduce resilience when facing such disasters.

For packages, both low-cost and operation-oriented packages exhibited excellent performance, surpassing any of the single measures. Considering that the design oriented package only focuses on envelope, and there is very limited improvement available for window performance in Florida, the design oriented package performs just slightly better than single design measures, and not as good as natural ventilation and reducing lighting and MELs. Note that the best performing passive measure package can eliminate all the occurrence of the “Danger+” level, keeping the hazard level at Extreme Caution and below. If a hazard level of Extreme Caution is acceptable, passive measure(s) could be an optimal choice in this situation.

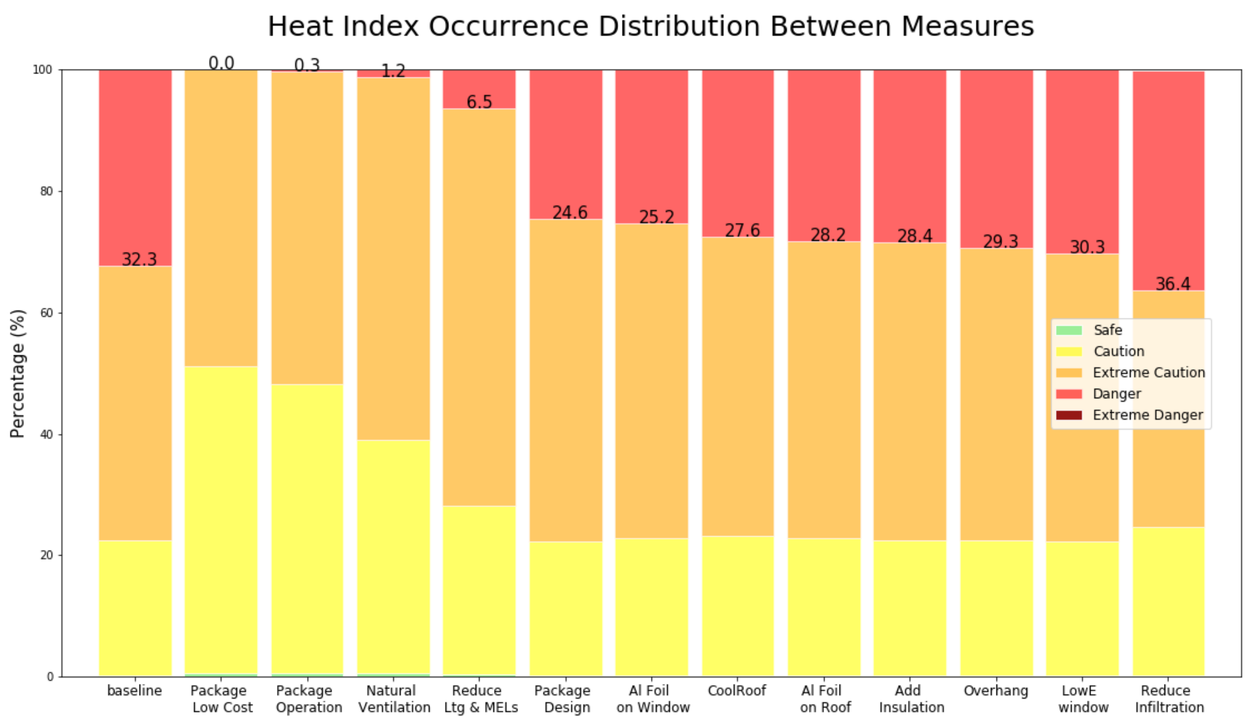


Figure 6. Heat Index Occurrence Distribution of Baseline and Passive Measures

4.2.2. Active measures

Figure 7 illustrates the heat index occurrence distribution of the baseline and all the active measures. Full power supply, which can provide 100% safe time, was added here as a reference point. Half power supply is able to provide more than 90% safe time. Thermal storage with 12-hour and 24-hour supply can both achieve 100% safety, while an 8-hour supply can achieve safety about 70% of the time. Note that, with 8-hour thermal storage, the temperature of a hotspot patient room would remain at a normal cooling setpoint for more than a day and a half after the incident happened, as shown in Figure 21 (Appendix). Afterwards, the thermal storage would run out and the indoor temperature would start to rise rapidly. Therefore, the efficacy of thermal storage actually depends on how long the event lasts. If the event lasts longer, thermal storage with small capacity can only guarantee the first couple of days, while the rest of the event could still be in danger.

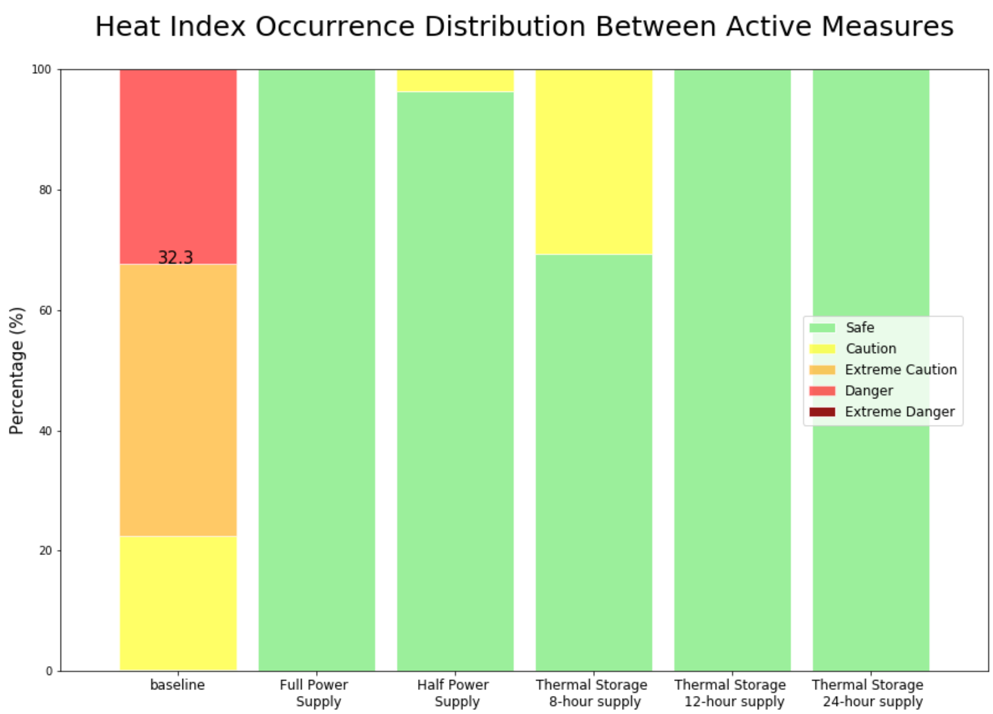


Figure 7. Heat Index Occurrence Distribution of Baseline and Active Measures

4.3. San Francisco

As stated in Section 3.5, we "moved" the nursing home from Florida to San Francisco (SF) and Chicago to evaluate the resilience and EEM impact in other climates. The 2017 SF heatwave from Aug 31 to September was selected as the outside environment and we assumed the same problem happened in the building—the HVAC system lost power. The SF heatwave lasted four days, which is the same length as the original incident, so the time span was kept the same.

4.3.1. Baseline

As shown in Figure 8, the indoor temperature of a hotspot patient room rose to as high as 110°F (43°C) during the incident. However, on the other hand, the heat index (Figure 9) remained no higher than the original Florida case. This is because even though the dry bulb temperature was higher in SF, the relative humidity in SF is much lower than in Florida. In other words, a hot and dry environment and a warm and humid environment could both be dangerous but result in no significant difference in terms of the overall impact on human bodies.

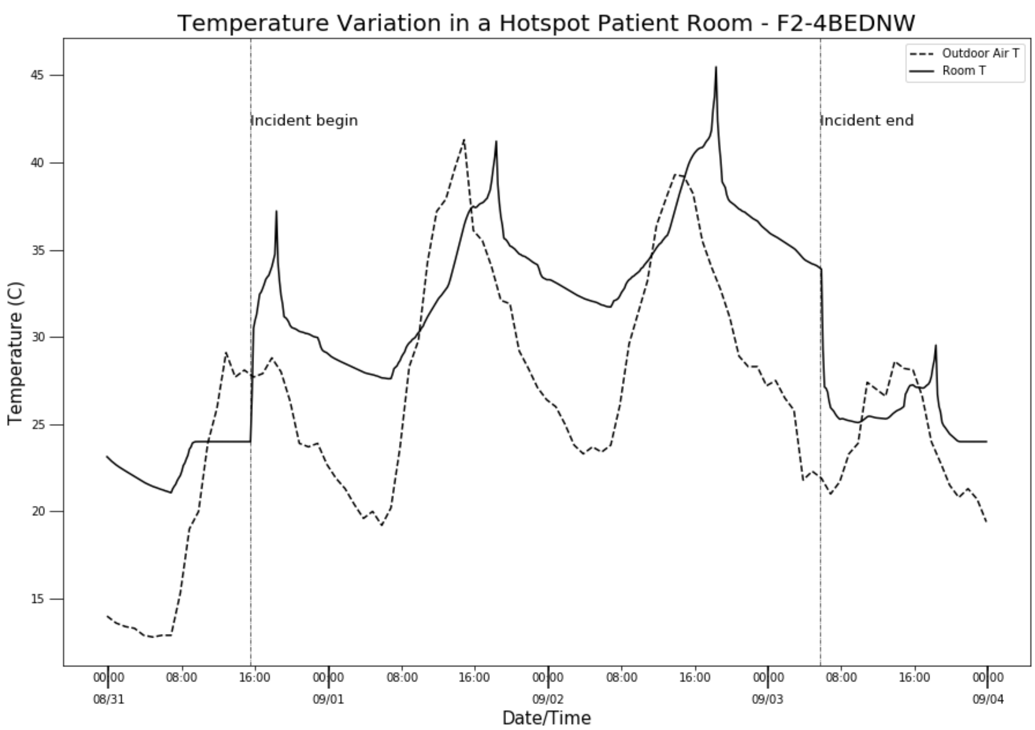


Figure 8. Temperature variation in a hotspot patient room during the incident - SF

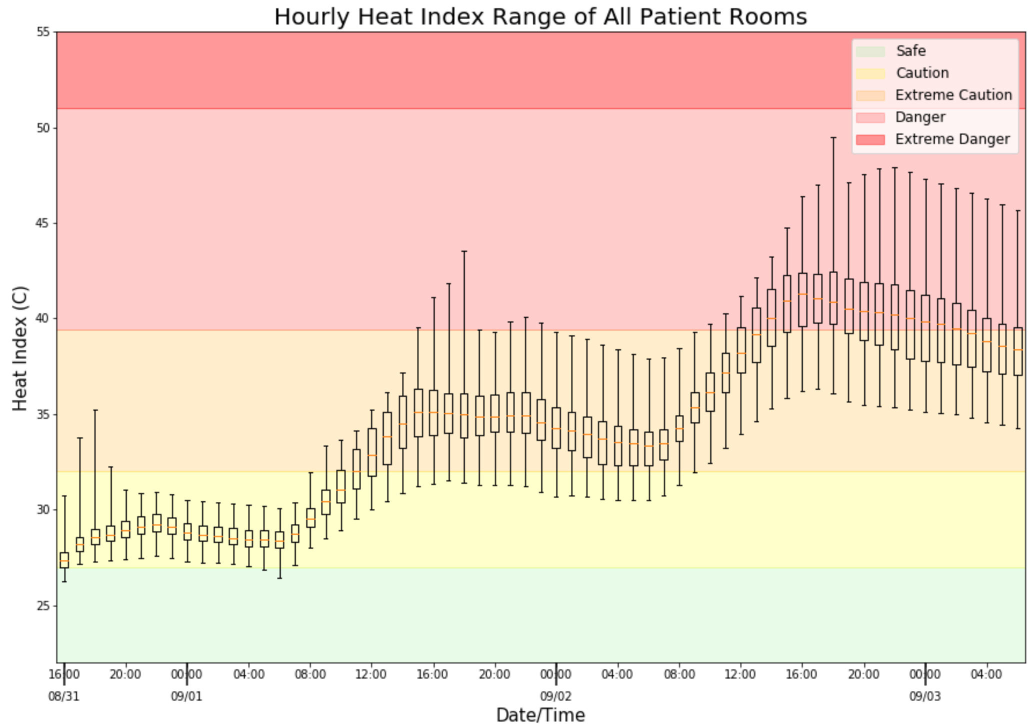


Figure 9. Hourly heat index box plot of all patient rooms - SF

4.3.2. Passive measures

For the passive measure packages, the results of SF (Figure 10) are similar to the original Florida case. However, for single passive measures, the results were quite different: (1) Natural ventilation was no longer the top performing single measure. This is because the outdoor temperature during the incident was much higher than in the Florida case, leading to much less time available for beneficial natural ventilation, especially during the daytime, as indicated in Figure 8. (2) All the window measures (aluminum foil on windows, low-e windows, and overhang shades) performed better than they did in Florida. This is because the building code for window performance in SF is not as stringent as it is in Florida, therefore the SF baseline leaves much more room for improvement. Besides, the best performing passive measure package could eliminate almost all occurrences of the “Extreme Caution+” level, keeping the hazard level at Caution and below. If a hazard level of Caution is acceptable, passive measure(s) could be an optimal choice in this situation.

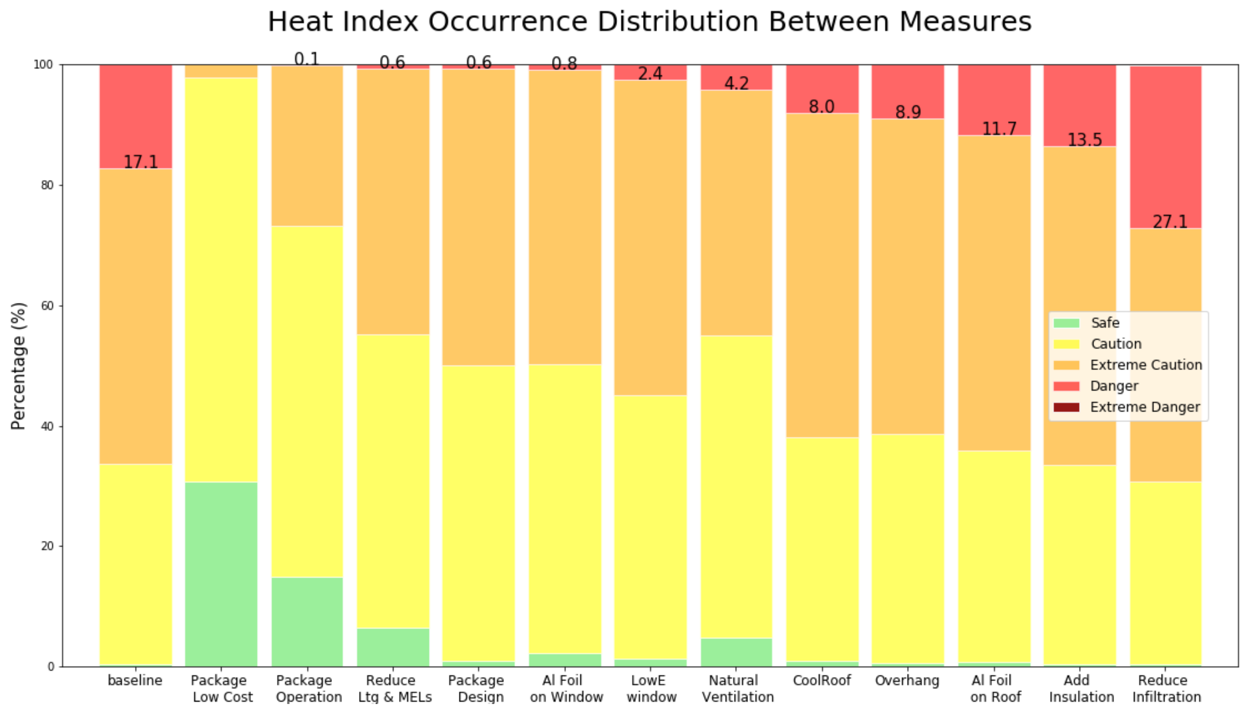


Figure 10. Heat Index Occurrence Distribution of Baseline and Passive Measures - SF

4.3.3. Active measures

The results of active measures (Figure 11) are similar to those of the original Florida case, except that thermal storage with 12-hour and 24-hour supply start to show a small portion of "Caution" time.

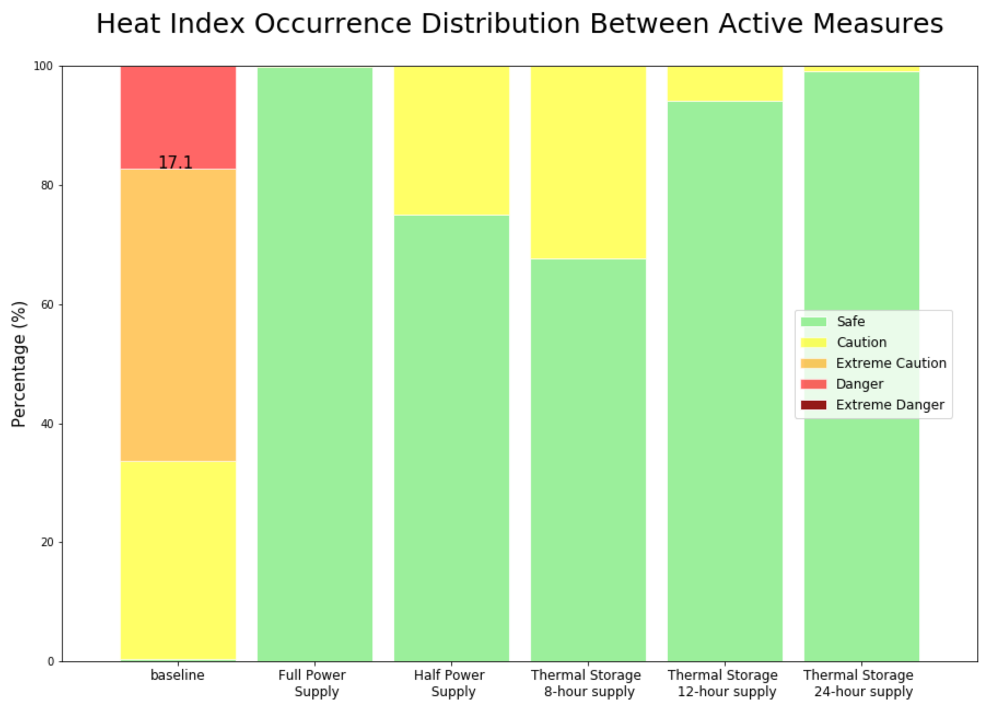


Figure 11. Heat Index Occurrence Distribution of Baseline and Active Measures - SF

4.4. Chicago

The 2012 Chicago heatwave from July 3 to July 7 was selected as the outside environment. We assumed the same problem happened in the building—the HVAC system lost power. As the Chicago heatwave lasted five days, which was one day longer than the original incident, the time span was extended one day.

4.4.1. Baseline

As shown in Figure 12 and Figure 13, the temperature of a hotspot patient room rose to over 105°F (41°C) during the incident, and the heat index rose to almost 140°F (60°C), far beyond the “Extreme Danger” boundary. In fact, starting from the evening of the third day, a small portion of the patient rooms had entered the “Extreme Danger” zone, and on the fourth day, more than half of the patient rooms were in “Extreme Danger.” Because the Chicago incident lasted a day longer, the indoor environment would become even more dangerous, especially for vulnerable populations such as the patients in the nursing home. Most of them do not have the ability to move freely, or may have to constantly rely on some medical equipment.

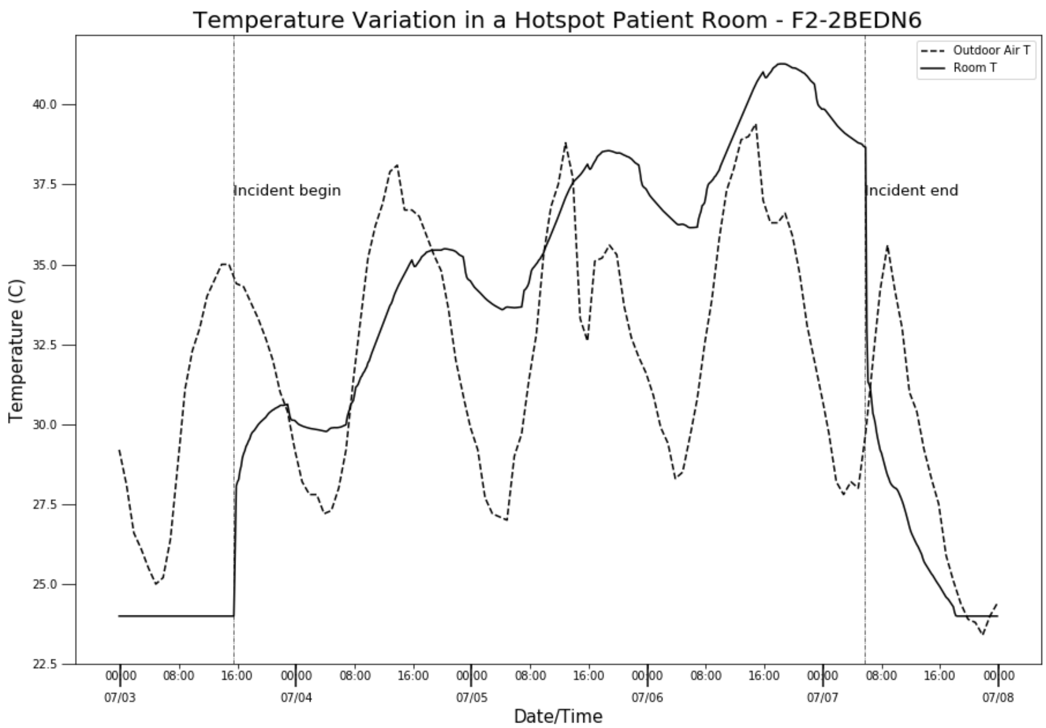


Figure 12. Temperature variation in a hotspot patient room during the incident - Chicago

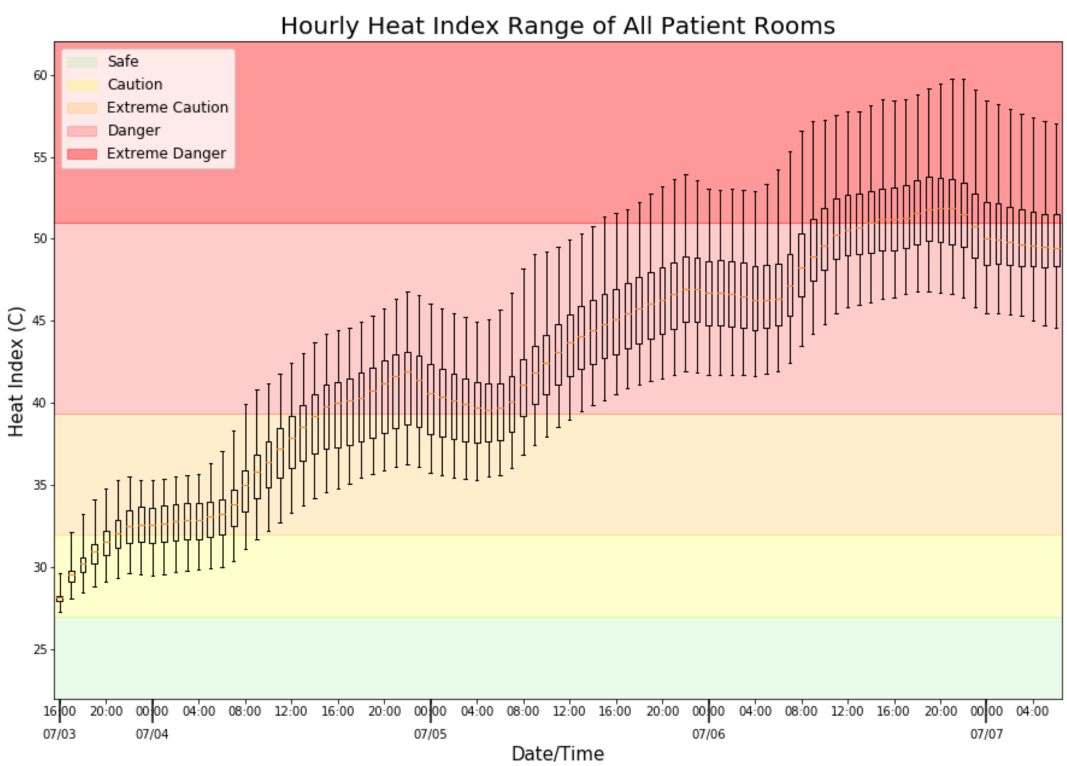


Figure 13. Hourly heat index box plot of all patient rooms - Chicago

4.4.2. Passive measures

Since the “Danger+” occurrence of the Chicago baseline reached as high as 65.2%, even the best performing passive measure package could only reduce the “Danger+” to 17.3%, which still exposed the patients to a considerable amount of danger, as shown in Figure 14. In this case, it was unlikely that resilience could be achieved with passive measures only.

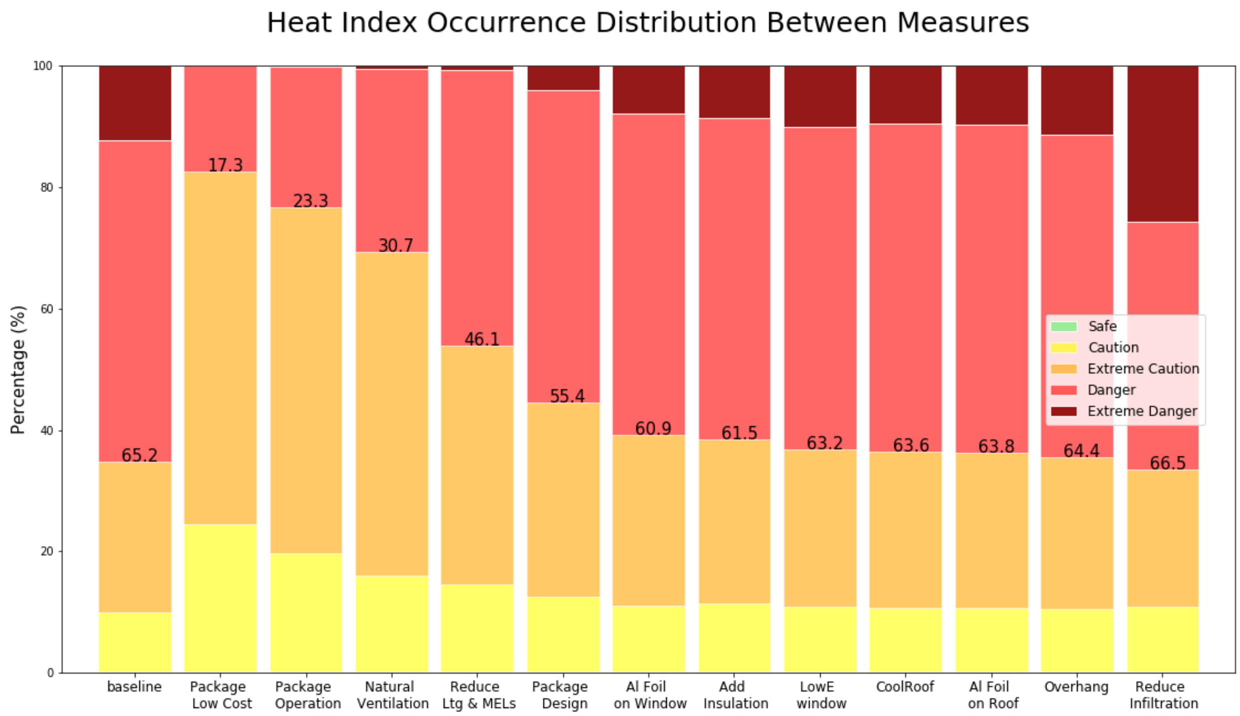


Figure 14. Heat Index Occurrence Distribution of Baseline and Passive Measures - Chicago

4.4.3. Active measures

Similarly, due to the high occurrence of “Danger+” in the Chicago baseline, even the active measures couldn’t guarantee 100% safety, as shown in Figure 15. A considerable amount of Extreme Caution occurred under thermal storage with an 8-hour supply. With a 24-hour supply, the nursing home could achieve more than 90% safety, which is the best that active measures accomplished so far.

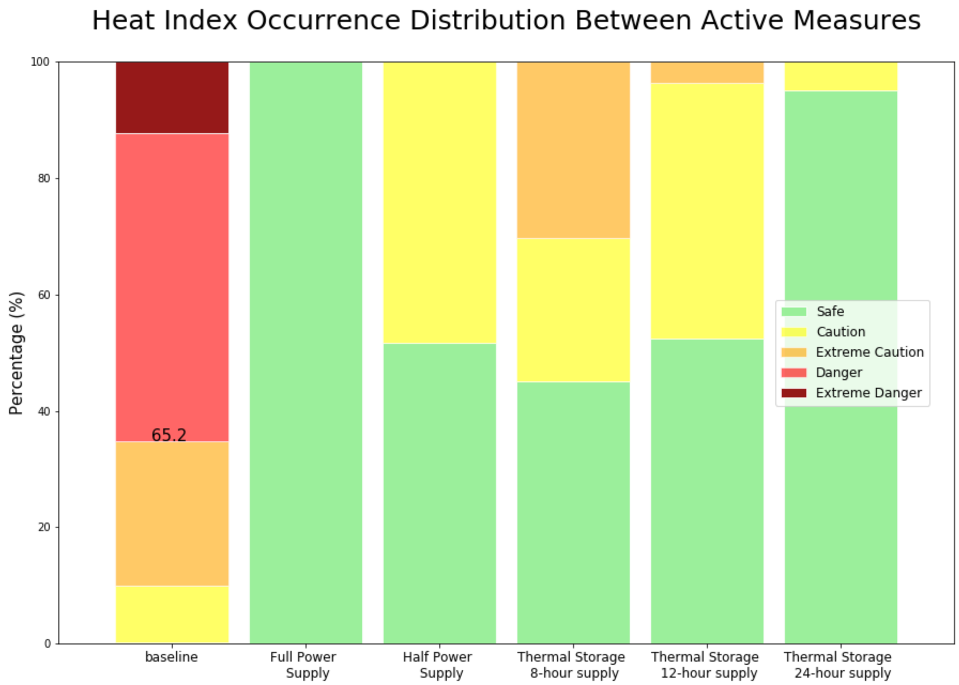


Figure 15. Heat Index Occurrence Distribution of Baseline and Active Measures - Chicago

4.5. Summary of measures' impacts across three climates

Across the three representative cities, it was found that natural ventilation and reducing lighting and plug load are generally very effective in improving indoor environment under extreme heat conditions. The benefit of natural ventilation may be moderately curtailed if the exterior environment is too harsh to benefit the interior environment, e.g., outdoor temperature is higher than indoors, outdoor air humidity is too high, or outdoor air is polluted.

At an extreme heat condition with no power supply, air tightness reduces the potential heat release from interior to exterior environment, which can make the situation worse. However, the conclusion will be completely reversed if the HVAC system is still functioning well, or if it is an extreme cold event.

The effectiveness of the window measures (aluminum foil on windows, low-e windows, and overhang shades) depend heavily on the original window performance of the baseline building. For regions with less stringent building code requirements, the window measures would have more significant impact. Adding cool roof and insulation both have marginal benefits in the three climates.

For measure packages, the low/no cost package and operation-oriented package are the best performers. It is encouraging that operation improvement and some low-cost simple measures can be very effective in improving thermal resilience. The performance of design oriented package, similar to the window measures, varies with the envelope properties of the baseline building.

Across the three climates, while the passive measures, including the packages, can potentially do a good job in reducing dangerous occurrences, neither of them can achieve 100% safe, or even 50% safe conditions for occupants. For stakeholders, it is critical to identify their resilience target and risk threshold before making decisions on prioritizing the measures.

4.6. Impact on Energy Consumption

The simulation also calculated the impact of EEMs on energy use. Active measures were not included in this analysis because: (1) half power supply lowers the power supply temporarily, which does not affect the energy use outside the incident, (2) thermal storage can save utility cost by charging at night with a lower utility price and discharging during the day, especially during peak hours; however, it does not save total energy use or even consume more due to extra pump usage. Therefore, for the energy consumption impact, only passive measures were evaluated. In the future, we'll explore further into the cost impact due to energy consumption change.

Figure 16 illustrate the impact of all passive EEMs on annual energy consumption. It is noted that the energy consumption did not change for the natural ventilation measure. This is because natural ventilation is generally disabled in conditioned zones unless advanced concurrent control of natural ventilation and the HVAC system is supervised by a specialist. With the HVAC system always running for the nursing home, we assumed natural ventilation was no longer applicable outside the incident. Other major findings are highlighted below:

(1) Reducing lighting and plug load and related EEM packages (Package Operation and Package Low-Cost) have the largest energy saving potentials.

(2) Adding insulation, though only improving heat resilience minimally, has very good energy performance in heating dominant climates like Chicago, and it is relatively good in mild climates like SF.

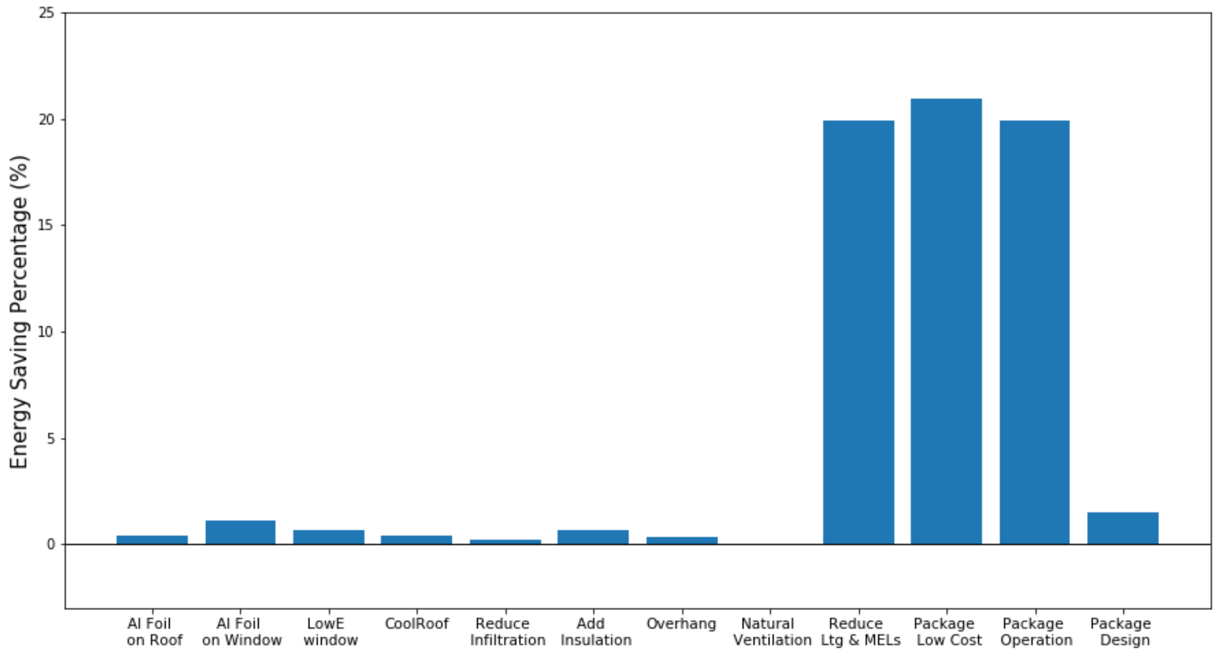
(3) Reducing infiltration, though having a negative impact on heat resilience in the nursing home case, has considerable energy saving potential, especially in heating dominant climates.

(4) Cool roofs deliver high solar reflectance and high thermal emittance, which reduces solar heat gain during the day and increases heat emission to the sky during the night. This is a perfect characteristic for cooling dominant climates like Florida, but not so good, or even negative, for the mild and heating dominant climates in terms of overall energy performance throughout the year. Roof-mounted aluminum foil, on the other hand, delivers even higher solar reflectance but very low thermal emittance, thus it performs a bit better than a cool roof in mild and heating dominant climates.

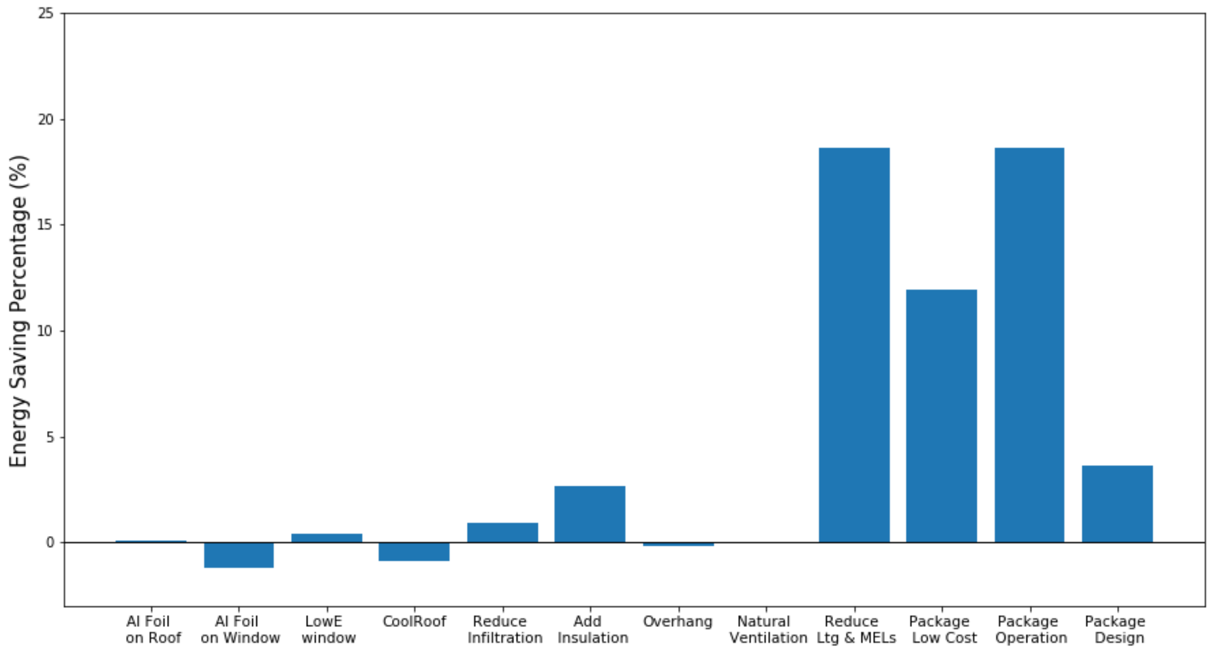
(5) For window measures, adding aluminum foil on windows, adding overhangs, and upgrading to low-e windows all reduce solar heat gain through the windows. Meanwhile, the low-e window measure also improves thermal conductivity, while the former two have little impact on thermal conductivity. Therefore, all three window measures can save energy in cooling dominant climates. But for mild and heating dominant climates, adding aluminum foil on windows and

adding overhang would have negative impacts on energy consumption. In this case, adding aluminum foil can serve as a good temporary solution that can be effective in improving heat resilience facing disasters, but it should not be kept over the long-term.

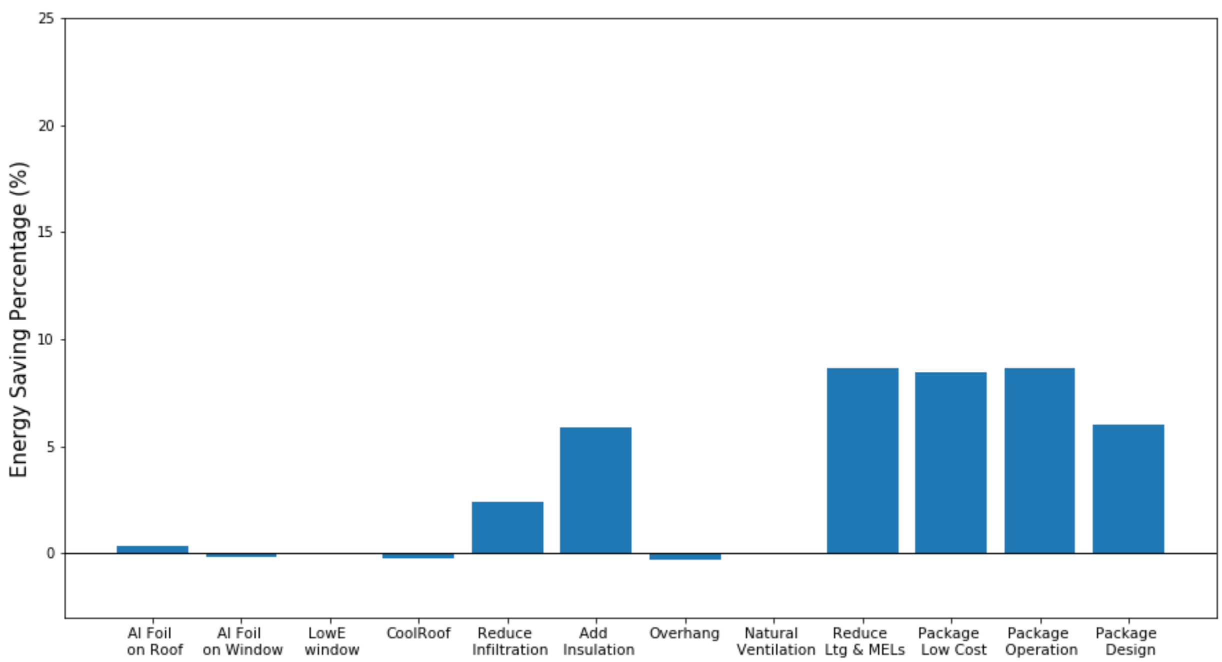
The impact of EEMs on resilience varies by climate zones. It is recommended that benefits of energy savings and resilience should be considered together for evaluating the EEMs for specific building types and climate zones. Passive measures that significantly improve heat resilience may not be cost-effective purely from an energy savings perspective, however, they should be considered in the building design or retrofit process.



(a) Florida



(b) SF



(c) Chicago

Figure 16. Impact of EEMs on annual energy consumption: (a) Florida; (b) SF; (c) Chicago.

5. Cost Estimation

This section estimates the cost (materials + labor) of EE measures, to help stakeholders make decisions and prioritize the measures to improve building resilience. However, note that this is not a life cycle cost analysis, as resilience benefits (e.g., occupants' well-being and people's lives) are difficult and/or controversial to quantify financially.

Figure 17, Figure 18, and Figure 19 illustrate the up-front incremental cost estimation of each EEM for the resilience improvement based on different criteria. Take Figure 17(a) as an example: the size of each bubble illustrates the cost of that EEM, while the height of each bubble refers to the resilience improvement, which is quantified by the metric of "Danger+" occurrence reduction in this case. Therefore, bubbles that are smaller and higher are optimal EEMs for resilience improvement. If more stringent resilience criteria are adopted, the metric for quantifying resilience improvement will switch from "Danger+" occurrence reduction to "Extreme Caution+" or even "Unsafe" (i.e., Caution+) occurrence reduction. In other words, not only the hazard level at and beyond "Danger" is unacceptable, but "Extreme Caution" or even "Caution" levels are unacceptable as well.

It is tricky to estimate the cost of the half power supply measure because it can be achieved by multiple methods, such as a photovoltaic (PV) system, onsite generators, and batteries. In addition, its costs vary significantly. Therefore, this measure's cost is not listed in the figures.

The following bullets summarize the findings, based on the cost estimation results:

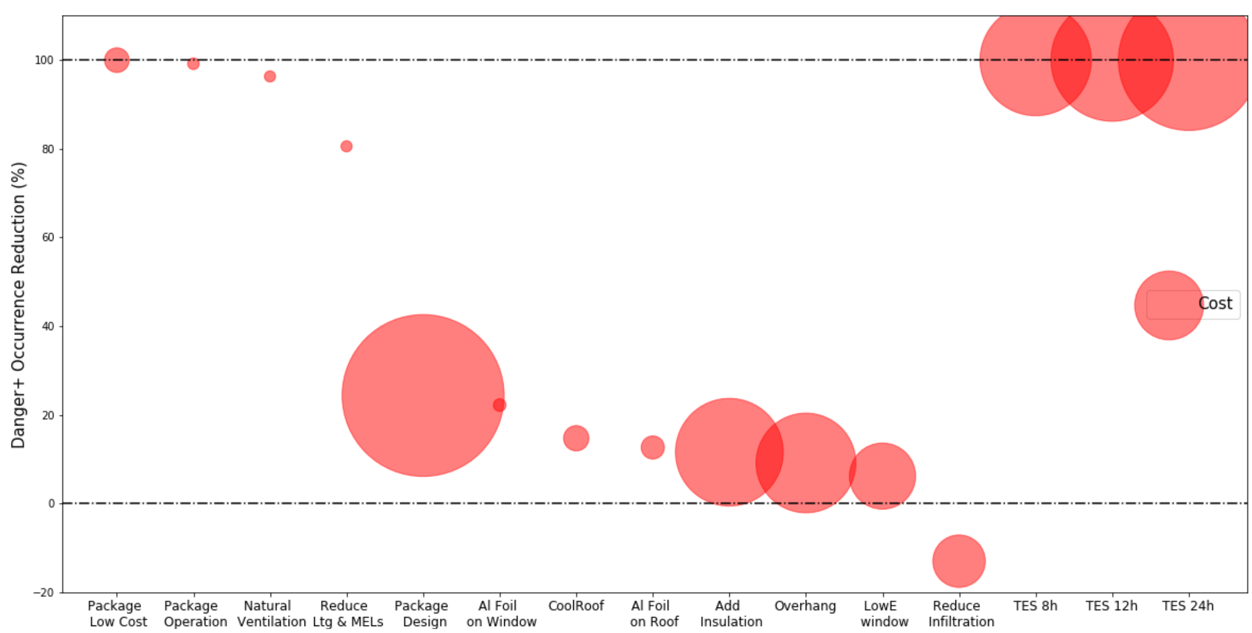
(1) Cost-effectiveness for resilience varies significantly with climate and baseline characteristics. In different climate zones, the buildings are designed based on local codes and standards, leading to different baseline characteristics, which impact the effectiveness of measures. For example, adding aluminum foil can reduce the "Danger+" occurrence by over 90% in San Francisco, but only 20% in Florida. This is caused by the different window performance in the baseline model, which complies with the same building code but different climate zone requirements.

(2) Cost-effectiveness is also influenced by the duration and strength of the extreme events. For events that are more severe or last longer, the measures' effectiveness will be reduced. For example, the heatwave in Chicago lasted one day longer than those in Florida and San Francisco. As a result, the low-cost package and operation-oriented package can completely eliminate the Danger+ occurrences in the latter two cities, while they can only achieve at most 70% reduction in Chicago. As discussed in the Introduction section, accelerating climate change will cause increasingly frequent and strong extreme climate events. Therefore, the EEM effectiveness will likely be discounted in the future and this should be taken into consideration while performing the EEM evaluation.

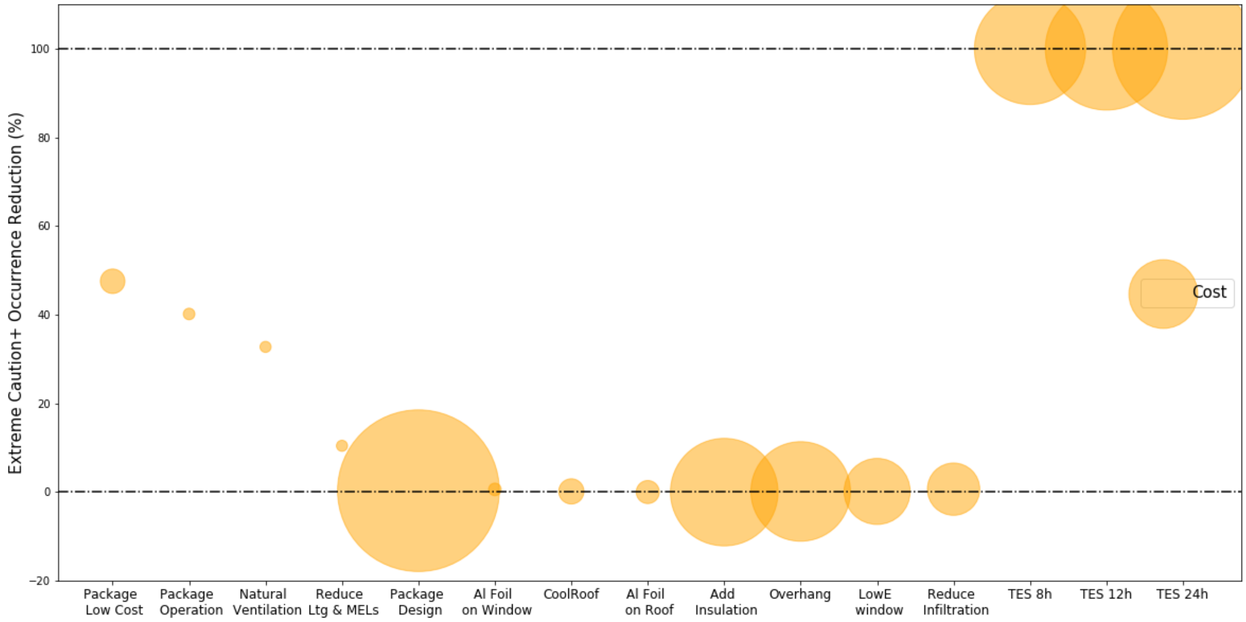
(3) The selection of resilience criteria is critical. The resilience criteria are in fact the maximal risk threshold that the decision makers are able to take. For example, if "Danger+" is adopted as the resilience criteria, the target of EEM selection would be eliminating the hazard levels occurrences of Danger and beyond; if "Unsafe" were to be

adopted instead, the target would be boosted to eliminate all the occurrences that are "unsafe", including Extreme Danger, Danger, Extreme Caution, and Caution. With different criteria selected, the EEMs that can meet the criteria will be very different. Take the Florida case as an example: With the "Danger+" criteria, multiple measures, including package low-cost, package operation, natural ventilation, and all three thermal storage options can meet the criteria; among which, natural ventilation is the most cost effective (Figure 17(a)). In contrast, with the "Unsafe" criteria, only thermal storage with a 12- and 24-hour supply can fully meet the criteria, and all the passive measures are knocked out (Figure 17(c)). Therefore, decision makers should comprehensively compare and prioritize EEMs for resilience improvement by balancing their risk threshold and investment capability.

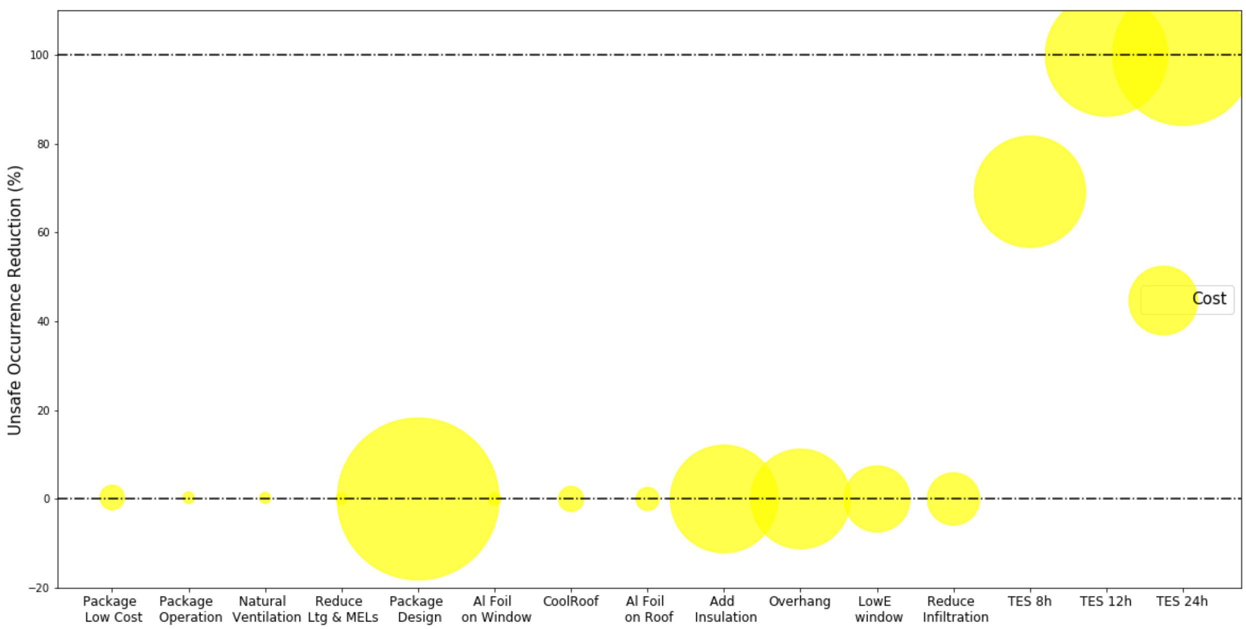
(4) All active measures can largely improve safety, but are relatively expensive compared with passive measures. Passive measures are effective at reducing dangerous conditions, but cannot be 100% safe. For example, based on Figure 17(a), Figure 18(a), and Figure 19(a), at least one-third of the passive measures are quite effective at reducing the "Danger+" occurrence. But based on Figure 17(c), Figure 18(c), and Figure 19(c), almost none of the passive measures have any effect on reducing the "Unsafe" occurrence; in other words, when passive measures are applied, the entire building is still in an unsafe condition throughout the incident. Therefore, if the target is to guarantee 100% safety, the active measures will be a must-have. However, it does not mean that passive measures should be fully dumped in this case; in fact, they can be integrated with active measures to achieve the best performance.



(a) EEM cost over "Danger+" occurrence reduction

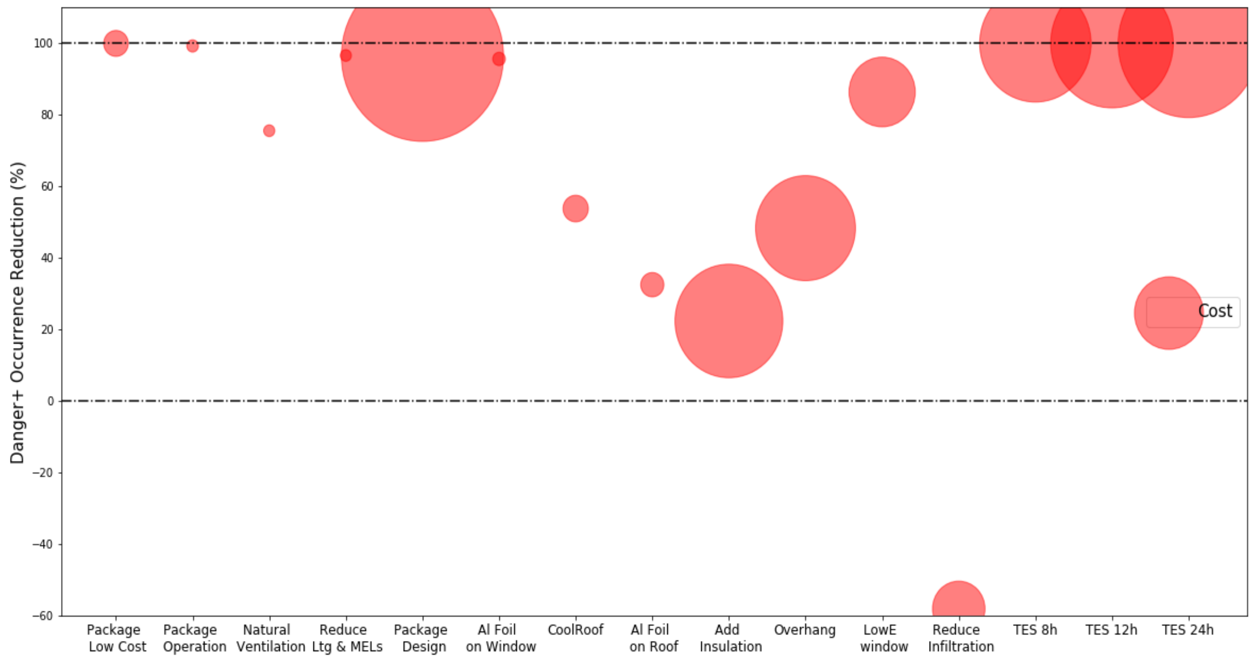


(b) EEM cost over “Extreme Caution+” occurrence reduction

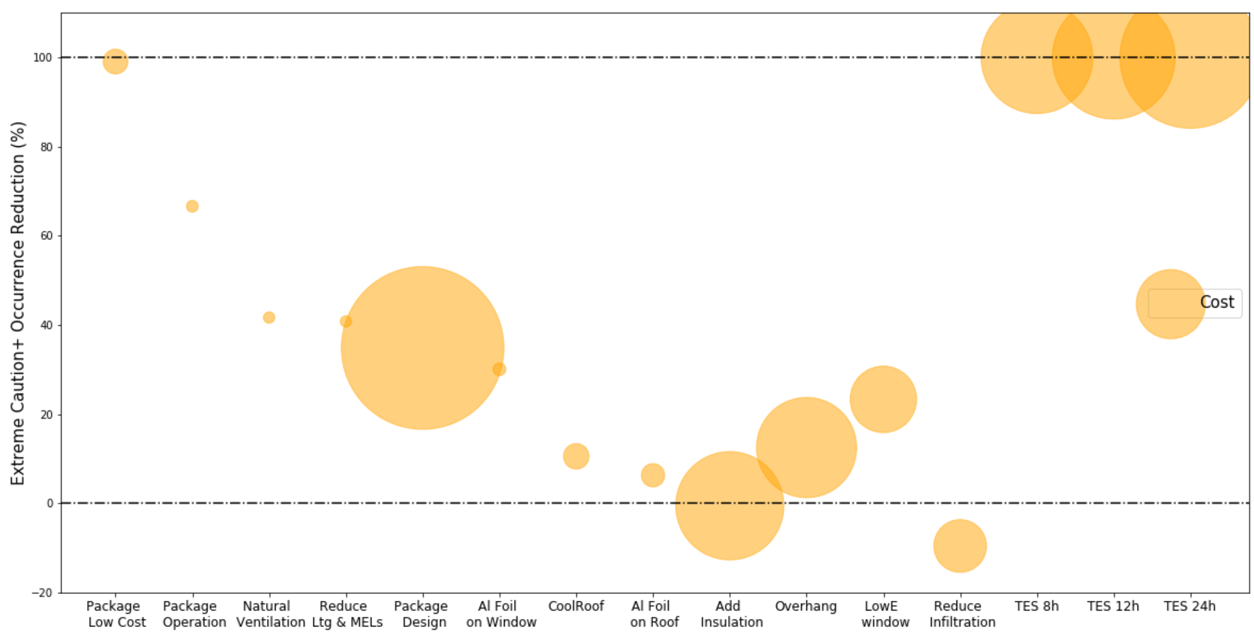


(c) EEM cost over “Unsafe” occurrence reduction

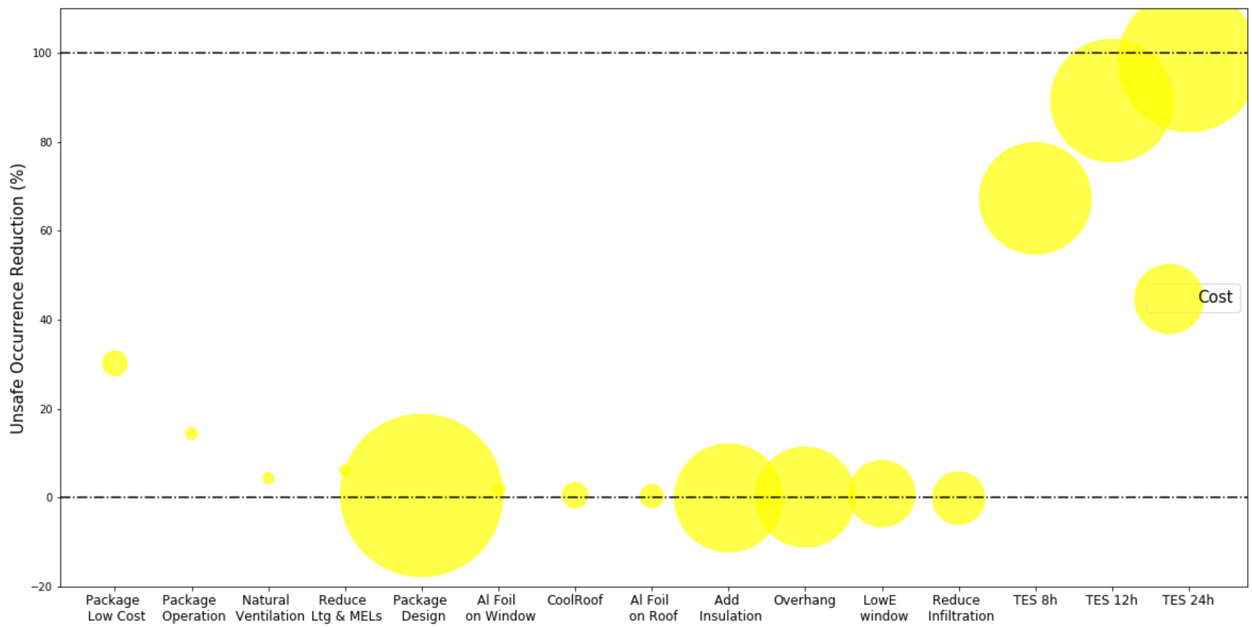
Figure 17. EEM cost-effectiveness of the nursing home in Florida based on different resilience criteria: (a) “Danger+”; (b) “Extreme Caution+”; (c) “Unsafe”.



(a) EEM cost over “Danger+” occurrence reduction

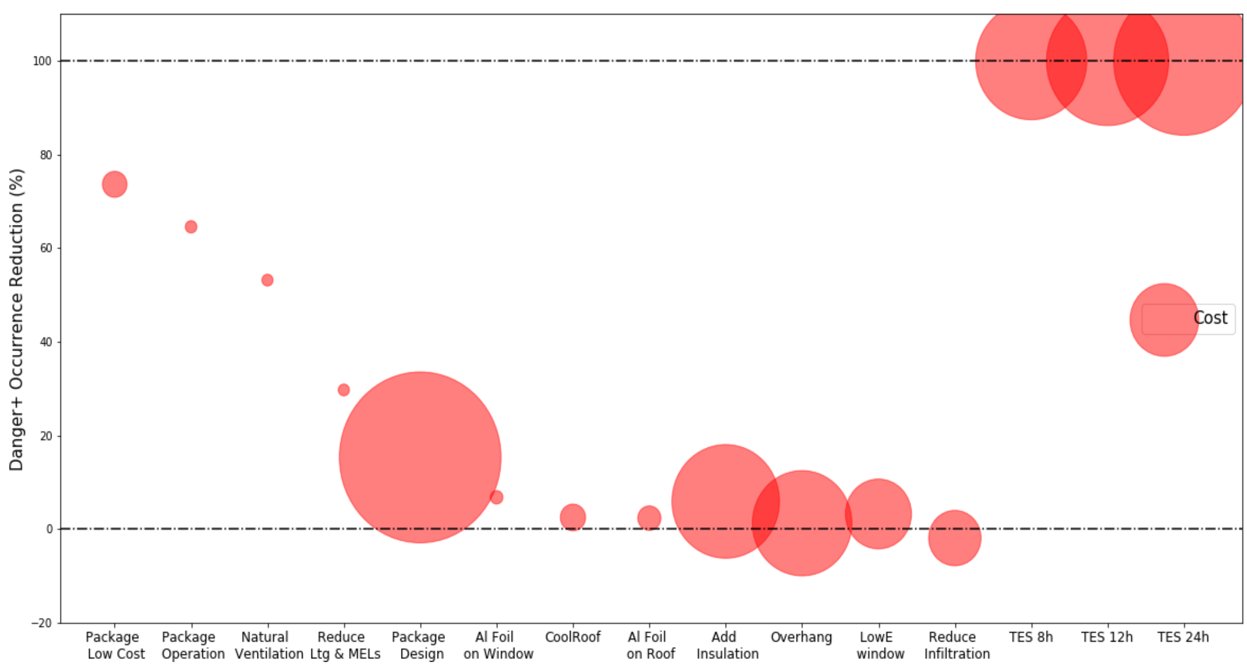


(b) EEM cost over “Extreme Caution+” occurrence reduction

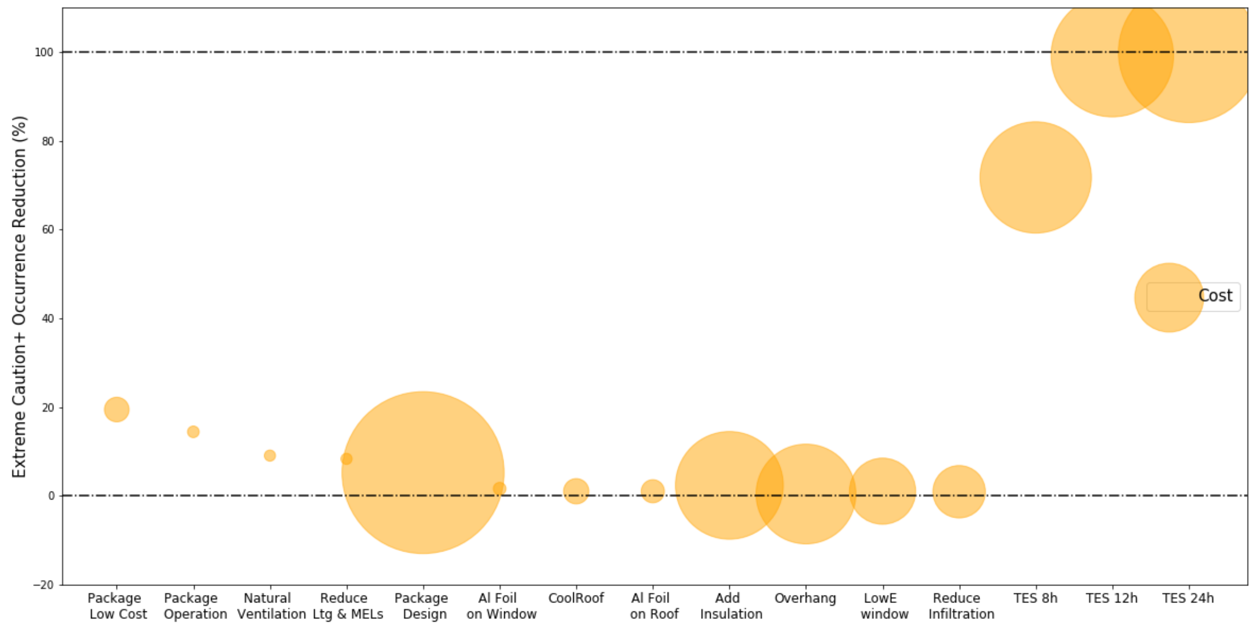


(c) EEM cost over “Unsafe” occurrence reduction

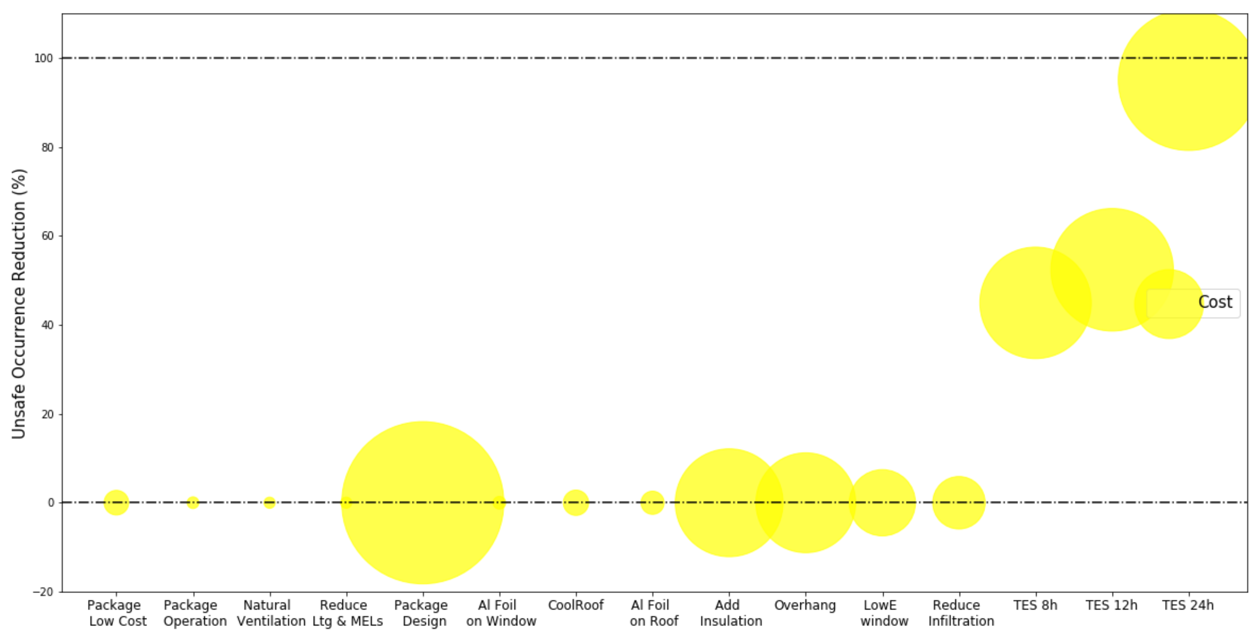
Figure 18. EEM cost-effectiveness of the nursing home in San Francisco based on different resilience criteria: (a) “Danger+”; (b) “Extreme Caution+”; (c) “Unsafe”.



(a) EEM cost over “Danger+” occurrence reduction



(b) EEM cost over “Extreme Caution+” occurrence reduction



(c) EEM cost over “Unsafe” occurrence reduction

Figure 19. EEM cost-effectiveness of the nursing home in Chicago based on different resilience criteria: (a) “Danger+”; (b) “Extreme Caution+”; (c) “Unsafe”.

6. Discussion

Global climate change has already resulted in a wide range of impacts across the globe. While extreme heat is becoming the new normal [130], there are no comprehensive policies in place to adapt existing homes and other buildings to high temperatures, manage urban heat islands, nor safeguard new homes [21]. The level of risk from overheating is unknown for hospitals, care homes, schools, prisons, and places of work [21]. If new air-conditioning systems are installed to address such overheating risk, there will be a significant increase in cooling related electricity use. If it is deemed necessary to install cooling systems in a portion of these buildings, the buildings should be retrofit first, to increase energy efficiency and reduce cooling demand.

The benefits of energy savings and resilience should be considered together when evaluating energy efficiency measures for specific building types and climate zones. Passive measures that significantly improve heat resilience, which may not be cost-effective purely from an energy savings perspective, should be considered in the building design or retrofit process. Even though the nexus of resilience and energy efficiency is important, resilience requirements have not been incorporated in current building energy codes and standards, such as ASHRAE 90.1, ASHRAE 189.1, or California Title 24. The LEED rating systems give credits for passive survivability, which improves heat resilience. It is good to have, but not mandatory. Resilience requirements need to be implemented in building energy codes and standards in order to achieve extensive improvement of resilience, especially from the early design stage.

Florida's emergency generator laws require that nursing homes and assisted living facilities have backup power [131]. The rules do not require a specific type of cooling. Some facilities may opt to power the entire HVAC system, while others provide an emergency-specific cooling solution. In practice, operation and maintenance (O&M) issues may disable the functioning of the backup power. Therefore, periodic testing of the backup power system is recommended.

There are limitations in this study: (1) Only limited data (e.g., the reported maximum indoor temperature of 99ºF) were available for the model calibration. We did not have access to actual utility bill data, as the building has been closed since the tragedy happened; (2) There are some trees surrounding the nursing home, which may affect the building's solar heat gains to a certain degree. We didn't consider trees in our modeling; and (3) Cost estimation is subject to uncertainty, which varies with manufacturers, implementation locations and contractors, etc. It should be used as a reference only.

Evaluating measures for improving resilience of buildings requires different modeling and analysis approaches (e.g., assuming the building is in free-floating mode without power, using extreme weather rather than typical meteorological year [TMY] weather data) from those used to evaluate measures for energy savings or utility cost savings. Although case studies like this emerge, the nexus of energy efficiency and resilience of buildings needs more research in order to provide useful tools, best practices, and clear guidance for practitioners and policy makers. Future work includes extending this analysis framework to residential and commercial buildings and critical facilities in different climate zones, and buildings subject to different weather events (e.g., heatwaves, polar vortices, and wildfires). Future studies may also look at more specific resilient criteria for the vulnerable population that is more sensitive to heat hazards. As cities attempt to adapt to more prevalent heatwaves, building-level solutions may be preferable to city-scale urban planning options, which are often far harder to implement. Resilience at the city block or district scale may need different technologies and strategies because of interactions between buildings or between buildings and urban microclimate, as well as potential use of district energy systems serving such a group of buildings. As climate change introduces more frequent and severe extreme weather events, future study can also investigate the impact of climate change on the interactions between thermal resilience and energy efficiency of buildings.

Future work also should include the establishment of tools that can identify the most effective energy efficiency measures for resilience purposes as a function of circumstance using optimization techniques. Improved building architectures that co-optimize for both efficiency and resilience should be considered, including vernacular designs that are sometimes ignored in favor of more modern solutions. Building energy codes should be reconsidered through a resilience lens, and the idea of what a “resilient code” actually is should be clarified. Answering these questions will provide a better way to quantify the value that energy efficiency provides for resilience. Doing so would convey multiple benefits, including incentivizing energy efficiency upgrades, enhancing the ability to recoup efficiency investments in buildings at the point of transaction, and providing a justification for organizations to invest in energy efficiency as part of a rigorous cost-benefit analysis.

7. Conclusion

In this study we examined the impact that energy efficiency measures in buildings have on occupant resilience during a weather-related disaster. We focused on an example of a real-world building failure—extreme indoor heat buildup in a Florida nursing home following an air conditioning outage caused by Hurricane Irma in 2017. This case study was selected deliberately so that we might better understand how energy efficiency manifests itself as a resilience resource in a realistic scenario caused by the deadliest weather-related phenomenon in the United States, and one that is projected to only become more severe: extreme heat. We attached price estimates to each efficiency measure as a means to quantify in monetary terms the up-front cost at which efficiency measures would have reduced the fatality risk for all residents, but particularly the 12 senior citizens that did not survive the tragedy.

We gathered the actual building data through publicly available records and recreated the nursing home in EnergyPlus modeling software. We introduced a number of passive efficiency measures and discovered that most provided a resilience benefit. These benefits were unequal, however. We found that natural ventilation was most effective at reducing the indoor heat index in Florida, followed by a reduction of the building’s miscellaneous electrical loads. Other measures like placing aluminum foil on the roof and windows, installing a cool roof, modifying windows, and adding more wall insulation were also beneficial to a lesser degree. These passive measures can reduce the risk of dangerous conditions but could not guarantee safe conditions for occupants. Active measures, such as cool energy storage or PV that powers half capacity of cooling systems, are needed to provide cooling to maintain safe conditions for occupants.

Our analysis generated three high-level takeaways. First, energy efficiency is not uniformly beneficial for resilience, as different efficiency characteristics convey different resilience impacts. In particular, we found that reduced air infiltration—a staple of modern energy efficiency practices—actually made it more difficult for the nursing home to expel excess heat when indoor air temperature was higher than it was outdoors. And it would have, on its own, increased the heat index beyond the status quo. Second, the effectiveness of specific energy efficiency measures varied as a function of circumstance. By transplanting the Florida nursing home to Chicago and San Francisco during real heatwaves, we found that the value of individual measures varied as a function of multiple parameters, including climate zone, outdoor temperature, length of air conditioning outage, insolation, and local building codes. Third, the most effective efficiency measures were also the least expensive to implement. This encouraging result indicates that low- to no-cost measures could potentially be deployed in buildings in near-real time to enhance passive survivability by allowing residents to shelter in place.

Further analysis will be needed to characterize the efficiency/resilience connection more holistically. While improved insulation was one of the most expensive options for delivering a resilience benefit, we did not in this study calculate the lifetime benefits of such a measure, which would include energy savings, greenhouse gas mitigation, reductions in demand charges, health and productivity gains, and so on. Moreover, we limited our assessment to the value efficiency provides to building occupants. There may be additional value conveyed to building owners, business operators, and utilities under different circumstances.

Emergency responders and taxpayers may benefit as well, particularly if people do not need to be triaged, relocated, and housed elsewhere should their residences become uninhabitable. While a full suite of solutions, including a coordinated community response and distributed energy resources, is called for, passive measures that improve the chances of survival when other options are unavailable are of high importance. This is especially true given that the United States currently lacks the capacity to respond to a catastrophic power outage, the likes of which struck Puerto Rico following Hurricane Maria (The President's National Infrastructure Advisory Council, 2018).

Findings from this study indicate energy efficiency technologies should be evaluated not only by their energy savings performance but also by their influence on a building's thermal resilience to extreme weather events. Current building energy efficiency standards lack consideration of nexus of energy efficiency and resilience of buildings, which can be improved to promote measures or technologies that save energy while improving or neutral to thermal resilience of buildings. Such policy changes are critical to the pathway of energy efficient, resilient and healthy buildings and communities.

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Appendix

Table 4. Heat Index Chart (National Oceanic and Atmospheric Administration, 2018a)

Relative Humidity (%) \ Temperature (°C)	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
40	27	28	29	30	31	32	34	35	37	39	41	43	46	48	51	54	57
45	27	28	29	30	32	33	35	37	39	41	43	46	49	51	54	57	
50	27	28	30	31	33	34	36	38	41	43	46	49	52	55	58		
55	28	29	30	32	34	36	38	40	43	46	48	52	55	59			
60	28	29	31	33	35	37	40	42	45	48	51	55	59				
65	28	30	32	34	36	39	41	44	48	51	55	59					
70	29	31	33	35	38	40	43	47	50	54	58						
75	29	31	34	36	39	42	46	49	53	58							
80	30	32	35	38	41	44	48	52	57								
85	30	33	36	39	43	47	51	55									
90	31	34	37	41	45	49	54										
95	31	35	38	42	47	51	57										
100	32	36	40	44	49	54											

Caution   Extreme Caution   Danger   Extreme Danger

Table 5. Heat Hazard classification and impact on the body (National Oceanic and Atmospheric Administration, 2019)

Heat Index (°C)	Category	Effect on the body
27-32	Caution	Fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps.
32-39	Extreme Caution	Heat cramps and heat exhaustion are possible. Continuing activity could result in heatstroke.
39-51	Danger	Heat cramps and heat exhaustion are likely; heatstroke probable with continued activity.
Above 52	Extreme Danger	Heatstroke is imminent.

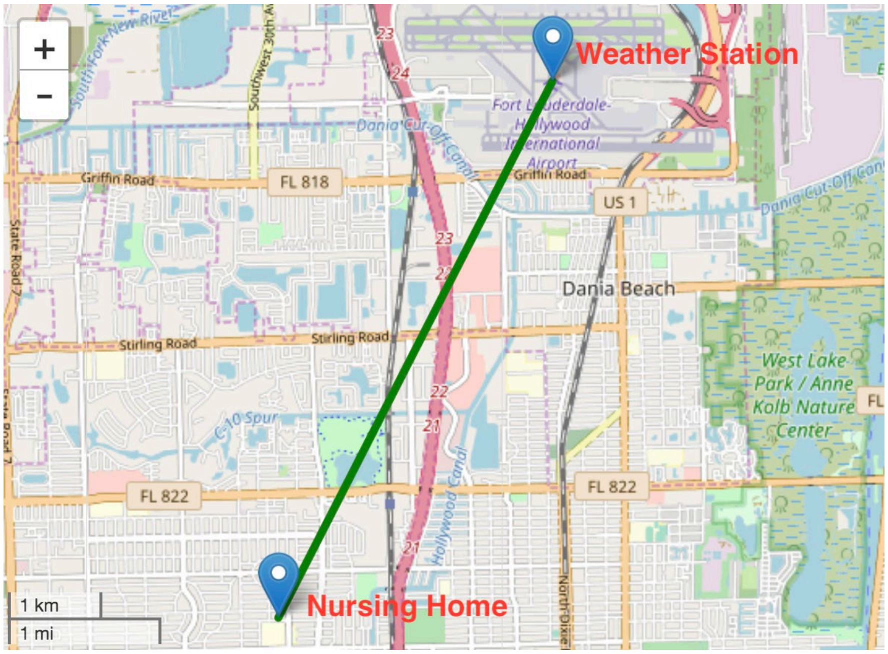

Figure 20. Locations of the case study building and applied weather station

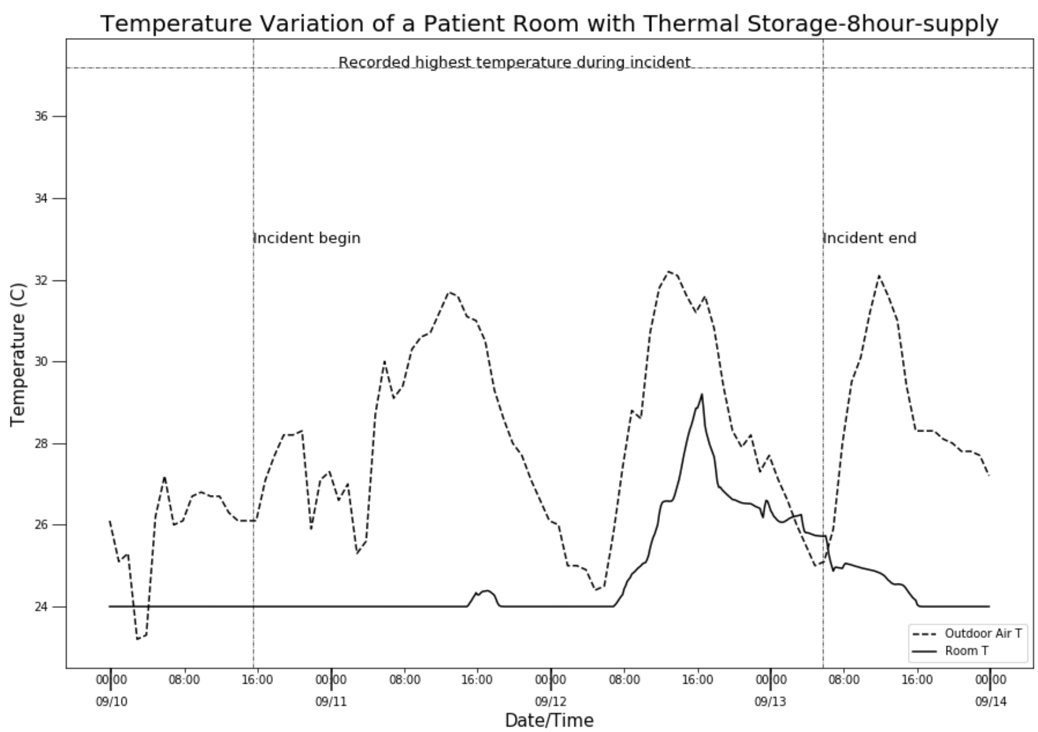

Figure 21. Temperature variation in a hotspot patient room under thermal storage with eight-hour supply

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