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Enhancing Resilience in Buildings Through Energy Efficiency

July 2023

Pacific Northwest National Laboratory
Ellen Franconi, Luke Troup, Mark Weimar, Yunyang Ye, Chitra Nambiar, and Jeremy Lerond

National Renewable Energy Laboratory
Eliza Hotchkiss, Jordan Cox, Sean Ericson, Eric Wilson, Philip White, Conor Dennehy, Jordan Burns, Jeff Maguire, and Robin Burton

Lawrence Berkeley National Laboratory
Tianzhen Hong, Linqian Sheng, and Kaiyu Sun

Department of Energy
Michael Reiner, Christopher Perry, and Jeremy Williams

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Enhancing Resilience in Buildings Through Energy Efficiency

Standardized Methodology and Resulting Analysis Demonstrating the Value of Codes and Above Code Measures to Hazard Resilience

July 2023

Department of Energy
Jeremy Williams, Christopher Perry, and Michael Reiner
Pacific Northwest National Laboratory
Ellen Franconi, Mark Weimar, Luke Troup, Yunyang Ye, Chitra Nambiar, and Jeremy Lerond
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Pacific Northwest National Laboratory
Richland, Washington 99354

Disclaimer

Foreword

Enhancing Energy Resilience in Buildings

Many of us watched news coverage of Hurricane Katrina as it ravaged New Orleans in August 2005. We saw residents evacuated to the Superdome, then evacuated *from* the facility a day later—because it was uninhabitable without electricity for keeping the space cool.

Similarly, we observed that, during the ensuing power outage—which lasted for weeks and even over a month in some locations—older homes along the Gulf Coast often fared better than newer homes. Prior to the widespread availability of air conditioning, houses were designed for the local bioclimate. In the hot, humid Southeast, that meant features like wrap-around porches that shaded windows from direct sunlight and designs that channeled summer breezes through the houses for passive cooling.

A month after Katrina, the U.S. Green Building Council (USGBC) organized a design charrette in Atlanta to address how to rebuild New Orleans in a manner that would be more sustainable and resilient. Out of that charrette emerged *The New Orleans Principles*. One of the ten principles articulated in that publication was to “Provide for Passive Survivability.”

Those of us in the Atlanta design charrette in 2005 reasoned that, with climate change, we would be seeing more frequent and longer duration power outages and interruptions in fuel deliveries. Shouldn’t we be designing homes that could keep families safer during those disruptions? This is the principle we defined as *passive survivability*. We recognized this design criterion as a motivation to build more energy-efficient buildings across all sectors that would rely on passive design features such as optimized insulation levels, strategic thermal mass, sun shading, passive solar heating, natural ventilation, and daylighting.

The idea that more energy-efficient buildings could keep occupants safer during power outages was a key element of a pilot credit on passive survivability in USGBC’s Leadership in Energy and Environmental Design (LEED) rating system. That pilot credit has done a lot to connect energy efficiency to resilience and life-safety, but those of us involved in the development of this pilot credit have seen the need for more rigorous verification of the fundamental tenant of passive survivability: that more energy-efficient buildings would demonstrably maintain safer, more habitable conditions during extended energy outages or interruptions in fuel deliveries.

In 2020, the Department of Energy Building Technology Office (BTO) launched a research and development effort to provide the technical foundation for furthering the strategic deployment of energy efficiency to enable energy resilience. BTO assembled a team comprised of experts from three national labs—Pacific Northwest National Laboratory, the National Renewable Energy Laboratory (NREL), and Lawrence Berkeley National Laboratory. The outcome of that work is reported here.

Within this report, readers will find a rigorous methodology and analysis that clearly makes the case that higher performance buildings are safer for their occupants. There are many other compelling reasons to build more energy-efficient buildings: reducing operating costs, improving air quality, and reducing carbon emissions among them. Enhancing resilience—by keeping occupants safer during power outages or fuel supply disruptions—is another important reason to build energy-conserving buildings.

This report provides a strong justification for municipalities and states to strengthen energy codes *to better ensure public health, safety, and welfare*, and for building owners and developers of all types—whether nonprofit housing authorities, school districts, or homebuilders—to establish more robust specifications for energy and resilience performance.

Alex Wilson

Alex Wilson is president of the nonprofit Resilient Design Institute and founder of BuildingGreen in Brattleboro, Vermont. He has been engaged with renewable energy, energy efficiency, green building, and resilient design since the late-1970s. He co-led the effort to create USGBC's LEED pilot credits on resilient design.

Executive Summary

The number and cost of disasters are increasing over time, exposing the vulnerability of buildings and energy systems against extreme weather events. Over the past two decades, the United States has experienced 265 weather and climate disasters that exceeded $1 billion in damages (NCEI 2022). In 2017, the United States faced the costliest disaster year, with 16 distinct billion-dollar events totaling over $320 billion.

The built environment will likely face extreme weather events of greater magnitude and extent over the next half-century. The frequency and duration of extreme temperature events, most notably heatwaves, will also increase in frequency and intensity, impacting new regions of the United States to unanticipated temperature conditions (Dahl et al. 2019). Extreme weather events often trigger power outages that extend beyond the initial disaster. In 2017, Hurricane Maria hit Puerto Rico as a category 4 hurricane, imparting damage that would leave the island without full power for 328 days (Campbell 2018). In the fall of 2019, dry conditions and high winds led Pacific Gas and Electric to preemptively stage power outages across parts of California in an effort to reduce the risk of power lines sparking a wildfire. Forced outages, occurring for periods as long as 5 days, impacted over 3 million customers, leading to school closures and over $2 billion in estimated economic losses (Hussain 2019).

While climate-driven disasters are increasing, attention is focusing on reducing the contributions of buildings to the greenhouse gas emissions that are driving this increase. Policymakers and the building industry need methodologies and data to support a holistic approach to policy development and investment decision-making that most effectively addresses resilience and reductions in energy use.

The Department of Energy's (DOE's) Building Technologies Office (BTO) recognizes the need to better understand the relationship between energy efficiency and resilience, including the need for standardized metrics, establishment of evaluation methods, and impact assessment for residential and commercial buildings. To address these needs, BTO commissioned three national research laboratories to develop a standardized methodology to quantitatively assess how energy-efficiency measures affect building thermal resilience. The study builds on previous BTO efforts to identify resilience metrics and outstanding analytical needs. It was completed under the guidance of a technical advisory group comprised of industry experts and representatives experienced in building resilience. This report summarizes the research effort conducted by Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory, reports initial findings resulting from the efficiency-resilience valuation effort, and identifies areas of need for continued research and analysis.

Approach and Methods

This study examines the ability of existing and new residential buildings to withstand extreme temperatures and the associated impacts on occupants and property. Assessment attributes include geographic location, building type, building baseline condition, and improved efficiency condition. Figure ES 1 presents the scope established for the study. It includes single-family (SF) homes and multifamily (MF) apartment buildings located in six U.S. cities that span three diverse geographic regions. The study also includes the resilience assessment of an assisted living facility, which provides insights on efficiency impacts for residential critical care facilities.

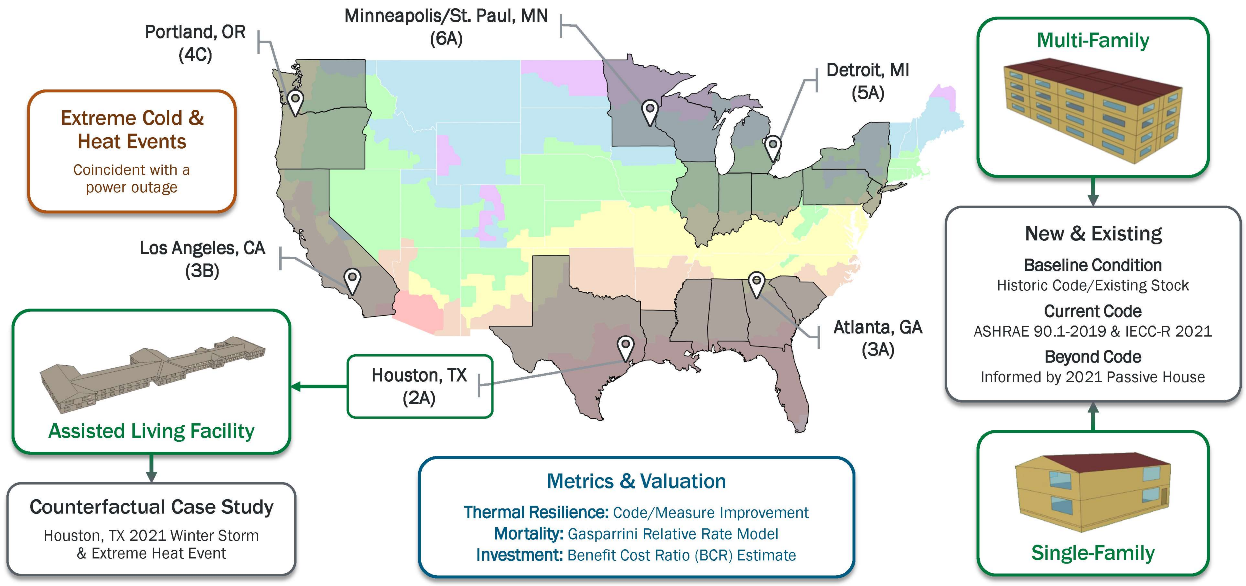

Figure ES 1. Key Components of Study Scope

The study develops a methodology to quantify the resilience benefits of building energy efficiency. The intention is to more fully value efficiency by capturing traditional benefits, such as reduced annual operating energy costs and the associated greenhouse gas emissions, as well as diverse aspects of resilience. The quantified resilience aspects of the analysis that can be used to inform mitigation action include:

- Shelter-in-place capability
- Excess mortality
- Property damage
- Investment benefit–cost assessment

Specifically, the methodology accounts for the expanded value of efficiency investment by considering (1) the hazard occurrence probability, (2) passive survivability, (3) occupant damage, (4) property damage, (5) operational energy use and emissions, and (6) the associated monetary benefits and costs. A brief overview of innovative methodology components is provided below. Further details describing the overall methods, supporting data sources, and applied analytical procedures are provided in the main report.

Extreme temperature events coincident with a power outage

To identify extreme events for the six locations considered and develop weather files for performance modeling, the study followed the method defined by Ouzeau et al. (2016). Events considered are extracted from historical weather data spanning from 2000 through 2020. The determination of the annual coincident probability of a power outage occurring during an extreme temperature event is based on the historical extreme temperature event data and information published in the DOE Office of Cybersecurity, Energy Security and Emergency Response dataset (DOE 2018).

Measurement of passive survivability

A measurement of passive survivability is applied in the study to indicate the ability to shelter in place is the standard effective temperature (SET). SET is a comfort indicator that considers indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. SET values representing expanded indoor comfort conditions are considered to fall between 54°F and 86°F. Following industry guidance, a cumulative value of SET degrees falling outside the SET thresholds (expressed as SET degree hours) that exceed 216 over a 7-day period indicate uninhabitable conditions.[1]

Occupant and property damage

The study evaluates the impact of extreme temperatures on occupant health and well-being by estimating relative rate, excess mortality, and the associated loss-of-life monetary value at risk. Fragility curves published by Gasparrini et al. (2015), developed for 384 global locations, are used to estimate the effect of extreme temperatures on loss of life. The relative rate data are developed from epidemiological analysis that establishes the average daily mortality in a given city as a function of outdoor temperature.

Property damages associated with extreme temperatures concurrent with loss of power can include burst pipes, truss lift, buckling floors, and foundation damage, as well as mildew and mold growth. Such damages are challenging to model since they are dependent on construction practices, building design and materials, and operation and maintenance. Therefore, property damage risk and the associated annualized cost estimates used in the study are based on historical data published by the Federal Emergency Management Agency (FEMA 2021) as part of their National Risk Index database. However, the data appear to be deficient and underestimate damages when compared to published damage values for recent U.S. extreme temperature events.[2]

Benefit–cost analysis

The study demonstrates how the benefits of efficiency, achievable through meeting and exceeding energy code provisions, can be represented in terms of a benefit–cost ratio (BCR). The BCR accounts for costs associated with efficiency measures and annual energy consumption and benefits associated with the societal value of greenhouse gas emission reduction, occupant damage reduction, and property damage reduction. The BCR is based on annualized values. The passive efficiency measure first costs are annualized assuming a lifetime of 30 years and discount rate of 3%. The monetized values of occupant and property damages, assessed for each representative heat and cold temperature event, are annualized using the extreme event power outage annual joint probability value.

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[1] The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) green building program includes a pilot credit, Passive Survivability and Back-up Power During Disruptions, referred to as IPpc100 that defines “livable conditions” as SET values between 54°F and 86°F. To receive the LEED credit for residential buildings, the unlivable SET (below 54°F or above 86°F) degree hours must not exceed 216 for a 7-day power outage during an extreme heat or cold event.

[2] For example, the Texas Department of Insurance reports the paid claims for residential and commercial property damage for the 2021 winter storm total $5.7 billion; however, zero annualized losses for Houston County for property damages are reported in the FEMA NRI database for extreme cold. https://tdi.texas.gov/reports/documents/feb2021-tx-winter-weather-summary-july2021.pdf

Results

The methodology focuses on the quantification of resilience metric values to understand the effect of improving the building envelope on habitability, excess mortality, property damage, and investment cost effectiveness. The study assessed two passive efficiency packages reflected specified in current code and beyond-code requirements.[3]

Sample results in Table ES 1 show the effect of improved passive efficiency on metric values. The metrics include SET degree hours, habitability, and excess mortality. The values are based on a 7-day period for the extreme temperature event coincident with a power outage. The days of habitability indicate the time elapsed before the SET degree hours reach a cumulative value of 216, which is the established threshold for maintaining livable conditions.[4] The table "improvement" data are changes in value relative to the base case existing building condition.

Table ES 1. Impact of Improved Efficiency on Resilience for Existing Single-Family Buildings

Data for the median building in the population sample for a 7-day analysis period.

Location (Climate Zone)	Event	SET Degree Hours*			Habitability: Days of Safety			Habitability: Improvement†		Mortality†: Lives Saved (per Event)		Mortality†: Improvement	
		Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Cold	749	222	-	3.8	6.9	7.0	82%	85%	20.0	43.2	32%	69%
	Heat	600	141	-	4.0	7.0	7.0	75%	75%	42.1	50.2	80%	96%
Atlanta, GA (3A)	Cold	2,558	1,610	200	1.4	2.3	7.0	64%	409%	3.6	8.7	21%	52%
	Heat	438	59	-	2.9	7.0	7.0	140%	140%	0.9	5.9	14%	93%
Los Angeles, CA (3B)	Cold	87	-	-	7.0	7.0	7.0	0%	0%	5.2	5.4	25%	25%
	Heat	100	-	-	7.0	7.0	7.0	0%	0%	126.9	202.8	53%	84%
Portland, OR (4C)	Cold	2,963	1,849	237	1.1	2.4	6.8	123%	523%	3.2	8.6	22%	58%
	Heat	371	319	-	4.7	5.5	7.0	16%	49%	-2.6	24.5	-8%	71%
Detroit, MI (5A)	Cold	4,248	3,020	1,778	0.9	1.7	2.4	82%	159%	5.1	10.8	14%	30%
	Heat	223	53	0.3	6.8	7.0	7.0	2%	2%	6.9	26.0	9%	35%
Minneapolis/ St. Paul, MN (6A)	Cold	5,397	3,699	2,190	0.6	1.2	1.8	100%	214%	7.3	14.0	19%	36%
	Heat	215	66	5	7.0	7.0	7.0	0%	0%	4.4	14.7	8%	27%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Existing Stock

[3] Model energy codes are available for adoption by states and local jurisdictions. Once adopted, they form the basis for minimum requirements. The model code that regulates SF buildings is the 2021 IECC (ICC 2021). The code that regulates MF requirements is Standard 90.1-2019 (ANSI/ASHRAE/IES 2019). The beyond-code measures reference performance criteria consistent with the Passive House Institute U.S. (PHIUS) 2021 Standard https://www.phius.org/phius-2021-performance-criteria-calculator.

[4] The U.S. Green Building Council's LEED green building program includes a pilot credit, Passive Survivability and Back-up Power During Disruptions, referred to as IPpc100 (USGBC 2022), that defines "livable conditions" as SET values between 54°F and 86°F. To receive the LEED credit for residential buildings, the unlivable SET (below 54°F or above 86°F) degree hours must not exceed 216 for a 7-day power outage during an extreme heat or cold event.

For example, for a SF building in Atlanta during a 7-day cold event, the typical existing building will maintain habitable conditions for 1.4 days, while a building built to the 2021 IECC will maintain habitable conditions for 2.3 days, nearly a full day longer. However, a highly efficient home built to Passive House Institute U.S. (PHIUS) Standards can maintain temperature within the habitability threshold for the full 7 days, five times as long as the typical existing building. The analysis results also show that increased passive efficiency will save 3.6 and 8.6 lives for the current code and beyond-code cases, respectively.

The metric data in Table ES 1 indicate that increased efficiency improves habitability during extreme heat and cold for all study locations and event types. There is a direct correlation between the passive survivability metrics and reduction in excess deaths for all locations except Portland for extreme heat. This may indicate a shortcoming in the procedures followed to apply the Gasparrini curves in the study, which is discussed in more detail in the body of the report.

Table ES 2 indicates the stacked value of building efficiency investments. The BCR values account for the cost of efficiency improvements and the achieved energy and resilience benefits, which include energy cost savings, the societal value of reduced greenhouse gas emissions, and decreases in monetary losses associated with property damage and excess mortality. BCR values greater than 1 signify that the efficiency investment is cost effective. The authors deem the table values as preliminary due to limitations of some analysis components, including an upward bias in extreme temperature–power outage coincident probability values (increasing BCR values) and underestimates of property damage and excess mortality (decreasing the BCR). More robust results are anticipated with the refinement of methods and improvements in supporting data, as detailed in the main report. The data indicate that the investment benefit is greater for new buildings than existing buildings. This is primarily due to measure costs being considered incremental for new construction but not for existing building retrofits. If considered incremental to a planned business-as-usual retrofit though, the BCR values for existing buildings would be higher than indicated in the table.

Table ES 2. Preliminary Benefit–Cost Ratios (BCRs)

Location (Climate Zone)	New Single Family		Existing Single Family		New Multifamily		Existing Multifamily	
	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	6.3	3.0	0.6	0.7	6.6	3.1	0.8	0.6
Atlanta, GA (3A)	3.8	2.1	0.6	0.6	5.5	2.0	0.8	0.7
Los Angeles, CA (3B)	2.9	1.3	0.3	0.3	3.2	1.0	0.4	0.3
Portland, OR (4C)	2.1	1.1	0.6	0.3	3.8	0.4	0.7	0.3
Detroit, MI (5A)	2.5	1.6	0.7	0.5	6.8	0.8	1.0	0.5
Minneapolis/ St. Paul, MN (6A)	2.9	1.8	0.8	0.4	7.6	0.9	1.3	0.7

Conclusions

The study reveals that in nearly every situation, improving passive efficiency in residential buildings to meet or exceed current energy code saves lives during extreme temperature events. Installing passive measures in existing SF buildings to meet code requirements extends habitability by as much as 120% during extreme cold and by up to 140% during extreme heat. Installing passive measures in new SF buildings to meet or beat current code is cost effective for the locations investigated. For the new MF apartment, it is cost effective for current code for all locations and for beyond-code for warm to mild locations. The BCR values for current code for new SF buildings range from 2 to over 6 and for new MF buildings from 3 to over 7, making a strong financial case for state and local government adoption. The BCR values for beyond-code range from 1 to 3 for new SF buildings and are above 1 for new MF buildings for three of the six locations. BCR values tend to be lower for existing buildings due to higher first costs although investment may prove cost effective if considered incremental to a planned retrofit.

The developed methodology lays the foundation for establishing standardized procedures for quantifying the resilience benefits of increased passive efficiency in buildings. It expands upon traditional efficiency studies focused on annual energy operating costs to include monetized impact assessments related to greenhouse gas emissions, occupant damages in terms of excess mortality, and property damage. Two robust valuation metrics analyzed include the passive survivability metrics SET degree hours and the heat index. These values are included in the output reports of the EnergyPlus building simulation program and can be readily applied to indicate the resilience benefit of increased efficiency.

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The authors would like to acknowledge the valuable guidance and input provided by Michael Reiner, Christopher Perry, and Jeremy Williams, DOE Building Technologies Office (BTO). Including such parameters (property damage) in the cost effectiveness assessment more broadly informs efficiency investment. While future work will improve analysis robustness, the resilience metrics provide an indication of the relative benefit of efficiency improvements to inform building design decisions, hazard risk planning. The authors are also grateful for the feedback and policy making-guidance provided by the members of the Technical Advisory Group, all of whom volunteered their time, including:

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Acronyms and Abbreviations

ACEEE	American Council for an Energy Efficiency Economy
ALF	assisted living facility
ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BCR	benefit–cost ratio
BTO	Building Technology Office
CZ	climate zone
DOE	Department of Energy
EEM	energy-efficiency measure
EIA	U.S. Energy Information Administration
EUI	energy use intensity
FEMA	Federal Energy Management Administration
HI	heat index
HVAC	heating, ventilating, and air conditioning
IAT	indoor air temperature
IBC	International Building Code
IECC	Internal Energy Conservation Code
IRC	International Residential Code
LEED	Leadership in Energy and Environmental Design
MF	multifamily
MMC	Multi-Hazard Mitigation Council
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NRI	National Risk Index
PHIUS	Passive House Institute U.S.
PNNL	Pacific Northwest National Laboratory
PS	passive survivability
SET	standard effective temperature
SF	single family/single-family
SHGC	solar heat gain coefficient
TAG	Technical Advisory Group
USGBC	U.S. Green Building Council
VSL	value of a statistical life

Contents

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Tables

1.0 Introduction

The number and cost of disasters are increasing over time, exposing the vulnerability of buildings and energy systems against extreme weather events. Over the past two decades, the United States has experienced 265 weather and climate disasters that exceeded $1 billion in damages (NCEI 2022). In 2017, the United States faced the costliest disaster year, with 16 distinct billion-dollar events totaling over $320 billion.

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1.1 Definitions

The National Academy of Sciences (NRC 2012) defines resilience as "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events." For example, a resilient building supports passive survivability (PS) by maintaining safe indoor conditions during an extreme temperature event that may coincide with an extended power outage or loss of power supply. A resilient building can also support a reliable grid by shedding loads during peak capacity periods to avoid blackouts. With higher frequency of severe temperature events, concerns around resilience of buildings are gaining increased attention. While many studies have quantified the benefit of imposing higher standards for building construction and infrastructural improvements for hardening and withstanding different conditions, the benefits of energy efficiency have yet to be quantified. Understanding the role that energy efficiency plays in resilience, the ability to shelter in place, and PS are key to quantifying the benefits of efficiency. Expanding building-specific resilience assessments to include energy efficiency can more accurately account for investment benefits and potential societal impacts.

There are several definitions of resilience but no single metric that applies across every infrastructure sector or energy domain. The resilience of a building is dependent on its ability to provide continuous services or safety in the face of a hazard effecting the building or its energy sources, such as the grid. With an increasing occurrence of severe weather events, building resilience and the ability of occupants to shelter in place is becoming more essential. Expanding the assessment of efficiency measures to their impact on PS and the ability to shelter in place can more accurately inform their investment benefits. PS is a building's ability to maintain critical life-support conditions in the event of an extended disruption to utilities (Wilson 2015). This concept has been highlighted as essential in the wake of extreme weather events, such as Winter Storm Uri and heatwaves in the Pacific Northwest.

1.2 Growing Focus on Building Safety, Public Health, and Climate Justice

At the individual building level, with limited or no power, the way a building performs during a disruption drastically changes, as temperature controls, ventilation, and other energy services, such as electric supply, are compromised. The resulting impacts present a critical risk to the health and safety of building occupants, particularly vulnerable populations such as those dependent on energy for medical needs or the elderly. A power outage following Hurricane Irma in 2017 left a nursing home without electricity to run air conditioning (Maltz 2019). Despite outdoor temperatures being in the mid-80s, indoor air temperatures (IATs) rose to almost 100°F, contributing to the deaths of 12 residents.

Extreme weather and disaster events—in both the impact from and recovery efforts following—expose the underlying vulnerabilities of a community. Lower income households, in addition to vulnerable populations, suffer disproportionately from the effects of a disaster, living in older, lower quality homes that offer less thermal and structural protection (Ferris 2016). With fewer financial resources to afford the necessary insurance policies and rebuilding costs, poorer communities are unable to partake in recovery efforts. A study concluded that recovery efforts further exacerbate social and economic disparities within a community (Howell 2019).

1.3 Efficiency–Resilience Nexus

Energy-efficiency technologies and design strategies can provide resilience benefits for buildings and the energy system at large before, during, and after a major disruptive event. Energy-efficient buildings lower power demand, reducing the stresses to the grid. Grid-enabled technologies, such as smart thermostats and heat pump water heaters, can adjust load consumption to support time-sensitive peak demand periods. Efficiency measures play a critical role in supporting building resilience for extreme temperature events that present additional risk to building occupants when disruptions lead to power outages. Strategies such as insulation, efficient windows, envelope air tightness, and passive ventilation can prolong comfortable indoor temperature conditions during a power outage. Efficient buildings, particularly when combined with an on-site back-up power or energy storage systems, are better equipped to function and maintain operability under such conditions. Following disaster, certain efficiency strategies, such as mechanical ventilation systems, can also help the building rebound by ensuring adequate access to fresh air and reducing the potential for mold growth and other lasting moisture damages.

Strengthening the resilience of buildings equips communities, states, and the nation at large against the complex risks and uncertainties disruptive events impose. As government agencies and businesses grapple with how to make buildings and energy infrastructure more resilient, many are turning to building codes as the policy mechanism of choice. While building codes currently accommodate a very broad range of functional needs and design considerations, including many aspects of resilient design, they can also evolve to address resilience more comprehensively in the built environment.

Building codes establish minimum requirements for the design, construction, and performance of building systems, and have long contained numerous provisions supporting resilience, from structural specifications for wind and snow loads, to fire and moisture resistance. Building energy codes, a subset of building codes, establish minimum requirements for building energy performance, making energy efficiency an inherent and fundamental component of resilience. Energy codes have a direct impact on energy-resilience outcomes, from increased thermal resistance and ability of the building to maintain comfortable indoor environments, to limiting unwanted air infiltration, which is a primary source of moisture and durability issues, while maintaining healthy levels of ventilation and indoor air quality. Energy codes also contain accepted methods for specifying and sizing building systems, such as heating, ventilating, and air conditioning (HVAC) and lighting, which ultimately determine a building's operational power needs and peak demand, thereby impacting the resilience of the broader utility grid.

As a policy instrument, building energy codes are uniquely positioned to promote resilience. They are readily adopted and implemented by federal, state, and municipal governments. Their provisions are typically coordinated with related industry standards, meet established criteria such as technological feasibility and cost effectiveness, and are familiar to the insurance sector. Building codes can be an efficient and effective strategy to reduce risks in disaster-prone areas that either lack them entirely or have dated codes. FEMA found that 30 percent of current construction activity is occurring in jurisdictions without building codes or with cods that pre-date 2000 (FEMA 2020a). Today building codes, and specifically energy codes, are adopted in some form in every U.S. state (DOE 2022). As building codes are updated in an ongoing manner to take advantage of evolving technologies and design practices, the code development also represents an opportunity for further resilience enhancements.[5]

1.4 Standardized Methodology Needed to Assess Benefits and Savings

Accepted metrics and methods for evaluating energy-efficiency benefits to justify investment are commonplace, typically reported as impacts on energy use (e.g., energy use intensity), cost (e.g., return on investment), or equivalent environmental impacts (e.g., tonnage of CO_2). In considering potential code changes, code development and consensus bodies, such as the International Code Council, typically require statements attesting to expected energy or cost impacts. Such benefits are generally accepted as quantifiable and reasonably certain for decision-making purposes. However, many resilience benefits are risk based, intended to

[5] Model energy codes, such as the International Energy Conservation Code (IECC) and ANSI/ASHRAE/IES Standard 90.1, are updated on a regular three-year development cycle, as administered by the International Code Council and ASHRAE, respectively.

mitigate or prevent damages associated with hazards or system malfunctions, and when successful may avoid such damages altogether. This presents a challenge to assess and quantify based on current criteria required to support proposed code changes. In addition, resilience benefits often extend beyond the building itself, as is the case with building–grid integration and connected HVAC systems which mitigate peak demands on the utility grid. Traditional analytical methods used to assess energy efficiency do not currently capture the true impacts of these connected systems. and new methods are needed to quantify time-sensitive impacts on energy use and efficiency. This study establishes a methodology to capture a holistic set of metrics that can provide a common basis for deliberation during the code development process.

Resilience efforts must confront the structural and socioeconomic conditions that leave communities most susceptible to major disruptions. Building-level interventions can break the recurring burden that disaster events perpetuate, in turn enabling resilience outcomes for communities. Energy efficiency is broadly recognized as a contributor to increased resilience in the built environment. However, energy efficiency and resilience objectives are not always complementary depending on the disaster event and specific circumstance.

While energy efficiency is broadly recognized as a contributor to increase resilience in the built environment, these goals can sometimes share a complex relationship, as with many aspects of integrated building design. Design conditions commonly vary by climate region, must remain flexible to meet a variety of different building types and a wide range of functional needs, and be responsive to varying hazard risks. For example, seasonal advantages associated with technologies, such as windows with low solar heat gain characteristics, can provide inverse effects—desirable vs. undesirable—between cooling and heating seasons, which can be particularly important during a power outage while trying to maintain comfortable living conditions. Likewise, buildings elevated in floodplains exhibit different energy use profiles compared to those constructed on traditional foundations. These represent only a few of numerous technological examples that must be carefully evaluated to adequately characterize and understand their true relationship and net benefits.

1.5 Research Objective and Supporting Analysis

The purpose of this study is to assess how increased energy efficiency can impact building resilience under extreme temperature scenarios. It aims to provide a technical foundation for quantitatively validating the benefit of efficiency to resilience. This initial effort is intended to inform follow-on research and development, further the strategic deployment of efficiency measures, and establish the importance of considering resilience benefits in future energy codes and standards. The study marks initial development of an industry-accepted framework, analysis protocols, metrics, and building thermal resilience valuation procedures. The effort also exposes some of the limitations of available data sources and damage models, as well as the need for method validation.

Analysis conducted as part of the study to achieve the research objective and develop the valuation methodology include the following:

- Develop, apply, and test procedures that expand building performance analysis beyond assessing efficiency impact on energy costs to include the cost impact associated with occupant health, property damage, and greenhouse gas emissions.
- Investigate the ability for thermal resilience metrics, incorporated as part of building performance analysis, to serve as proxy indicators of health impacts.

- Account for the probability and severity of extreme temperature events and the likelihood they coincide with an electrical power outage.
- Assess the sensitivity of location on resilience benefits associated with increased efficiency.
- Demonstrate methods for scaling building performance analysis results to populations of buildings and occupants.

These novel aspects of the work represent an expansion of conventional building efficiency performance analysis procedures that are needed to consider and quantify thermal resilience benefits. Such methods need to be further developed to support their routine application as extreme temperature events coupled with electrical power outages are occurring more frequently. If energy code is to uphold a minimum level of health and safety, its valuation in terms of thermal resilience is necessary. Doing so will value energy codes in a similar manner as other building codes addressing fire, storm, flood, and earthquake protection.

1.6 Technical Advisory Group

A TAG contributed to the development of the project scope, approach, and methodology, and reviewed results and findings. The 19 members included experienced professionals working on related topics and fields such as the insurance industry, building sciences, building codes, emergency management, disaster recovery, energy policy, energy economics, occupational health, research labs, and federal agencies. Members are listed with their affiliations in Appendix A. Their input helped the project team find a reasonable balance between establishing meaningful scope and effective methods while meeting project objectives and acknowledging budget constraints.

1.7 Report Overview

This report provides a building thermal resilience methodology focused on the ability to shelter in place during extreme temperature events. Its application can enhance current hazard mitigation activities to include building efficiency considerations. The methodology can also be used to expand current valuation considerations as part of energy code development, utility efficiency programs, and state and community resilience mitigation planning. The following sections provide background information, explain the development methods, and present results and findings. Section 2 describes a general methodology for assessing building thermal resilience. Section 3 introduces the applied methodology, which is a refinement of the general methodology to address PS during extreme temperature events and quantify the value of efficiency to support sheltering in place. Shifting to the report's central findings, Section 4 outlines the analysis scope undertaken in the study. Section 5 presents the analysis results and Section 6 checks health impact results against actual published data. Section 7 is a case study for an assisted living facility (ALF). Section 7 discusses the methodology application, identifies areas for improvement, and suggests opportunities and recommendations for further study. Section 8 concludes the study, providing a high-level summary of the key outcomes, implications to current energy-efficiency benefit assessment methods, and natural hazard mitigation.

2.0 Scope

This study examines the ability of buildings, whether existing, newly constructed, or high performance, to withstand extreme temperatures and the associated impacts on occupants and property. Scope-defining elements for the assessment include hazard selection locations, building types, baseline building characterization, and considered efficiency improvements. Figure 1 outlines the scope established for the study. It includes the evaluation of the resilience-related benefits and costs for two residential building types, single family (SF) and multifamily (MF) apartment, for six U.S. cities spanning three regions. A case study features a counterfactual baseline analysis for an existing assisted living facility (ALF), which provides insights on efficiency and resilience as it relates to residential critical care facilities. The study scope of analysis and assessment components are explained in more detail in Sections 2.1 through 2.3.

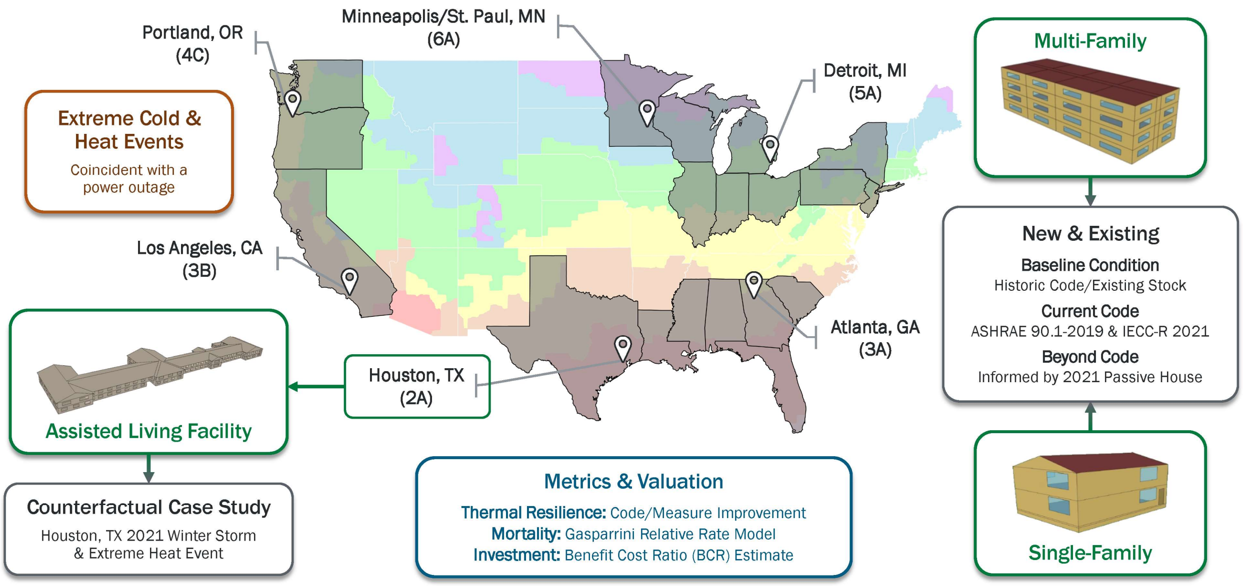


Figure 1. Key Components of the Analysis Scope

2.1 Extreme Temperature Natural Hazard Regions

In this study, the term hazard region applies to a geographic area sharing common climate conditions and hazard risk profiles. To investigate the effect of energy-efficiency mitigation across the United States, three hazard regions are analyzed: (1) Gulf Coast; (2) upper Midwest Great Lakes; and (3) Pacific Coast, as outlined in Table 1. The regions represent a range of varying conditions that influence extreme temperature risk, including climate zones (CZs), weather patterns, building stock, and population demographics. A map of U.S. CZs is provided in Appendix B. A high-level assessment was performed to select the representative range of hazard regions and CZ locations. The assessment was informed by data from the Federal Emergency Management Agency (FEMA) National Risk Index (NRI) describing natural hazard risk, social vulnerability, and community resilience (FEMA 2021).[6] Two representative cities were selected within each of the three regions to capture differences that might exist due to

[6] https://www.fema.gov/flood-maps/products-tools/national-risk-index

climate, building stock, social vulnerability, and community resilience. The six cities selected include Houston, Atlanta, Minneapolis/St. Paul, Detroit, Los Angeles, and Portland, Oregon.

Table 1. Regional Considerations Contributing to Natural Hazard Risk

	Gulf Coast	Pacific Coast	Great Lakes
Climate Zones	1A, 2A, 3A	3C, 3B, 4B	5A, 6A, 7
Population	Mid-high	Mid-high	High
Population vulnerability	Med-High	Low-Med	High
Building code adoption rates	Low-high	High	Low
Extreme hot days	Very high	Med	Med-high
Extreme cold days	Low	Low	High
Additional natural hazards	Hurricanes, high winds, winter storms	Earthquakes, wildfire, winter storm (wind)	Winter storms, tornadoes
Representative location (Climate Zone)	Houston, TX (2A); Atlanta, GA (3A)	Los Angeles, CA (3B); Portland, OR (4C)	Detroit, MI (5A); Minneapolis/St. Paul, MN (6A)

2.2 Building Types and Conditions

Three residential building types are included in the analysis: SF, MF, and ALF. A counterfactual baseline case study analysis performed for an existing ALF is included to gain insights on energy resilience as it relates to a vulnerable occupant population. Table 2 summarizes base case and improved performance conditions used in the analysis, which are explained below. A full description of the base case and improved conditions is provided in Appendix C.

The base case conditions for the existing SF and MF buildings are based on published survey data. For new buildings, the base case condition is based on historic model energy code requirements. Model code requirements for SF buildings are specified by residential code, which is recognized as the Internal Energy Conservation Code (IECC)-R (ICC 2021). Model code requirements for MF buildings are specified by commercial code, which is recognized as American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) Standard 90.1 (ASHARE 2019). Two improved conditions that include passive efficiency measures are also analyzed. They are aligned with (1) current model energy code requirements and (2) a beyond-code efficiency package based on the passive efficiency requirements specified in the Passive House Standard (PHIUS 2021).[7] For existing buildings, the improvements are amended to the base case condition. For new buildings, the historic and current model code conditions are characterized using the DOE model code prototype building models,[8] which include all energy-related requirements (Goel 2014). The beyond-code passive measures are amended to the current code requirements. These subtleties are reflected in Table 2.

The base case condition for the ALF is characterized based on the as-built construction details of an actual building located near Houston, Texas. The ALF study investigates the impact of passive and active efficiency measures on passive survivability (PS) and back-up power

[7] For SF buildings the Passive House U.S. (PHIUS) requirements

[8] https://www.energycodes.gov/prototype-building-models

requirements. Its performance is assessed in two additional conditions, including (1) passive efficiency requirements associated with historical commercial energy code, and (2) select improvements of passive and active efficiency measures.

Table 2. Building Models and Efficiency Conditions

Building Type	New			Existing		
	Base Case	**Current Code**	**Beyond Code***	**Base Case**	**Current Code**	**Beyond Code***
Single Family	IECC 2006	IECC 2021	2021 IECC plus passive beyond-code measures	ResStock data[9]	Passive measures from IECC 2021	Passive beyond-code measures
Multifamily Apartment	ASHRAE 90.1 2004	ASHRAE 90.1 2019	ASHRAE 90.1 2019 plus passive beyond-code measures	ASHRAE 90. - 2004 plus U.S. survey data	Passive measures from 90.1 2019	Passive beyond-code measures
	Base Case		**Older Building**		**Improved Design†**	
Assisted Living Facility	As-built construction		Select measures from 90.1 1999		Select passive and active beyond-code measures	

* The passive measures address envelope performance including window U-factor, window solar heat gain coefficient (SHGC), wall R-value, ceiling R-value, and floor R-value.

† For the ALF, passive measures also include reduced infiltration, natural ventilation, window shades and cool roof and wall coatings. The facility's active measures include ceiling fans, improved cooling efficiency, daylighting control, improved lighting efficiency, and reduction in plug loads.

2.3 Assessment Scope

The project study assesses the impacts of current code adoption and beyond-code efficiency measures as strategies to mitigate damages caused by extreme temperature events and support sheltering in place. The supporting analysis steps includes:

1. Quantifying hazard risk
2. Determining occupant exposure
3. Evaluating occupant damages
4. Estimating property damages
5. Calculating benefits and costs associated with mitigation.

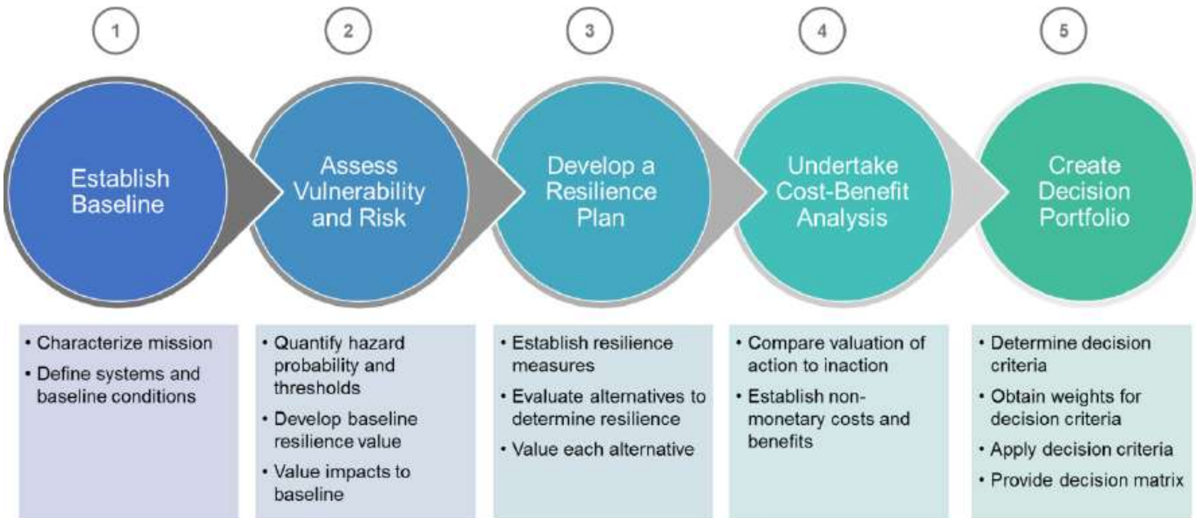
The five analysis components listed above are applied in the SF and MF building analysis. The buildings are analyzed in the six hazard region locations. Their thermal performance is modeled during a typical weather year and during a representative extreme heat and cold event defined for each hazard location.

The ALF analysis focuses on step 2, the determination of occupant exposure. Performance is analyzed based on a typical weather year and for representative extreme heat and cold events defined for Houston. The impact of implementing individual and packages of efficiency measures are compared to the baseline condition. The performance analysis also includes the impact of efficiency improvements on back-up power capacity requirements.

[9] ResStock couples statistically represent residential household and efficiency characterizations with the OpenStudio building modeling interface, which is powered by the EnergyPlus simulation engine (Langevin 2019).

3.0 Approach

A general methodology for performing resilience assessments is provided in Figure 2. The five-step process reflects the method outlined by Weimer et al. (2018). The procedure is rooted in establishment of metrics related to the cost and benefits of a resilient building.



Source: Weimar et al. 2018

Figure 2. Overview of Resilience Valuation Process

3.1 Methodology

As indicated in Figure 2, the metrics are defined and adopted in step 1 and used to establish the building condition. In steps 2 and 3, the metric values are assessed for the baseline and improved condition. The intention is to capture a building's energy-resilience performance considering its diverse aspects, including impacts on occupant health and well-being, building operational energy use, and asset value. Steps 3 through 5 include the assessment of monetary and nonmonetary mitigation benefits to inform implementation decision-making. The prioritization of actions involves the weighting of decision-making criteria to establish and compare measured benefits. The stakeholder assigns weighting factor values that reflect their assessment objectives, which influence the assessment outcome. The resulting decision portfolio provides a framework for prioritizing resilience measures to implement when limited capital is available.

The general resilience assessment approach, outlined in steps 1 through 4 above, is consistent with procedures followed in published work that evaluates the societal benefits of mitigation related to current code adoption, above code adoption, and investments made by FEMA (MMC 2018). The 2018 assessment indicates that investing in hazard mitigation measures can result in significant savings in terms of safety, prevention of property loss, and disruption of day-to-day life. The benefit–cost ratios (BCRs) for mitigation strategies studied in the report are based on four specific natural hazards: riverine and coastal flooding, hurricanes, earthquakes, and fires at the wildland–urban interface. In the study, costs include the upfront construction and maintenance costs. The benefits account for the present value of the reduction of future losses associated with property damage, as well as loss of life, medical treatment, mental health impacts, lost wages, additional living expenses, and lost household productivity.

The estimated national-level BCRs for mitigation across these hazards are provided in Table 3. As indicated, meeting common code requirements, as represented by the 2018 International Building Code (IBC) and the International Residential Code (IRC) versus a 1990-era design, results in a national benefit of $11 for every $1 invested. The estimated BCR is based on design improvements impacting the listed natural hazards, the population exposed to high hazard risk, and the probability of occurrence. The benefits of mitigation are based on a sampling of typical cases of community conditions and residential structures. The costs, benefits, and probability are annualized to determine the aggregated national BCR.

Table 3. Hazard Mitigation National BCR

National Benefit-Cost Ratio Per Peril *BCR numbers in this study have been rounded	Exceed common code requirements	Meet common code requirements	Utilities and transportation	Federally funded
Overall Hazard Benefit-Cost Ratio	4:1	11:1	4:1	6:1
Riverine Flood	5:1	6:1	8:1	7:1
Hurricane Surge	7:1	Not applicable	Not applicable	Too few grants
Wind	5:1	10:1	7:1	5:1
Earthquake	4:1	12:1	3:1	3:1
Wildland-Urban Interface Fire	4:1	Not applicable	Not applicable	3:1

Source: MMC 2018

A natural hazard not addressed in the 2018 Multi-Hazard Mitigation Council (MMC) study is extreme temperature events, which the IBC and IRC also provide benefit for mitigation. Specifically, the IECC referenced by the IBC and IRC includes minimum efficiency requirements that reduce a building's annual energy consumption. Such strategies also support improved comfort conditions that can reduce casualties, health impacts, and property damage during extreme temperature events.

In this study, the general methodology is applied to quantify the resilience benefits of building energy efficiency. The intention is to more fully value efficiency by capturing traditional benefits, such as reduced annual operating energy costs and the associated greenhouse gas emissions, as well as diverse aspects of resilience, including shelter-in-place capability, occupant health impact, and property damage.

3.2 Terminology

Specific terminology describes conditions related to building resilience. Understanding these terms is important for comprehending the overarching resilience valuation process as applied to extreme temperature events. The term "assets" used in the descriptions below refers to people, buildings, and related property.

Resistance: The ability of assets to withstand the effects of extreme temperature conditions. Their condition is indicative of their resistance, which affects their vulnerability.

Exposure: The presence of assets in places where they could be adversely affected by extreme temperature events.

Vulnerability: The extent to which assets will be negatively impacted from exposure to extreme heat and cold events.

Value at risk: The monetary value associated with the resulting damage from exposure to extreme temperatures.

Benefit–cost ratio (BCR): A net present value costing approach that assesses whether the benefits are greater than the costs needed to obtain the benefits.

The valuation process examined in this study includes procedures for completing a passive survivability (PS) assessment. The method accounts for the annual probability of extreme heat and cold events coinciding with an electricity power outage. The characteristics of the building and occupants indicate their resistance. Building simulation analysis provides performance results that indicate occupant exposure. Vulnerability, which is an outcome of exposure, influences damages, indicating the extent to which the building and occupants are negatively impacted. The value at risk is determined by associating a monetary value to damages incurred. The BCR reflects the annual probability of damages avoided and the cost of mitigation. The mitigation valuation assessment can also include qualitative resilience metrics. These metrics can be compared individually or in combination with qualitative values, with customized weighting factors applied to each metric. The approach supports the prioritization of mitigation efforts in accordance with the specific valuation objectives established for the analysis, which reflect their perceived value as assessed by stakeholders.

4.0 Methods Overview

The building resilience assessment applied in this study includes procedures to quantify risk or impact that are not typically conducted in building efficiency performance analyses. An overview of the assessment components, referenced data sources, and analysis methods are provided in Figure 3. These procedures include the determination of (1) the risk of extreme temperature event hazard occurrence, (2) the exposure of occupants during events, (3) the vulnerability and damage assessment of occupants and assets, and (4) the benefits and costs associated with hazard mitigation. The applied methods, which were developed under the guidance of the project TAG, are described in detail below.

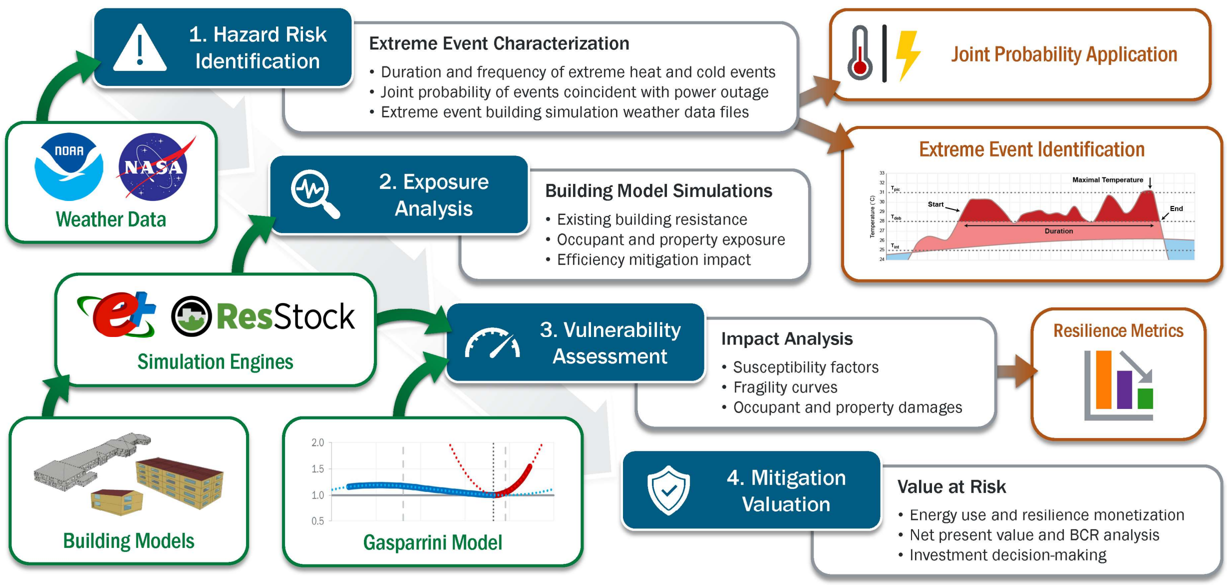


Figure 3. Applied Analytical Methods

4.1 Extreme Temperature Events Coincident with Power Outage

A key component of the natural hazard assessment is the determination of the risk of extreme temperature events coinciding with a power outage. Establishing this joint probability is important because of the pervasiveness of buildings outfitted with space-conditioning systems in the United States, which result in negligible risk of ill effects to the population and building when power is available during extreme heat or cold. Multiple data sources are used to identify historical extreme heat and cold events that likely coincide with an electrical power outage and pose a threat to building occupant health. There are two goals for the weather data analysis: (1) define the probability of extreme temperatures coincident with a power outage, and (2) develop weather data files characterizing extreme events to be used in building simulation modeling. The study used historical weather data from National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA), news articles of heatwaves and cold snaps, and reported power outages in the geographic regions.

4.1.1 Extreme Temperature Event Characterization

The study applied a method defined by Ouzeau et al. (2016) for identifying extreme heat events, which was developed in response to the 2003 heatwaves in France that killed upward of 15,000 people. The method has been adopted for the use in the International Energy Agency's Energy in Buildings and Communities Annex 80 Resilient Cooling project.[10] The method involves converting hourly weather data into daily mean temperature data. The approach uses three temperatures, as indicated in Table 4, to detect an extreme weather event relative to the daily mean data, which includes a threshold of detection (T_{pic}), a threshold indicating the beginning and ending of the duration of the event (T_{deb}), and a threshold of interruption (T_{int}). The interruption threshold allows users to merge or separate two neighboring events as needed. These thresholds are computed as the percentile of mean daily temperature distribution. The published method only set the percentile thresholds for extreme heat events. In this study, the same approach was adopted, with modified percentile thresholds, to determine corresponding temperatures for characterizing extreme cold events.

Table 4. Thresholds to Detect and Characterize Extreme Temperature Events

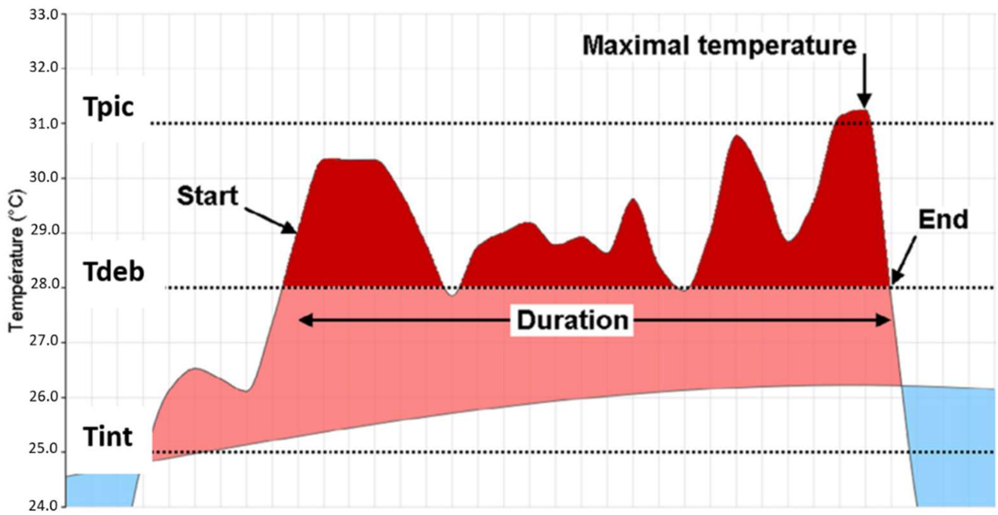
Threshold	Extreme Heat Event (Percentile)	Extreme Cold Event (Percentile)
Detection (T_{pic})	99.5	0.5
Duration (T_{deb})	97.5	2.5
Interruption (T_{int})	95.0	5.0

Source: Ouzeau et al. 2016

Two publicly available weather datasets were used to identify historical extreme temperature events for the study. They include the NASA POWER (Prediction of Worldwide Energy Resources) project (Stackhouse 2021; Sparks 2018), and NOAA's Local Climatological Data (NOAA 2021). These resources provide data files describing weather conditions, including hourly outdoor air temperature and humidity. Historical data from 1980 to 2020 published by NASA and NOAA were extracted and analyzed using code scripts developed by the research team. Separately, NASA and NOAA data were examined using Ouzeau's method to identify extreme temperature events, which were cross-referenced to find both a short- and long-term event. Events that appeared in the NASA dataset were favored but were seconded by NOAA data. Events that occurred since 2011 were prioritized as they were readily available in the EnergyPlus weather file format. To check the data for reasonableness, they were compared to values accessed from the NOAA Climate Resilience Toolkit (USGCRP 2018).

As noted, the Ouzeau et al. (2016) methodology uses a combination of the top 0.5%, 2.5%, and 5.0% temperatures to identify heatwaves. Specifically, the historical data are scanned to flag temperatures exceeding the 0.5% of all recorded measurements (hot or cold for heat and cold waves respectively), then the data are scanned forward and backward from the 0.5% measurement. If the temperature stays in the top or bottom 2.5% of recorded temperatures it is included as part of an extreme event. If the temperature falls outside the 2.5% temperature measurements but stays within the 5% highest or lowest recorded temperatures, the heatwave can continue with other neighboring heatwaves. Figure 4 shows an example of this heatwave calculation.

[10] For more information, see https://annex80.iea-ebc.org/.



Source: Ouzeau et al. 2016

Figure 4. Identification of an Extreme Heat Event using Daily Mean Temperature as an Indicator

The result of this methodology is creation of an array of dates and temperatures that can be used to plot heatwave and cold snap events as shown in Figure 5 for Portland, Oregon. The size of the circle indicates the relative intensity, which considers duration and temperature.

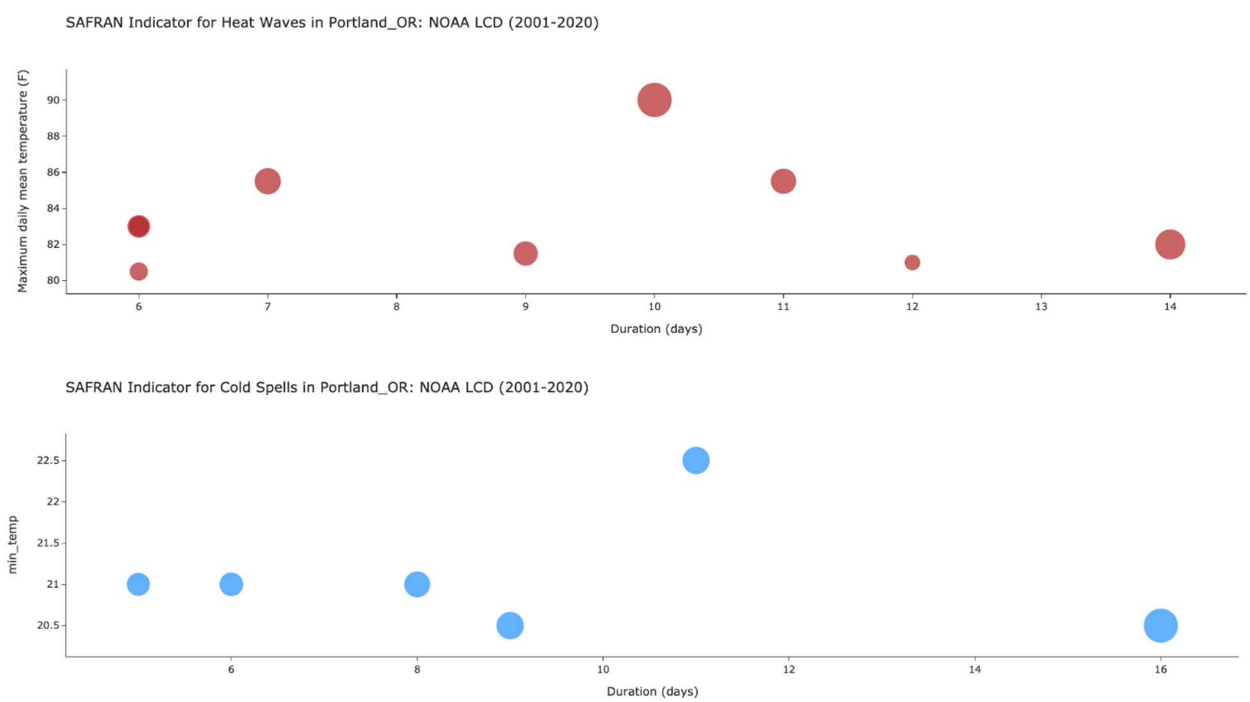


Figure 5. Extreme Heat and Extreme Cold Event Characterization for Portland, Oregon

The collection of events identified, following the procedure outlined above, provides the basis for determining the annual likelihood of an extreme temperature event. The value is calculated in accordance with Equation 1.

$$\textit{Annual Extreme Temperature Event Probability} = \frac{\textit{Number of extreme temperature events detected}}{\textit{Number of years examined}} \quad \text{(Eq. 1)}$$

4.1.2 Extreme Temperature Weather File for Building Performance Simulation

Applying the previously described approach to the historical hourly weather data from NASA and NOAA, data were identified for the short (shorter historical event duration, two-day analysis period) and long (longer historical event duration, 7-day analysis period) extreme heat and cold events for each of the six studied cities. Details of the representative weather event selected for analysis are listed in Table 5. The NASA POWER project web app provides weather data downloadable in the EnergyPlus[11] format. NOAA Local Climatological Data were converted to epw format using a script developed by the team.

Table 5. Representative Extreme Events Identified for the Six Study Locations

Location (Climate Zone)	Event Type		Start Date	End Date	Duration (Days)	Max Temp (°C)	Mean Temp (°C)	Min Temp (°C)
Houston, TX (2A)	Heat	Long	6/11/2011	6/21/2011	10	37.2	30.1	22
		Short	7/26/2015	7/31/2015	5	37.5	30.6	24.1
	Cold	Long	1/2/2010	1/13/2010	11	13.1	4	-5.7
		Short	1/6/2017	1/8/2017	2	18.3	6	-5.7
Atlanta, GA (3A)	Heat	Long	6/29/2012	7/8/2012	9	40.6	29.3	18.3
		Short	8/8/2010	8/13/2010	5	34.7	28.6	22.4
	Cold	Long	1/2/2010	1/13/2010	11	7.8	-2.9	
		Short	1/9/2011	1/14/2011	5	13.9	0.2	-7.2
Los Angeles, CA (3B)	Heat	Long	8/29/2017	9/3/2017	5	35.6	24	18.2
		Short	7/6/2018	7/9/2018	3	33.1	25.1	17.8
	Cold	Long	1/12/2007	1/18/2007	6	20.8	10.6	1.9
		Short	12/28/2010	12/30/2010	2	18	12.1	5.7
Portland, OR (4C)	Heat	Long	7/25/2009	8/2/2009	8	40.6	25.6	15.2
		Short	7/31/2007	8/3/2007	3	32.2	20.9	13.3
	Cold	Long	1/2/2017	1/16/2017	14	4.4	-0.8	-7.3
		Short	11/21/2010	11/25/2010	4	8.3	1.4	-7.9
Detroit, MI (5A)	Heat	Long	7/21/2016	7/27/2016	6	33.9	25.6	15.6
		Short	7/31/2007	8/3/2007	3	33.9	27.2	18.1
	Cold	Long	2/3/2014	2/13/2014	10	2.2	-7.9	-17.7
		Short	1/6/2014	1/9/2014	3	0.4	-10.5	-24.4
Minneapolis/ St. Paul, MN (6A)	Heat	Long	6/27/2012	7/22/2012	25	37.8	27.5	15.6
		Short	8/8/2010	8/12/2010	4	34.5	26.7	17.8
	Cold	Long	1/31/2014	2/11/2014	11	0.3	-14.7	-23.2
		Short	2/23/2010	2/25/2010	2	0	-7.9	-16.7

[11] EnergyPlus is the building simulation engine utilized in the study (EnergyPlus 2022).

4.1.3 Joint Probability of a Power Outage Coincident with an Extreme Temperature Event

Establishing the coincidence of a power outage occurring with extreme temperature events supports the study's assumption that the unavailability of space conditioning may lead to negative health impacts, including mortality. To establish the coincident risk, the historical extreme temperature events identified from the NASA data are cross-referenced against local power outage data. However, there does not exist a uniform, national, customer-weighted database of power outages to produce an annual power outage or coincident extreme heat/cold event probability, referred to here as the 'joint probability'. In lieu of this, DOE's Office of Cybersecurity, Energy Security and Emergency Response Electrical Emergency Incident and Disturbance data, collected on Form OE-417, were used (DOE 2018). The data include information on electric incidents and emergencies. DOE uses the information to fulfill its overall national security and other energy emergency management responsibilities, as well as for analytical purposes. Electric utilities that operate as Control Area Operators and/or Reliability Authorities, as well as other electric utilities, as appropriate, are required to file the form. The form is a mandatory filing whenever an electrical incident or disturbance is sufficiently large enough to cross the reporting thresholds. Reporting coverage for Form OE-417 includes all 50 states, the District of Columbia, Puerto Rico, the U.S. Virgin Islands, and the U.S. Trust Territories. The dataset is used in the study since it is the best currently available source identified. To make the data usable, several assumptions were made, namely that an outage recorded in OE-417 affected the entire state and power was restored to all customers at the time listed in the record.

These assumptions will produce an overestimation of power outage frequency and duration. To reduce the uncertainty of the results, scenario analysis was employed to develop low, medium, and high bounds to the power outages informed by the OE-417 data. The medium case was taken as the calculated value outage probability, with low and high biasing upward and downward by a fitted bathtub curve based on reliability practices and the cold and hot temperatures. For the purposes of this research, this approach was viewed as acceptable, though future work should both refine the power outage data assessment and perform a more detailed analysis of the temperature and power outage distribution.

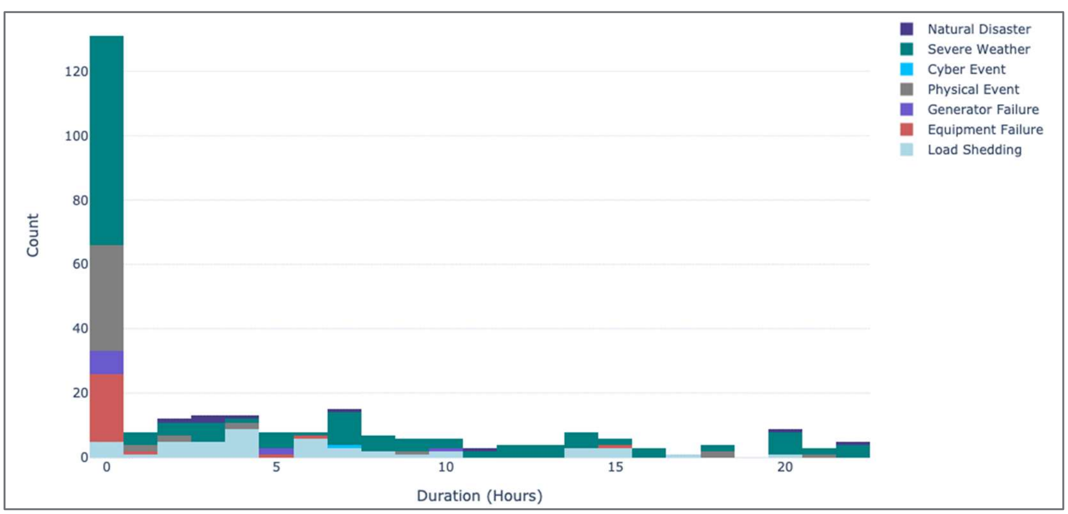


Figure 6. Frequency of Power Outages Due to Natural Hazards in Texas

The OE-417 dataset records reported power outage incidents resulting from natural hazard events dating back to 2000. The data used in the study are associated with "Severe Weather" (Figure 6). While not robust, the OE-417 data were used as a proxy for determining the likelihood of an outage occurring during an extreme heat or cold event. For example, during an average year, Texas experienced 16.4 large-scale outages based on the OE-417 form. Using the months of December through March for extreme cold, and June through August for extreme heat, the joint probability can be determined using Equation 2.

$$Annual\ Joint\ Probability = \left(\frac{Number\ of\ extreme\ temperature\ events\ with\ power\ outages}{Number\ of\ extreme\ events}\right) * Annual\ Extreme\ Temperature\ Event\ Probability \quad \text{(Eq. 2)}$$

The estimate determined for Texas is shown in Table 6. The approach results in a distribution of outage probability and duration associated with the occurrence of extreme hot and cold temperatures. As noted previously, these numbers will be biased upward, and future work should seek to correct this.

Table 6. Annual Probability of Extreme Temperature Events Coinciding with a Power Outage in Texas

	Joint Probability of an Extreme Event Power Outage > 24 hours	Extreme Event Annual Probability	Annual Joint Probability	Approximate Equivalent Rate
Extreme Heat	58%	130%	75%	1 every 1-2 years
Extreme Cold	33%	10%	3.3%	1 every 30 years

4.2 Occupant and Property Exposure

The building condition can affect the level of exposure that occupants and the property have during an extreme temperature event. Increased exposure for occupants can result in damage in terms of reduced productivity, negative health impacts, and even loss of life. Exposure for the property might include burst pipes, water damage, condensation, and mold. The characteristics of the building influence its resistance to extreme temperatures. The resistance of the building influences the indoor conditions, which affect the occupant and building exposure.

4.2.1 Thermal Resilience Metrics

Thermal resilience metrics that indicate the severity of the indoor environment without availability of mechanical systems can be used to indicate occupant and property exposure. These metrics may characterize comfort conditions, thermal autonomy, passive habitability, or other consequences. Some metrics include threshold conditions that indicate an overheating or underheating penalty. Building indoor conditions determined from the building simulation results provide the input data needed to calculate the resilience metrics and compare values associated with different building and temperature conditions.

Industry and academics have so far not agreed upon a set of metrics or a standard that can be used to evaluate the thermal resilience of buildings (Kesik et al. 2020). In this study, two passive survivability (PS) metrics are used, which are a subset of thermal resilience metrics, that include livable conditions thresholds aligned with occupant health and mortality risk. While these metrics target occupant health, they can also serve as a proxy for assessing the severity of indoor condition and property exposure. Further research is needed to relate the risk of occupant comfort thresholds to property damage. In this study, the direct exposure of property was not assessed. Instead, published property damage costs that account for annual risk and exposure were used as described in Section 4.4.

4.2.2 Passive Survivability Metrics

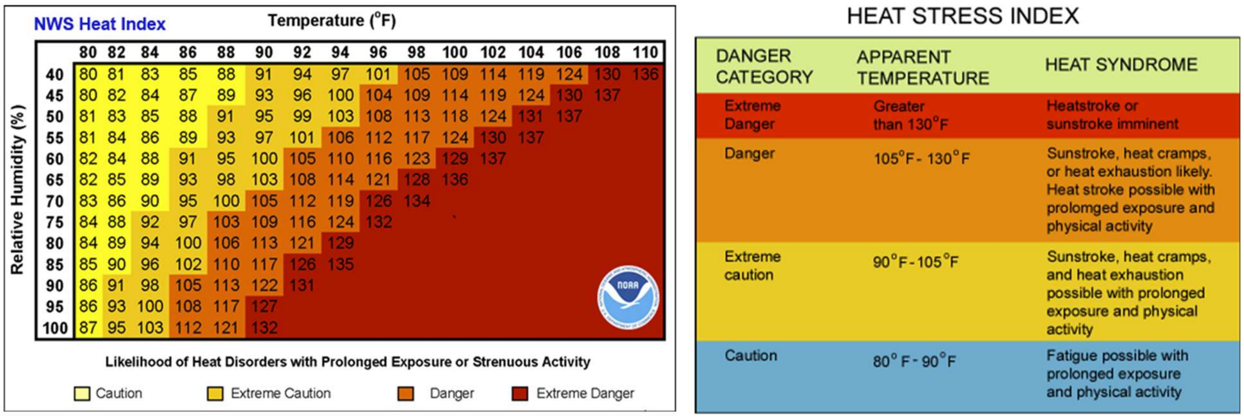
Considering the various needs of stakeholders (e.g., building occupants, owners or operators, regulators, public health agencies), two metrics were adopted to indicate PS: (1) standard effective temperature (SET), and (2) heat index (HI) for heat events. In addition, a cumulative SET metric, expressed as SET degree hours, was used to express the cumulative hourly SET relative to a livable condition threshold, which was determined during the extreme temperature event period. These metrics are used to quantitatively evaluate the PS of the baseline building conditions as well as improvements to thermal resilience through mitigation. The EnergyPlus building simulation engine (EnergyPlus 2022) calculates and reports SET, cumulative unlivable SET degree hours, and heat index (HI) hours.[12] A description of the metrics is provided below.

SET is a temperature metric that considers indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, as well as the activity rate and clothing levels of occupants. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) green building program includes a pilot credit, Passive Survivability and Back-up Power During Disruptions, referred to as IPpc100 (USGBC 2022), that defines “livable conditions” as SET values between 54°F and 86°F. SET can be used to assess thermal survivability in both heat and cold events (Wilson 2015). To receive the LEED credit for residential buildings, the unlivable SET (below 54°F or above 86°F) degree hours must not exceed 216 for a 7-day power outage during an extreme heat or cold event.

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 for extreme heat conditions (Sun et al. 2020). There are five levels of risk based on HI (Figure 7), including Safe (HI ≤ 80°F), Caution (80 < HI ≤ 90°F), Extreme Caution (90 < HI ≤ 105°F), Danger (105 < HI ≤ 130°F), and Extreme Danger (HI > 130°F). The HI hazard level hours are calculated as the accumulated number of hours when HI falls within a certain hazard level.

The PS metric values are determined for a given building thermal zone. For single-family (SF) buildings, the models have one thermal zone; however, for multifamily (MF), the models have multiple thermal zones. For these buildings, the thermal resilience metric values are determined for each occupied space. To capture the range of conditions across the building population and within the building, several sets of values are assessed. The existing building population SET values represent the range of conditions depicted by the median, best, and worse (5% and 95%) conditions.

[12] Release version 9.4 and later



RH (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

HEAT STRESS INDEX

DANGER CATEGORY	APPARENT TEMPERATURE	HEAT SYNDROME
Extreme Danger	Greater than 130°F	Heatstroke or sunstroke imminent
Danger	105°F - 130°F	Sunstroke, heat cramps, or heat exhaustion likely. Heat stroke possible with prolomged exposure and physical activity
Extreme caution	90°F - 105°F	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and physical activity
Caution	80°F - 90°F	Fatigue possible with prolonged exposure and physical activity

Source: NOAA 2017

Figure 7. Heat Index Chart and Heat Stress Levels

4.3 Damage Risk Assessment

The third component of the process, the damage risk assessment, quantifies likely damages incurred during an extreme temperature event. The calculation uses data describing the event frequency probability, occupant and building exposure metrics, and vulnerability imposed by indoor conditions. The product of these three parameters (Equation 3) characterizes the risk associated with building conditions during hazard events in terms of property damage, excess mortality, or injuries, as well as the impact of efficiency upgrades in terms of avoided damage.

$$Damage\ Risk = Frequency * Exposure * Vulnerability \qquad \text{(Eq. 3)}$$

In the equation, frequency is the probability of extreme temperature events coincident with power outages in a given year. Exposure is the number of people or buildings exposed to unsafe indoor conditions during events described by the frequency term according to building model simulation. Vulnerability is the relationship between indoor conditions during extreme events and consequences like discomfort, injuries, or mortality. Frequency data (e.g., the probability of an extreme event and power outage coinciding) are collected using the methods described in Section 4.1. Exposure data are determined using the data and modeling methods described in Section 4.2. Data to describe the vulnerability of occupants regarding the building indoor conditions during extreme temperatures are not well established. The approach adopted by the study to assess occupant damage analysis is described below.

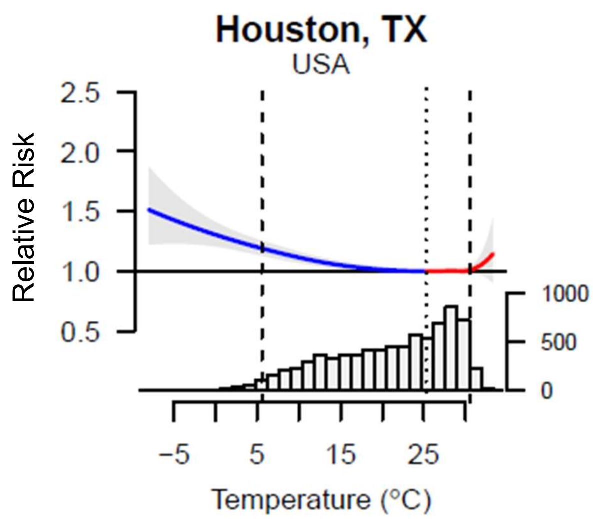
4.3.1 Property Damage Risk

Methods to assess property damage risk were not developed since historical property damage cost data were used. Instead, property monetary damages were determined from National Risk Index (NRI) data (FEMA 2021), as described in Section 4.4.2.

4.3.2 Occupant Damage Risk

The impact of severe temperature on human health is dependent on several factors, including age, gender, socioeconomic status, and climate adaptation; thus, there is no specific damage curve that can be generalized for the population of the United States. Damage curves that provide death rates by temperature are needed for each city/county of interest. Additional negative health impacts can be caused by exposure associated with extreme temperature events, including hospitalization, emergency room visits, and self-treated illness. However, adequate information in published literature was not found for these associated damages.

Gasparrini et al. (2015) published data can be used to estimate the effect of extreme temperatures on loss of life. Gasparrini continued previous epidemiological work to create an estimate of the increase in relative risk for mortality (Anderson and Bell 2009; Basagaña et al. 2011). This relative-risk calculation uses death records to establish the average daily mortality in a city. The work also calculates the mortality based on cause, though the causes are not as relevant for this work. Then, using recorded extreme temperature events, Gasparrini and others estimate the increase of mortality rates during the events and correlate this to temperature to produce an estimated increase in relative risk based on temperature. Figure 8 shows example results from this methodology. A relative-risk value of 1 indicates that the associated temperature resulted in no increase in the rate of mortality.



Source: Gasparrini et al. 2015

Figure 8. Example Gasparrini Damage Function to Determine Excess Mortality

The steps below outline the procedure to determine occupant damage associated with mortality using the Gasparrini data.

1. Calculate the average daily deaths that occur in the location of interest based on published annual death data (Equation 4).
2. Determine the average daily indoor temperature occurring during the representative long-term extreme temperature event from the building simulation results.
3. Determine the relative rate for each event day based on its daily temperature using the Gasparrini damage function.
4. Calculate the attributable death fraction (Equation 5).
5. Determine the attributable deaths for each event day (Equation 6); total the attributable deaths associated with the event.
6. Multiply the attributable deaths by the joint probability of the extreme event coinciding with a power outage.

7. Add the annualized attributable deaths determined for the extreme heat and extreme cold events.

$$Average\ daily\ deaths\ = \frac{Total\ annual\ deaths}{365} \quad \text{(Eq. 4)}$$

$$Attributable\ death\ fraction\ = \frac{(Relative\ Rate - 1)}{Relative\ Rate} \quad \text{(Eq. 5)}$$

$$Daily\ attributable\ deaths = \ Average\ daily\ deaths * Attributable\ death\ fraction \quad \text{(Eq. 6)}$$

The Gasparrini et al. (2015) data are developed for 384 global locations, including 132 U.S. cities, and can be used to estimate the impact building conditions have on excess mortality. Guo et al. (2017) found that heatwaves had more impact in moderately hot and moderately cold regions than they did in cold and hot regions. This aspect is apparent in the Gasparrini data and can be seen in the results. In this application, the data were used to evaluate changes in mortality based on average daily indoor temperature. While this approach appears to provide for a conservative estimate of mortality, the authors believe that the bias it introduces is reduced or eliminated since the change in mortality rates are used and not absolute numbers.

The Gasparrini method is a robust epidemiological method but has some flaws as it relates to building data, for example it is behavior agnostic. For instance, if a city uses technical solutions such as ‘cooling centers’ as publicly available climate-controlled spaces to help mitigate deaths during a heatwave, it would be difficult to measure the impact of these measures unless the study was completed before and after their use. Another factor influencing mortality rate is the impact that losing air conditioning has on people who are accustomed to it and have not climatized to the higher temperatures when heatwaves occur. This effect is not accounted for in the Gasparrini data since it assesses the relative rate of mortality based on outdoor daily average temperature conditions. Additionally, many cold-related deaths occur in vulnerable populations (such as the housing insecure) where residential building energy-efficiency standards may not have an impact. All of these considerations aside, Gasparrini is likely the most useful method for making comparisons of the impact of mitigation strategies in a city.

4.4 Value of Loss Determination

Quantifying the value of building thermal resilience involves assessing the benefits and costs associated with mitigation implementation. As summarized in Table 7, the mitigation benefits considered in this study include savings in annual energy costs, reductions in annual greenhouse gas emissions, and avoided losses associated with occupant health and property damage. Components not considered in the analysis but are in the 2018 MMC study regarding the 2018 IRC and IBC assessments for other natural hazards. Some of the MMC study cost components are not relevant to the scope of this study. For example, the environmental benefit in the MMC study is associated with enhancing utilities and transportation lifelines (specifically water supply and electric utility grid) in response to seismic and flooding hazards. However, impacts such as maintenance costs, additional living expenses, and general health could be accounted for thermal resilience in future work.

Table 7. Resilience Benefit and Cost Factors Considered in the Study

	Included	Excluded
Benefits	Annual energy costs savings Annual greenhouse gas emissions reductions Avoided loss of life Avoided property damage	Additional living expenses and direct business interruption Indirect business interruption Post-traumatic stress disorder Environment
Costs	Measure first costs	Measure maintenance costs

4.4.1 Occupant Loss Valuation

The value of a statistical life (VSL) was used to calculate the value of saved lives due to building mitigation measures. A value of $10 million per life, based on 2020 dollars, was used. The value is in the range of different estimates, with FEMA (FEMA 2020b) having the lowest assigned value and Viscuzzi (2020) having the highest. Viscuzzi has long been a cited source for VSL estimates. He valued the cost health risks from the COVID-19 pandemic using an $11 million (2019 dollars) estimate of VSL. The value was composed of a set of estimates including a sample of all VSL estimates at $13.2 million (2019 dollars) and a best set sample of $13.3 million (2019 dollars). The National Bureau of Economic Research uses the Environmental Protection Agency's $10.95 million per human life in its calculations (Carlton et al. 2020). The Department of Transportation provides a VSL estimate of $11.6 million in 2020 dollars (Putnam and Coes 2021). FEMA uses a VSL estimate of $7.6 million (2020 dollars) (FEMA 2020b), and provides estimates for hospitalization ($1.3 million), treat and release ($0.1 million), and self-treat ($0.01 million) (FEMA 2009).

4.4.2 Property Loss Valuation

Property damages associated with loss of space heating during extreme cold events could include frozen and/or burst pipes and truss lift, whereas extreme heat event damages may be related to buckling floors, foundation damages, and mildew or mold growth. It is challenging to estimate such damages and attribute them to the combined risk of extreme temperatures coinciding with a power outage. Generally, whole-building simulation models are not developed at the level of detail needed to evaluate the risk of property damage based on the building structural design, system layouts, and construction details; nor do they account for preventive maintenance activities that could mitigate damage. Some potential impacts, such as foundation damage or damage from snow and hail, are independent of whether a power outage occurs. The damages associated with extreme temperatures depend on weather characteristics such as humidity, building characteristics such as materials and design, and occupant influences such as operation and maintenance. Similarly, economic impacts associated with building damages vary significantly depending on the type of damage, location of the building, and extent of repairs needed.

In light of these challenges, property damage risk and the associated annualized damage cost estimates used in the study stem from data published by FEMA (2021). The NRI uses data published in Arizona State University's SHELDUS (Spatial Hazard Events and Losses Database of the United States). The reported data are annualized values based on historical costs incurred. Annualized damage values are reported as determined from historic data applied to the FEMA Hazus model (FEMA n.d.). Damage values include those associated with population health and mortality, and damage associated with property, vehicles, and infrastructure. Table 8 includes the NRI damage data for population and property for the six locations considered. The table includes two additional NRI metrics that influence vulnerability and damage, the social vulnerability score and the community resilience score. Higher values for social vulnerability indicate an increased likelihood of damage. Higher values for community resilience indicate a decreased chance of damage.

Table 8. FEMA Hazus Model Vulnerability and Loss Values

City	County	Social Vulnerability Score	Community Resilience Score	Expected Annual Loss			
				Cold Snap		Heat Wave	
				Population	Building	Population	Building
Houston, TX	Harris	38.9	52.2	$0	$0	$1,240,086	$1,761
Atlanta, GA	Fulton	26.3	52.7	$0	$0	$0	$0
Los Angeles, CA	Los Angeles	44.9	51.9	$0	$0	$331,829	$24
Portland, OR	Multnomah	35.8	54.8	$40	$0	$115,427	$93,361
Detroit, MI	Wayne	48.6	55.0	$1,235,872	$478	$7,591,497	$31,949
Minneapolis, MN	Hennepin	26.1	56.8	$1,384,525	$1,965	$1,918,245	$4,971
	Average	**36.8**	**53.9**	**$436,740**	**$407**	**$1,866,418**	**$22,011**

Source: FEMA, National Risk Index Primer, December 2020

To estimate property damage as a function of increased efficiency, the NRI natural hazard data for heat and cold waves are scaled. Specifically for each location, the annualized expected building loss values listed in the table are multiplied by the mortality fraction reduction estimated using the Gasparrini model, as indicated in Equation 7. The damage values determined for heat and cold events using the equation are added together to assess the total potential annual damage.

$$\mathit{Reduction\ in\ property\ damage} = \mathit{NRI\ annual\ cost\ of\ property\ damage} * \left(\frac{\mathit{Mortality\ baseline} - \mathit{Mortality\ efficiency\ package}}{\mathit{Mortality\ baseline}}\right) \quad \text{(Eq. 7)}$$

Using the NRI data to estimate damages for the application has its limitations. For example, the data published for extreme temperatures are independent of whether a power outage occurs. In addition, historical data also lack damage details on a per-building level, which does not support evaluating impacts across building vintages and efficiency levels. These limitations are somewhat circumvented by scaling the annual results based on the relative reduction in mortality damages. In addition, the NRI data suggest that the population damage costs (e.g., occupants) are on average about 100-fold that anticipated for buildings. This implies property damages are negligible compared to population damages. However, when compared to published data for recent extreme temperature events, building damage was significant. For example, the Texas Department of Insurance reports the paid claims for residential and commercial property damage for the 2021 winter storm event total $5.7 billion (TDI 2021).[13] It is possible the NRI property damage costs data for heat and cold waves are incomplete, which warrants further investigation and future work to validate the reliability of the published values.

[13] The TDI value is for a specific event while the FEMA NRI value is an annualized value that accounts for the probability of occurrence. The estimated joint probability determined by this study is 3.3%, which implies that the annualized building loss value based on the recent winter storm is $1.9 M.

5.0 Results

The thermal resilience methodology, outlined in Section 3, is applied in its entirety for the single-family (SF) and multifamily (MF) apartment buildings in the six hazard locations considered. The application quantifies the benefits of efficiency improvements on thermal resilience in terms of (1) passive survivability (PS) metrics, (2) reduced rate of mortality, and (3) monetized losses and the estimated benefit–cost ratio (BCR) associated with efficiency investments.

To complete the assessment, thermal performance of the SF and MF buildings is evaluated using simulation modeling procedures and defined efficiency cases. New SF and MF buildings are modeled using the energy code prototype models. The existing SF building is modeled using the ResStock tool, which uses OpenStudio and draws on location-specific building survey and utility data to define base case conditions. The existing MF analysis stems from the code prototype building models including historic code requirements and reflecting national survey data. The applied modeling methods are described in detail in Appendix D. The detailed existing building stock characterizations for the ResStock analysis are provided in Appendix E.

The PS metrics quantified are the standard effective temperature (SET) and the cumulative hourly temperatures exceeding temperature thresholds that are summed over and expressed as SET degree hours. The occupant exposure, damage assessment, and value of loss determination follow the procedures outlined in Section 4. Results are discussed below with a focus on SF and more complete analyses are supplied in the appendices.

5.1 Coincident Risk Assessment

To annualize monetary impact, losses assessed for a representative extreme temperature event must be multiplied by the annual joint probability. Table 9 provides these values. The table also includes the current adopted residential energy code for each location for reference.[14,15]

Table 9. Annual Extreme Temperature Event Power Outage Probability

	Houston, TX (2A)	Atlanta, GA (3A)	Los Angeles, CA (3B)	Portland, OR (4C)	Detroit, MI (5A)	Minneapolis/ St. Paul, MN (6A)
State Adopted Code Equivalent*	IECC 2018	IECC 2009	IECC 2021	IECC 2018	IECC 2009	IECC 2009
Cold Event Annual Joint Probability	0.033	0.038	0.149	0.075	0.075	0.025
Heat Event Annual Joint Probability	0.754	0.099	0.342	0.099	0.165	0.150

* As of March 31st, 2022

Overall, the annual joint probability for extreme heat is higher than extreme cold for the locations of interest. The highest frequency extreme heat-power outages occur in Houston, every 1 to 2 years, and Los Angeles, every 1 out of 3 years.

[14] The energy code cycle specified is the based on the performance equivalent of the model code adopted by the state including amendments.

[15] On behalf of DOE, the Pacific Northwest National Laboratory assesses and publishes the model energy code efficiency equivalent associated with each U.S. state adopted residential and commercial energy code, which accounts for state amendments made to the published model code. For example, a state may adopt the 2021 IECC but with amendments the effective performance would be equivalent to the 2018 model code. Each state's adopted model code and amended code equivalent is provide at https://www.energycodes.gov/status/residential.

5.2 Occupant Exposure

Exposure charts for the new and existing SF and MF buildings in the six locations are presented in Appendix F. Sample charts are provided in this discussion for the new and existing SF buildings in Atlanta. The charts illustrate the comfort conditions occurring during long (7-day) heat and cold events. Each set of charts shows a decrease in SET degree hours with increased efficiency, which indicates that improving passive efficiency increases thermal resilience. As mentioned in Section 3.2, the LEED Passive Survivability Pilot Credit IPpc100 defines “livable conditions” as those that align with SET values between 54°F and 86°F. To receive the credit, the cumulative unlivable SET degree hours (number of degrees falling below 54°F or above 86°F) must not exceed 216 over a 7-day period during an extreme heat or cold event coinciding with a power outage. The SET degree hour values can be checked against this threshold. Changes in values caused by efficiency measures can be compared to gain insights on thermal resilience improvement and habitability. However, since different modeling methods (e.g., ResStock building population models using OpenStudio and building prototype models using EnergyPlus) are used for the existing and new SF buildings, it may not be meaningful to make cross-comparisons between them. Figure 9 presents occupant exposure data for new SF buildings in Atlanta during long extreme events. SET degrees are indicated on the left axis and cumulative SET degree hours on the right axis for the base case (orange), current code case (purple), and beyond-code case (green). The “x” indicates a cumulative SET degree hour value of 216. The label above the marker indicates the days of safety that coincide with reaching the threshold.

For the new SF analysis, the data trends show the number of habitable hours increases with increased efficiency, which indicate reduced occupant exposure due to passive efficiency improvements. The SET degree hours over the 7-day extreme heat event exceed the LEED livable condition requirement for homes built to the historic baseline. Comfort conditions for homes built to current code or beyond code are maintained and fall below the uninhabitable threshold. During the extreme cold event, the improved efficiency cases exceed the unlivable hours threshold (by about sevenfold). This suggests that mitigating damage through investments in on-site generation, energy storage, or community emergency shelters may be warranted.

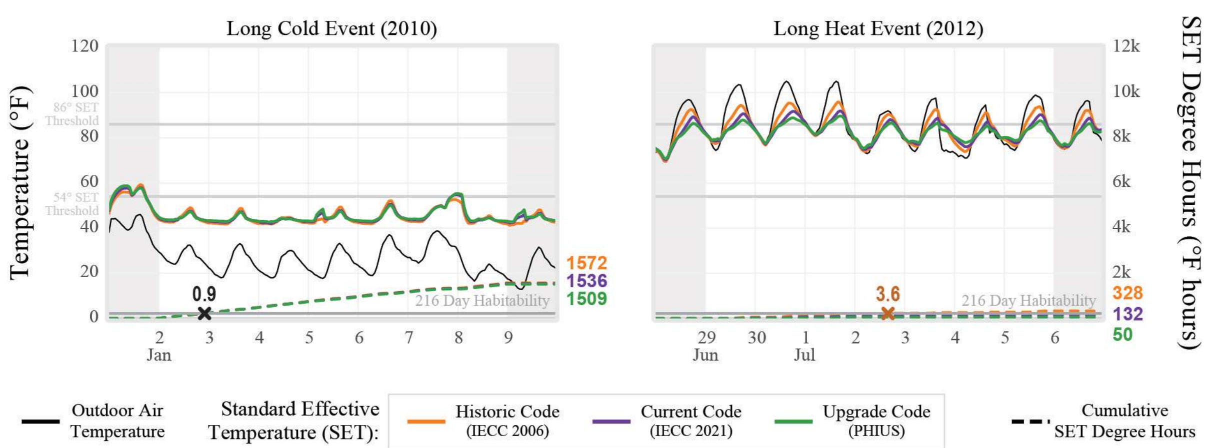


Figure 9. Occupant Exposure over Seven Days for New Single-Family Homes in Atlanta, GA (3A)

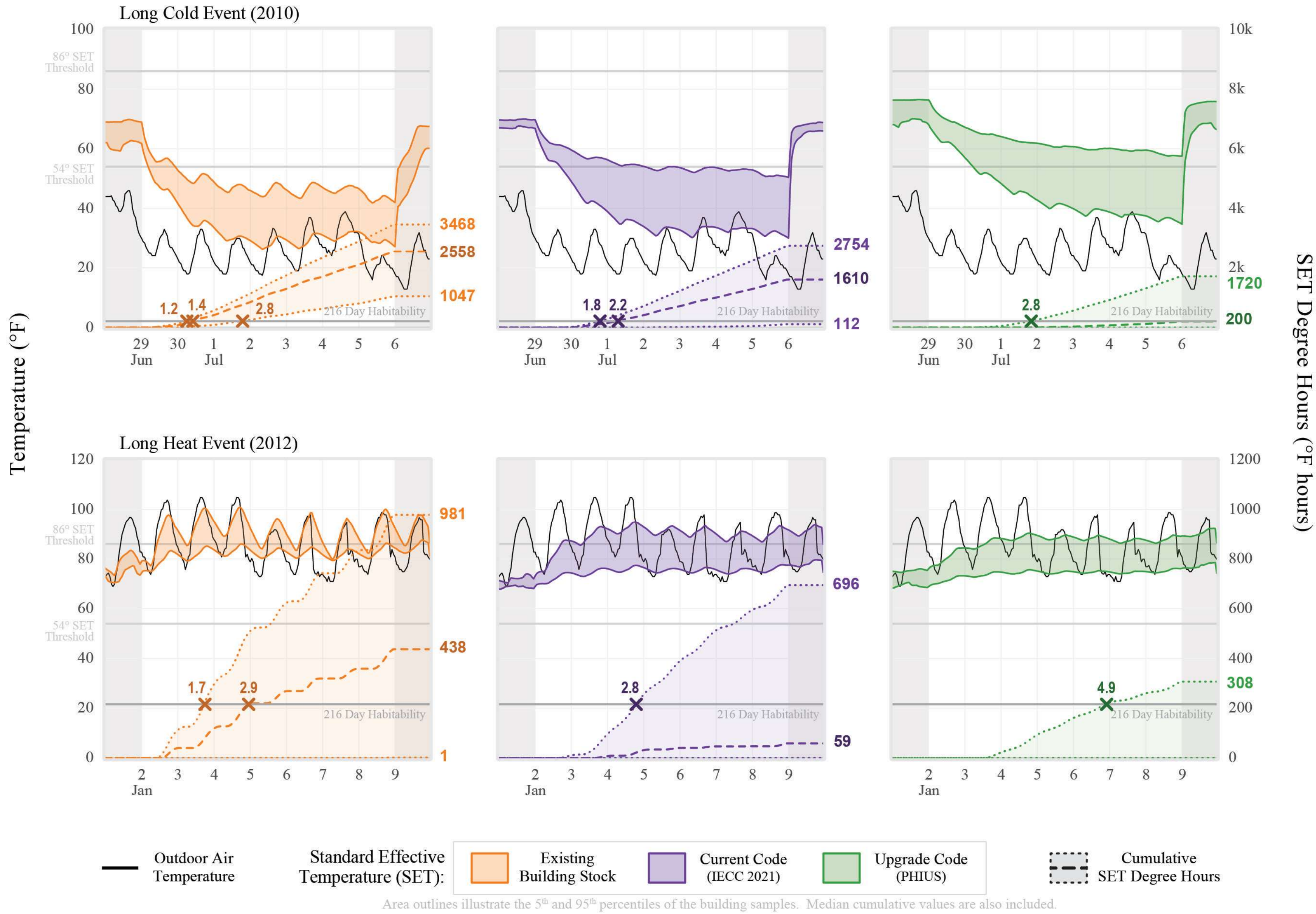


Figure 10. Occupant Exposure over Seven Days for Existing Single-Family Homes in Atlanta, GA (3A)

Figure 10 presents the results for existing SF buildings in Atlanta. The shaded bands indicating the SET timeseries data correspond to 5% (worst) and 95% (best) performance across the population of buildings. The cumulative SET degree hour values are indicated on the right axis for the 5%, median, and 95% cases. For example, in the 5% case for Atlanta long heat event for SF homes, the representative building will maintain habitable conditions for 1.7 days, while a home built to the 2021 IECC will maintain habitable conditions for 2.8 days, over a full day longer. However, a highly efficient home built to Passive House Standards can maintain temperature within the habitability threshold for almost 5 days, nearly three times as long as the existing building stock.

For the existing SF analysis, data trends show the number of habitable hours increases with increased efficiency, which indicate reduced occupant exposure due to passive efficiency measures. The SET degree hours over the 7-day extreme heat period do not exceed the LEED livable condition requirement for the best built home in existing conditions, the median and best built homes with current code, and beyond-code improvements. During extreme cold, comfort conditions are maintained for the better built homes improved to meet current code and for the median and better built homes improved to the beyond-code condition. While data trends are similar, there are notable differences between the SET and SET degree hour values for new SF analysis and existing SF analysis in the improved efficiency cases. While this warrants further investigation, it highlights the challenges of making cross-comparisons of absolute values between studies following different measure characterizations, modeling methods, software versions, and simulation engines.

Table 10 and Table 11 summarize the SET degree hour data indicated in the SF charts, above (Figures 9 and 10). The metric values indicate occupant exposure and potential health damage risk. The bar charts to the right highlight the trends determined across the three building efficiency conditions (existing stock, current code, and beyond code). The tables **Error! Reference source not found.** include values estimated for long extreme temperature events. SET degree hours for all events and buildings are reported at the beginning of Appendix F. To characterize the existing SF stock, the values in Table 11 are based on the 5%, median, and 95% performance distribution determined from the analysis.

The results show that occupant exposure is reduced as efficiency improves. In several instances, the number of hours of nonlivable conditions is reduced to zero for the current code. In many instances, the SET degree hour metric is reduced to zero for the most efficient package. However, for some locations during extreme heat events, nonlivable conditions worsen with increased efficiency. This is the case for (1) Portland's long heat event for the best existing SF condition, and (2) Detroit's long heat event for all existing SF conditions. This implies that the improved efficiency condition is causing heat to be trapped in the building due to high ambient temperatures, solar gains, insufficient natural ventilation, and limited nighttime cooling. The latter issue is more likely to occur in humid climates with limited diurnal temperature swings occurring during the summer. The incidences of overheating also appear to be linked to cool climates with less solar control than warm climates, which becomes an issue during extreme heat events.

Table 10. SET Degree Hours over Seven Days for Extreme Events in New Single-Family Buildings

Location (Climate Zone)	Event	SET Degree Hours* Historic Code IECC 2006	Current Code IECC 2021	Beyond Code PHIUS	Code Version Trend
Houston, TX (2A)	Cold	371	363	347	
	Heat	451	290	197	
Atlanta, GA (3A)	Cold	1,572	1,536	1,509	
	Heat	328	132	50	
Los Angeles, CA (3B)	Cold	90	70	54	
	Heat	34	1.7	-	
Portland, OR (4C)	Cold	1,366	1,328	1,289	
	Heat	195	149	101	
Detroit, MI (5A)	Cold	1,544	1,430	1,212	
	Heat	90	69	44	
Minneapolis/ St. Paul, MN (6A)	Cold	2,049	1,895	1,594	
	Heat	206	180	136	

* Cooling hours > 86°F, Heating hours < 54°F

Table 11. SET Degree Hours over Seven Days for Extreme Events in Existing Single-Family Buildings

Location (Climate Zone)	Event	SET Degree Hours* Existing Stock			Current Code IECC 2021			Beyond Code PHIUS			Code Version Trend		
		5%	Median	95%	5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	Cold	1,571	749	136	1,139	222	0.3	634	-	-			
	Heat	1,188	600	56	896	141	-	651	-	-			
Atlanta, GA (3A)	Cold	3,468	2,558	1,047	2,754	1,610	112	1,720	200	-			
	Heat	981	438	1.4	696	59	-	308	-	-			
Los Angeles, CA (3B)	Cold	360	87	-	20	-	-	-	-	-			
	Heat	423	100	-	349	-	-	95	-	-			
Portland, OR (4C)	Cold	3,687	2,963	1,692	2,492	1,849	379	1,234	237	-			
	Heat	857	371	3	1,014	319	-	569	-	-			
Detroit, MI (5A)	Cold	5,227	4,248	2,547	4,479	3,020	1,484	2,589	1,778	637			
	Heat	687	223	-	686	53	-	670	0.3	-			
Minneapolis/ St. Paul, MN (6A)	Cold	6,746	5,397	3,575	5,094	3,699	1,967	3,228	2,190	912			
	Heat	714	215	-	681	66	-	609	5	-			

* Cooling hours > 86°F, Heating hours < 54°F

5.3 Occupant Damage

The datasets published by Gasparrini et al. (2015) are applied in this study to estimate the impact of extreme temperature events on occupant mortality. The Gasparrini study evaluates the temperature impacts based on average temperatures in 272 locations around the world. The study provides data for a diverse set of U.S. cities (135), which aligns with the needs of this research. It also provides both heat and cold statistics and fragility curves for understanding the impact of the severe temperature on the population, which account for the social vulnerability and community resilience associated with each city. The Gasparrini data were deemed to be the most suitable for the application. More details about the method and related work are provided in Appendix G.

Table 12 and Table 13 summarize the excess death estimates at the county level for new SF and existing SF buildings, respectively. determined by applying the average daily indoor temperature values from the building simulation model to the Gasparrini algorithm. The results for all SF and MF building cases[16] are presented in Appendix H. The data highlighted in shades of green indicate the reduction in excess deaths for the representative event and the associated annualized value. The latter is the event excess death value multiplied by the annual joint probability value listed in Table 9. The annualized values are used in the BCR net present value calculation.

Table 12. Estimates of Excess Deaths over Seven Days Attributed to Extreme Events in New Single-Family Buildings

		Estimated Event Mortality			Event Mortality Reduction*				Annual Mortality Reduction*†	
		Deaths per Event			Lives Saved per Event		Improvement		Lives Saved per Year	
Location (Climate Zone)	Event	Historic Code IECC 2006	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Cold	80.1	78.6	76.3	1.46	**3.75**	1.8%	4.7%	0.05	**0.12**
	Heat	11.8	5.0	4.0	6.80	7.87	58%	**67%**	5.13	**5.94**
Atlanta, GA (3A)	Cold	21.2	21.1	21.0	0.08	0.15	0.4%	0.7%	0.00	0.01
	Heat	5.0	3.6	3.1	1.41	1.86	28%	37%	0.14	0.18
Los Angeles, CA (3B)	Cold	72.8	73.2	73.3	-0.42	**-0.51**	-0.6%	**-0.7%**	-0.06	**-0.08**
	Heat	138.2	129.6	133.4	**8.62**	4.79	6.2%	3.5%	2.95	1.64
Portland, OR (4C)	Cold	15.7	15.6	15.5	0.10	0.19	0.6%	1.2%	0.01	0.01
	Heat	28.9	28.9	28.6	0.01	0.28	0.0%	1.0%	0.00	0.03
Detroit, MI (5A)	Cold	32.8	32.3	31.4	0.47	1.37	1.4%	4.2%	0.04	0.10
	Heat	43.0	44.1	44.3	-1.13	**-1.31**	-2.6%	**-3.0%**	-0.19	**-0.22**
Minneapolis/ St. Paul, MN (6A)	Cold	34.1	33.5	32.3	0.63	1.78	1.8%	**5.2%**	0.02	0.04
	Heat	41.1	40.7	39.3	0.37	1.75	0.9%	4.3%	0.06	0.26

* Changes relative to Historic Code (IECC 2006)

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

16 The results for each building type are based on the entire county population living in the building type. The population division between SF and MF buildings are not accounted for to make more meaningful comparisons between the two housing types. Therefore, the results are not additive.

Table 13 presents excess mortality results representative of the existing SF building stock by listing values for the 5%, median, and 95% representative buildings (designated based on their 7-day SET degree hour value). For warm climates, the data show higher excess death rates occurring during cold events than heat events. For cold climates, the trends reverse. For the mild Pacific Coast climates, heat events result in higher mortality rates. This may be partially attributed to the fact that air conditioning is less widely installed in these areas.

In general, mortality decreases as efficiency increases, as anticipated. However, in some cases, the excess death estimate based on the median case does not fall between the 5% and 95% values. In addition, a few values in the table are negative, which indicate an increase and not a decrease in excess deaths. For some locations, such as Los Angeles, the occurrence coincides with cases having low SET degree hour values.

Comparing the values of SET degree hours with excess mortality reveal the disconnect between the hourly building simulation results and the Gasparrini mortality model results. Unlike SET degree hour metric, the excess death metric is (1) based on average daily temperature and (2) does not consider differences in daily temperature fluctuations. The Gasparrini model has less resolution than the simulation model, which may present some limitations in assessing the impact of increased efficiency on mortality. For example, the timeseries charts included in Appendix F indicate that the indoor daily temperature fluctuation decreases as the passive efficiency increases. The SET degree hour metric takes this into account, as well as the habitability metric. The Gasparrini does not account for it, but only considers the affect on average daily temperature.

A method application issue revealed from the excess death analysis is in the limits of the fragility curves. For example, in Portland, the increase in excess mortality for extreme heat stems from a deficiency in the application of the Gasparrini model. For several days in the 7-day analysis period, the Portland average daily temperature exceeds the maximum temperature in the Portland Gasparrini data. For these days, the excess death value is based on the value associated with the maximum temperature, which may result in an underestimation of the excess death. Another application consideration is the number of days to use in the excess mortality calculation. Table 12 values are based on a 7-day period to be consistent with the habitability analysis. This is lower than the event duration but longer than a typical power outage coincident with an extreme event would occur.

These insights highlight some application considerations for using the Gasparrini model for the study purposes. This includes: (1) better understanding the importance of taking into account daily temperature fluctuations to estimate excess death rate for efficiency-resilience studies; (2) the endpoint limits of the Gasparrini fragility curves; and (3) the number of days of the extreme event to use to calculate excess deaths. These considerations are discussed in more detail in Section 8 and Appendix J.

Table 13. Estimates of Excess Deaths over Seven Days Attributed to Extreme Events in Existing Single-Family Buildings

Location (Climate Zone)	Event	Estimated Event Mortality									Event Mortality Reduction*												Annual Mortality Reduction*†					
		Deaths per Event									Lives Saved per Event						Improvement						Lives Saved per Year					
		5th Percentile			Median			95th Percentile			Current Code IECC 2021			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS		
		Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Houston, TX (2A)	Cold	82.1	70.2	55.3	62.5	42.5	19.3	40.6	23.9	11.9	11.9	20.0	16.7	26.8	**43.2**	28.7	14%	32%	41%	33%	69%	71%	0.39	0.66	0.55	0.88	1.43	0.95
	Heat	80.6	71.6	55.1	52.4	10.3	2.2	2.1	1.8	0.6	9.0	42.1	0.3	25.5	50.2	1.5	11%	80%	14%	32%	**96%**	72%	6.77	31.7	0.22	19.2	37.8	1.12
Atlanta, GA (3A)	Cold	20.5	17.5	13.3	16.7	13.1	8.0	11.2	7.6	4.7	2.9	3.6	3.6	7.2	8.7	6.5	14%	21%	33%	35%	52%	58%	0.11	0.14	0.14	0.27	0.33	0.25
	Heat	8.4	7.7	7.3	6.3	5.4	0.4	2.5	1.8	1.9	0.70	0.89	0.64	1.08	5.87	0.55	8%	14%	26%	13%	93%	22%	0.07	0.09	0.06	0.11	0.58	0.05
Los Angeles, CA (3B)	Cold	40.6	30.6	18.5	21.2	16.0	15.8	15.8	16.9	15.3	10.0	5.2	**-1.2**	22.1	5.4	0.5	25%	25%	**-7%**	54%	25%	3%	1.49	0.77	**-0.17**	**3.30**	0.80	0.08
	Heat	392	370	306	241	114	38.0	18.1	7.0	10.0	22.1	126.9	11.1	85.7	**202.8**	8.1	6%	53%	61%	22%	84%	45%	7.56	43.4	3.79	29.3	**69.4**	2.76
Portland, OR (4C)	Cold	16.2	13.2	10.0	14.7	11.5	6.1	11.7	7.0	3.1	2.9	3.2	4.6	6.2	8.6	8.6	18%	22%	40%	38%	58%	**74%**	0.22	0.24	0.35	0.46	0.64	0.64
	Heat	36.5	39.5	38.8	34.4	37.0	9.9	24.0	1.8	1.9	**-3.0**	-2.6	22.1	-2.3	24.5	22.1	**-8%**	-8%	92%	-6%	71%	92%	**-0.29**	-0.26	2.19	-0.23	2.43	2.18
Detroit, MI (5A)	Cold	39.0	35.8	28.7	35.5	30.4	24.7	28.4	23.5	18.4	3.2	5.1	5.0	10.3	10.8	10.0	8%	14%	17%	26%	30%	35%	0.24	0.38	0.37	0.78	0.81	0.75
	Heat	109.5	105.9	103.4	75.1	68.2	49.1	6.3	1.3	1.7	3.6	6.9	5.0	6.1	26.0	4.6	3%	9%	79%	6%	35%	73%	0.60	1.14	0.82	1.01	4.29	0.75
Minneapolis/ St. Paul, MN (6A)	Cold	44.2	37.8	30.2	39.4	32.1	25.4	31.8	24.5	19.4	6.4	7.3	7.2	14.0	14.0	12.4	14%	19%	23%	32%	36%	39%	0.16	0.18	0.18	0.35	0.35	0.31
	Heat	72.8	71.7	64.9	54.2	49.8	39.5	3.2	0.7	0.6	1.0	4.4	2.4	7.9	14.7	2.6	1%	8%	77%	11%	27%	82%	0.16	0.66	0.37	1.19	2.21	0.39

* Changes relative to Existing Stock

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

5.4 Economic Value of Efficiency Mitigation for Thermal Resilience

The final valuation component of the methodology is the calculation of cost effectiveness for building efficiency investment that takes into account resilience benefits. The costs include first costs of the efficiency improvements and the annual building operation energy costs. The benefits include energy cost and carbon emission reductions and the annual monetized values associated with occupant damage and property damage reductions. In the analysis, occupant damages, in terms of excess mortality, determined for a representative extreme temperature event is multiplied by the annual joint probability to determine the annualized value. For property damages, the published data used is an annualized value.

5.4.1 Property Damage Cost

The annualized values for property damage costs associated with extreme heat and cold are based on values published in FEMA National Risk Index (NRI) (FEMA 2021) listed in Table 14 (also included in Table 8). The FEMA values are assumed to represent base case property damages. For the analysis, the reduction in damage values associated with passive efficiency improvement is based on the fractional reductions in excess mortality determined for occupant damage, as described in Section 4.4.2. While the approach is intended to provide a rough approximation of property damage reduction, the results emphasize that property damage source data indicate low costs and the reductions attributed to efficiency are negligible compared to the other costs evaluated. This may indicate a deficiency in the source data. The issue is discussed in Appendix J.

Table 14. Existing Building Annual Costs Damage Incurred from Extreme Temperature Events

	NRI Published Annual Building Damage		Estimated Building Damage Reduction*			
			Existing Single Family			
			Current Code		Beyond Code	
Location	Cold	Heat	Cold	Heat	Cold	Heat
Houston, TX	$ –	$1,761	$ –	$1,414	$ –	$ 1,686
Atlanta, GA	$ –	$ –	$ –	$ –	$ –	$ –
Los Angeles, CA	$ –	$24	$ –	$ 13	$ –	$ 20
Portland, OR	$ –	$93,361	$ –	$ –	$ –	$ 66,547
Detroit, MI	$478	$31,949	$ 69	$ 2,937	$170	$ 11,063
Minneapolis/ St. Paul, MN	$1,965	$4,971	$365	$402	$857	$1,350

* A strict application of the pro-rating method followed to estimate property damage reduction, which is based reducing the NRI reported value based on the fractional reduction in excess deaths, results in property damages increasing should excess deaths increase with passive improvements, which is illogical. This anomaly occurred for the existing SF building in Portland during extreme heat. For this case, the reduction in property damage was set equal to zero.

5.4.2 Occupant Damage Cost

The VSL, discussed in Section 4.4.1, provides a value for each life saved attributed to the building efficiency mitigation measures. The VSL used in the valuation analysis is $10 million per life, which is aligned with values given in published studies. The values range from a low of $7.6 million (FEMA 2020b) to a high of $13.3 million (Viscuzzi et al. 2020).

5.4.3 Measure Cost

Table 15 lists the normalized first costs associated with the current code and beyond-code passive efficiency improvements. The measured first costs are based on U.S. average estimates with multipliers applied to account for regional differences. For new buildings, the costs represent the incremental increase in implementation costs relative to base case construction costs. For existing buildings, the costs are not incremental. For example, in CZs 4C, 5A, and 6A, wall insulation costs are based on blown in cellulose on top of existing insulation plus rigid board insulation added with sheathing to meet measure R-value improvements. The value used in the BCR calculation is the normalized first cost values, which have been annualized assuming a life of 30 years and discount rate of 3%. These values are provided in Table 16.

Table 15. Efficiency Improvements First Costs

Location (Climate Zone)	New Single Family		Existing Single Family		New Multifamily		Existing Multifamily	
	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	$0.70	$2.50	$12.40	$15.10	$1.30	$2.80	$7.90	$9.40
Atlanta, GA (3A)	$1.30	$3.70	$13.50	$16.30	$1.40	$3.50	$8.20	$10.10
Los Angeles, CA (3B)	$1.30	$3.80	$13.60	$16.90	$1.40	$3.60	$8.30	$10.30
Portland, OR (4C)	$1.30	$4.30	$13.40	$31.30	$1.30	$10.60	$8.20	$17.30
Detroit, MI (5A)	$1.30	$4.80	$13.10	$31.90	$1.20	$10.70	$8.60	$17.60
Minneapolis/ St. Paul, MN (6A)	$1.10	$4.90	$13.80	$32.80	$1.20	$11.10	$8.50	$17.90

Table 16. Annualized First Costs for Efficiency Improvements ($/ft^2/year)

Location (Climate Zone)	New Single Family		Existing Single Family		New Multifamily		Existing Multifamily	
	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	$0.03	$0.13	$0.63	$0.77	$0.07	$0.14	$0.41	$0.48
Atlanta, GA (3A)	$0.07	$0.19	$0.69	$0.83	$0.07	$0.18	$0.42	$0.51
Los Angeles, CA (3B)	$0.07	$0.19	$0.69	$0.86	$0.07	$0.19	$0.42	$0.52
Portland, OR (4C)	$0.07	$0.22	$0.68	$1.60	$0.07	$0.54	$0.42	$0.88
Detroit, MI (5A)	$0.07	$0.24	$0.67	$1.63	$0.06	$0.55	$0.44	$0.90
Minneapolis/ St. Paul, MN (6A)	$0.06	$0.25	$0.70	$1.67	$0.06	$0.57	$0.43	$0.92

5.4.4 Annual Energy and Greenhouse Gas Emissions Cost

The BCR calculation includes the cost benefits that improved building efficiency provides to building owners in terms of annual energy cost reductions. It also considers the societal benefit of the associated reduction in greenhouse gas emissions. Energy costs are based on U.S. average costs published by the Energy Information Agency (EIA 2020a, 2020b) and adopted for use in model energy code development. The societal cost of greenhouse gas emissions is based on data prepared for the U.S. government and published by the Interagency Working Group on the Social Cost of Greenhouse Gases.[17] These values are summarized in Table 17. The costs are applied to annual energy use and greenhouse gas emissions reductions determined from the building simulation models using typical meteorological year weather data. To determine site greenhouse gas emissions in terms of metric tons of carbon equivalent, the building annual energy use is converted to greenhouse gas emissions by applying the energy resource factors listed in Table 18. As indicated, differences in emissions factors based on location are accounted for in the calculation.

Table 17. Energy and Greenhouse Gas Emissions Cost

		Social Cost of Carbon[18,19]		
Resource	**Energy Cost**	**CO_2**	**CH_4**	**N_2O**
Electricity	$0.132/kWh	$51/MT	$1,500/MT	$18,000/MT
Natural Gas	$0.940/therm			

Table 18. 100-Year Global Warming Potential Emissions

Resource	Location	eGrid Region	$CO2_e$ Emissions (lb/MWh)
Electricity	Houston	ERCOT	1078
	Atlanta	SRSO	1228
	Los Angeles	CAMX	655
	Portland	NWPP	844
	Detroit	RFCM	1438
	Minneapolis/St. Paul	MROW	1263
Natural Gas	United States	-	503

5.4.5 Benefit–Cost Ratio

Table 19 summarizes the costs, benefits, and BCR values determined from the methodology application. The values quantify efficiency, including the impact on thermal resilience supporting sheltering in place during extreme temperature events. BCR values greater than 1 indicate that investing in efficiency is cost effective.

New SF BCR values make a strong financial case for adoption of current code or beyond-code measures, although the benefit costs associated with reduced mortality is low. This

[17]The Technical Support Document presents interim estimates of the social cost of carbon, methane, and nitrous oxide developed under Executive Order 13990. Accessed on June 14, 2022 at https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[18] Ibid; 2020 annual average based on a 3% discount rate

[19] A metric ton or tonne equals 2204.6 pounds.

demonstrates the improved efficiency conditions associated with code-compliant buildings compared to the existing stock, which is substantially worse than the historic code baseline. The estimated BCRs determined for existing SF buildings are below 1. This is due to the relatively high estimates of retrofit costs compared to incremental new construction costs.

The BCR data indicates that accounting for the societal costs of carbon makes a noteworthy contribution to total benefits, ranging from about 11% to 27% depending on location and building type. Accounting for excess mortality in extreme temperatures ranges from 0% to 37% depending on location. It has the highest contribution for Houston and Los Angeles, which have the greatest risk of extreme temperatures coinciding with a power outage for the locations considered. For locations with high hazard risk, the estimated annualized cost benefit of reduced deaths is significant. For example, in existing SF, the reduction in excess mortality that results from meeting current code is 24% to 29% of the total estimated cost benefit determined for Houston and Los Angeles, respectively. If beyond-code requirements are met, the reduction in excess mortality is 22% and 37% for Houston and Los Angeles, respectively. This is a significant contribution that is not currently being considered in efficiency cost effectiveness calculations. The findings make a compelling case for including resilience considerations when considering efficiency investments in locations like Los Angeles, that have high risk coupled with low building energy use and carbon emissions due to a mild climate.

Table 19. Benefit–Cost Ratios (BCR) Determined for Passive Efficiency Measures

	Current Code						Beyond Code					
	Houston	Atlanta	Los Angeles	Portland	Detroit	Mpls/ St Paul	Houston	Atlanta	Los Angeles	Portland	Detroit	Mpls/ St Paul
New Single Family												
Mortality Reduction	0.02	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Savings	0.16	0.19	0.16	0.12	0.13	0.13	0.28	0.30	0.19	0.18	0.29	0.33
Carbon Cost Savings	0.04	0.06	0.03	0.03	0.04	0.04	0.07	0.09	0.04	0.05	0.10	0.11
Benefits	0.22	0.25	0.19	0.14	0.17	0.17	0.37	0.39	0.24	0.23	0.39	0.44
First Costs	0.03	0.07	0.07	0.07	0.07	0.06	0.13	0.19	0.19	0.22	0.24	0.25
BCR	**6.27**	**3.76**	**2.92**	**2.12**	**2.53**	**2.88**	**2.96**	**2.05**	**1.25**	**1.07**	**1.61**	**1.79**
Existing Single Family												
Mortality Reduction	0.09	0.00	0.06	0.00	0.01	0.01	0.12	0.01	0.10	0.05	0.04	0.02
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Savings	0.25	0.31	0.12	0.30	0.35	0.43	0.33	0.40	0.13	0.32	0.50	0.51
Carbon Cost Savings	0.06	0.09	0.03	0.08	0.13	0.15	0.08	0.12	0.03	0.07	0.19	0.18
Benefits	0.40	0.40	0.21	0.38	0.49	0.59	0.53	0.54	0.26	0.44	0.73	0.72
First Costs	0.63	0.69	0.69	0.68	0.67	0.70	0.77	0.83	0.86	1.60	1.63	1.67
BCR	**0.63**	**0.59**	**0.30**	**0.56**	**0.73**	**0.84**	**0.68**	**0.65**	**0.31**	**0.28**	**0.45**	**0.43**
New Multifamily												
Mortality Reduction	0.02	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Savings	0.35	0.31	0.19	0.21	0.32	0.37	0.34	0.29	0.16	0.16	0.33	0.39
Carbon Cost Savings	0.08	0.08	0.02	0.05	0.10	0.11	0.07	0.07	0.02	0.04	0.11	0.13
Benefits	0.44	0.39	0.22	0.26	0.42	0.48	0.44	0.36	0.19	0.21	0.44	0.53
First Costs	0.07	0.07	0.07	0.07	0.06	0.06	0.14	0.18	0.19	0.54	0.55	0.57
BCR	**6.58**	**5.52**	**3.18**	**3.82**	**6.81**	**7.60**	**3.08**	**2.02**	**1.02**	**0.39**	**0.80**	**0.93**
Existing Multifamily												
Mortality Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Property Damage Reduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Energy Cost Savings	0.25	0.27	0.13	0.22	0.33	0.40	0.25	0.27	0.12	0.21	0.35	0.44
Carbon Cost Savings	0.06	0.08	0.03	0.08	0.12	0.14	0.06	0.08	0.03	0.08	0.13	0.16
Benefits	0.31	0.35	0.15	0.30	0.45	0.54	0.31	0.35	0.15	0.29	0.48	0.60
First Costs	0.41	0.42	0.42	0.42	0.44	0.43	0.48	0.51	0.52	0.88	0.90	0.92
BCR	**0.77**	**0.83**	**0.37**	**0.71**	**1.03**	**1.25**	**0.64**	**0.67**	**0.28**	**0.32**	**0.54**	**0.65**

6.0 Texas 2021 Winter Storm Occupant Damages

Published data associated with damages estimated for recent extreme temperature events provide an opportunity to check values determined using analytical methods. In assessment, the Gasparrini damage curves were applied using building simulation data that indicate indoor building conditions during the Texas 2021 Winter Storm event. The excess deaths associated with the event can be matched with the Gasparrini outcomes to understand whether it provides reasonable results for this study's purposes.

In February 2021, Winter Storm Uri caused nearly 10 million people to lose power. Texas was hit the hardest with three-quarters of Texans experiencing rolling blackouts. Freezing temperatures caused natural gas generators that were not winterized appropriately to fail requests for generation (Postelwait 2022), leaving 4.5 million homes without power. The storm's economic toll is estimated to be as high as $295 billion (Watson et al. 2021). Residential and commercial building property damage claims resulted in $5.7 billion in paid losses (TDI 2021). More than two of three people interviewed lost power between February 14–20 for an average of 42 hours, and one-third of Texans suffered water damage due to the freezing temperatures (Watson et al. 2021).

The official number of cold-related deaths in Texas was 246 (Hellerstedt 2021). However, using an excess death approach, 755 deaths were estimated for the week ending February 20. The 95 percent confidence interval indicated that between 479 and 1,031 deaths occurred during that week. The study compared actual deaths during the 2015-2019 period accounting for demographic changes that occurred over the period, seasonal variation, and covid deaths (Aldhous and Hirji 2022). Assuming a value of statistical life of $10 million, the total estimated monetized loss for Texas for the 2021 Winter Storm totals $7.55 billion.

6.1 Estimated Mortality Based on the Gasparrini Approach

ResStock modeling of the Harris County existing single-family (SF) building stock was used to calculate the indoor temperatures for both the baseline condition and the Passive House Institute U.S. (PHIUS) upgrade. The hourly temperatures determined from simulation were averaged by day for each day of the cold event to get the average daily temperature to be applied in the Gasparrini dataset. Table 20 shows the relative risks associated with specific temperatures for existing buildings in the 5^{th} percentile with calculated mortality for existing and PHIUS improved buildings. The relative-risk value is used to calculate the attributable fraction associated with cold deaths where AF = (1-RR)/RR. The attributable fraction is then multiplied by the daily deaths for each temperature to determine each day's mortality and then summed for the event's total mortality due to severe winter weather.

Table 21 provides the mortality results using the Gasparrini study mortality curves for Harris County based on the ResStock existing housing stock characterization and modeling. The analysis evaluated the median housing stock, the 5% best and the 5% worst for efficiency and outdoor temperature penetration. Note that as would be expected, the 5% best and 5% worst had lowest and highest mortality, respectively.

6.2 Key Takeaways

The updated excess death analysis indicated that 755 people died in Texas during the week of the February winter storm. The attributed deaths occurring in Harris County were estimated at 247 by proportioning the total state deaths by the fraction of the population living in Harris

County, which is about 33 percent of the state population. Thus the 206 average deaths estimated by the Gasparrini study is well within the comparison. As applied in this study, the approach has the potential to underrepresent the number of deaths since indoor temperatures instead of outdoor temperatures are used. However, since the study focus is based on comparison and not absolute outcomes, the bias of outdoor ambient temperature versus indoor ambient temperature has been reduced due to cancellation of error. In summary, the methodology developed by Gasparrini et al. (2015) and applied to February 2021 Texas winter storm event for Harris County determined the number of deaths to be very near the actual recorded deaths based on state data pared down to the Harris County population.

Table 20 Calculation of Daily Excess Mortality from Gasparrini Relative-Risk Rate

Baseline		**PHIUS**		**Deaths**		
Indoor Temp (°C)	**RR**	**Indoor Temp** (°C)	**RR**	**Baseline**	**PHIUS**	**Change**
19	1.035	20	1.030	4	3	1
20	1.030	20	1.030	3	3	-
19	1.035	20	1.030	4	3	1
18	1.040	19	1.035	4	4	1
18	1.040	18	1.040	4	4	-
8	1.203	16	1.053	18	5	13
4	1.278	13	1.109	24	11	13
-2	1.391	7	1.222	31	20	11
0	1.353	5	1.259	28	22	6
3	1.297	5	1.259	25	22	3
4	1.278	6	1.241	24	21	3
6	1.241	7	1.222	21	20	1
9	1.184	9	1.184	17	17	-
14	1.091	12	1.128	9	12	(3)
16	1.053	16	1.053	5	5	-
15	1.072	16	1.053	7	5	2
19	1.035	18	1.040	4	4	(1)
20	1.030	19	1.035	3	4	(1)
21	1.025	20	1.030	3	3	(1)
21	1.025	21	1.025	3	3	-
21	1.025	21	1.025	3	3	-
21	1.025	21	1.025	3	3	-
			Totals	**246**	**198**	**48**
					Joint Probability	3.3%
					Expected Deaths	**1.57**

Table 21. Excess Mortality Estimates for Harris County, Texas

	5th Percentile			Median			95th Percentile		
	Base Case	**PHIUS**	**Change**	**Base Case**	**PHIUS**	**Change**	**Base Case**	**PHIUS**	**Change**
Cold Event Deaths	246	198	48	202	128	73	166	80	85
Annualized Deaths*			1.6			2.4			2.8

* Calculated by multiplying the change in deaths by the joint probability factor (0.033 or 3.3%)

7.0 Assisted Living Facility Case Study

An assisted living facility (ALF) primarily provides personal care in a homelike social setting, while a nursing home provides medical and personal care in a clinical setting. Residents in ALFs are usually seniors and most have some health issues, which makes this population group more vulnerable to impacts of extreme weather events, especially concurrent with a power outage.

We selected an actual ALF in Houston, which had to evacuate its residents during the Texas winter storm event in February 2021, that included record low ambient temperatures and widespread power outages. The as-built building was modeled to analyze impacts of building efficiency mitigation strategies on the thermal resilience of the building. Key research questions were explored, including the following:

- How resilient is the ALF under extreme hot and cold temperature events without any power supply?
- What are the impacts of EEMs on thermal resilience of the ALF?
- How much back-up power is needed to maintain the full services of the ALF during an extreme temperature event coincident with power outage? How much do EEMs reduce the back-up power capacity?

7.1 Technical Approach

This case study follows the methodology developed by the project. EnergyPlus version 9.6 was used to model the baseline ALF and mitigation measures under the selected two extreme temperature events (a 6-day heatwave in 2015 and a 3-day cold snap in 2021). The three thermal resilience metrics (unlivable standard effective temperature (SET) degree hours, heat index (HI) hours, and hours of safety) were calculated from EnergyPlus simulation results for further analysis and evaluation.

The ALF is a two-story building with 97 single-person suites and a total floor area of 116,134 square feet (Figure 11) located in the Houston metropolitan area. Without access to the detailed building footprint and floor plan, a previously developed nursing home model (Sun et al. 2020) was used and adjusted the building footprint and total floor area, efficiency levels of envelope, lighting and HVAC systems, operating schedules, and conditions to match the actual ALF settings.

The common areas of the building are served by packaged rooftop units with single duct, variable air volume air terminals with reheat, while each of the bedroom suites 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 building is equipped with LED lighting and has no major medical equipment. The cooling temperature setpoint varies within 70–72°F and the heating temperature setpoint varies within 72–73°F. Residents have control of the temperature setpoint in their bedrooms. Residents can open windows with a limited angle in their bedrooms for ventilation but not fully open for security reasons. The ALF does not have on-site power generation or back-up power except for a small one for oxygen equipment operation.

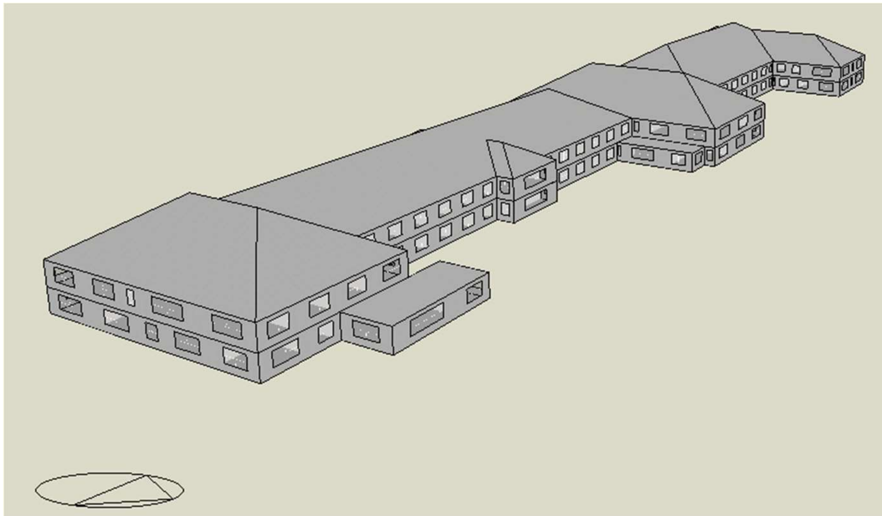


Figure 11. Three-Dimensional Illustration of the Baseline Assisted Living Facility Model

Two extreme temperature events were selected for this study: a 6-day heatwave that occurred from July 26 to 31, 2015, and a 3-day cold snap that occurred from February 17 to 19, 2021, which was part of the Texas snowstorm in February 2021. The 3-day cold event was selected because the ALF suffered a power outage starting from 10 p.m. on February 16 and ending late on February 19, 2021.

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 performed in thermal resilience under extreme temperature conditions. The back-up power scenario was used to determine the needs for back-up power for maintaining full services during grid power outages. For the no-power scenario, all energy-consuming equipment and systems (lighting, plug loads, and HVAC) were turned off, and the entire facility was assumed to be in free-floating mode during the extreme temperature events. For the back-up power scenarios, it was assumed that the facility had on-site back-up power to meet full services during the extreme temperature events, then the back-up power needs (in electricity [kWh] and peak kW) were defined using EnergyPlus simulation results.

Eight passive measures influencing the building passive performance were evaluated, including adding insulation to exterior walls and roofs, applying cool coating to walls and roofs, installing interior window shades, installing solar film on windows, sealing envelope to reduce air infiltration, and opening windows for natural ventilation when conditions fit. The passive package, excluding the interior window shades and natural ventilation, was also evaluated to consider the effect on thermal resilience. Since the ALF is a new facility, the baseline model was modified to emulate an older facility built about 20 years ago complying with ASHRAE 90.1-1999.

7.2 Results and Analysis

The ALF analysis results for the two extreme events and power conditions are presented below. For the thermal conditions in the residents' bedrooms, Figure 12 compares the hourly standard effective temperature (SET) distribution of all bedrooms at different percentiles with the outdoor air temperature during the 2015 heatwave with power outage for the baseline ALF model. The maximum SET and the 95th percentile SET quickly reach the upper threshold (86°F) for passive survivability (PS) in less than 12 hours. The median time for a bedroom to reach 86°F SET is 20 hours. Four bedrooms on the second floor have SET exceeding 86°F within 10 hours: two of them are the rooms at the corner with the largest east-facing window area, as they are the earliest rooms receiving incoming solar radiation since the start of the power outage; the other two are the rooms with the smallest floor area. Thirty-four bedrooms on the first floor have SET exceeding 86°F after 24 hours since the start of the power outage.

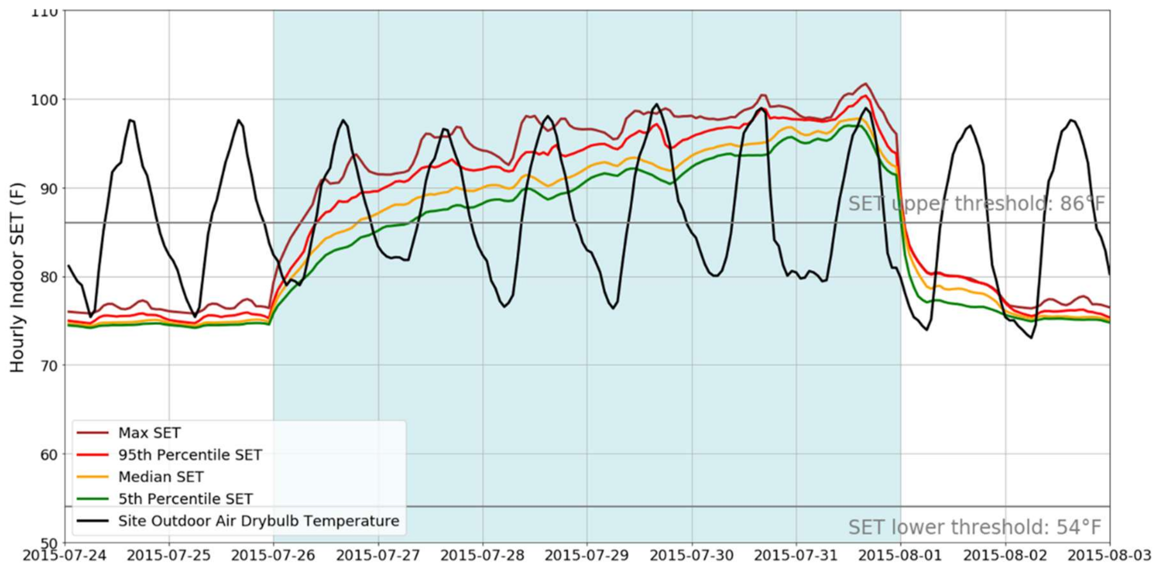


Figure 12. Hourly SET Distribution of All Resident Bedrooms and Outdoor Air Temperature of the Baseline Assisted Living Facility Model During the 2015 Heatwave

The LEED credit that addresses PS requires assessing thermal safety as indicated by the SET degree hours metric. In the cooling scenario, the cumulative SET degree hours shall not exceed 216 above 86°F for residential areas. In the 2015 heatwave baseline model, the average time to exceed LEED PS criteria (216 SET degree hours) is 76 hours. Four corner bedrooms with the largest window area on the second floor exceed the 216 SET degree hours threshold within 48 hours. One bedroom on the first floor with the least exterior window area does not exceed the criteria until 96 hours after the power outage.

Using the HI metric to indicate hazard levels, Figure 13 compares the hourly HI distribution of all bedrooms for different percentiles based on the outdoor air temperatures occurring during the 2015 heatwave for the existing conditions baseline model. The median number of hours for a bedroom to reach Caution, Extreme Caution, and Danger levels are 0.3, 8, and 45 hours, respectively. Most bedrooms quickly reach the HI metric Caution level (80°F) in less than an hour.

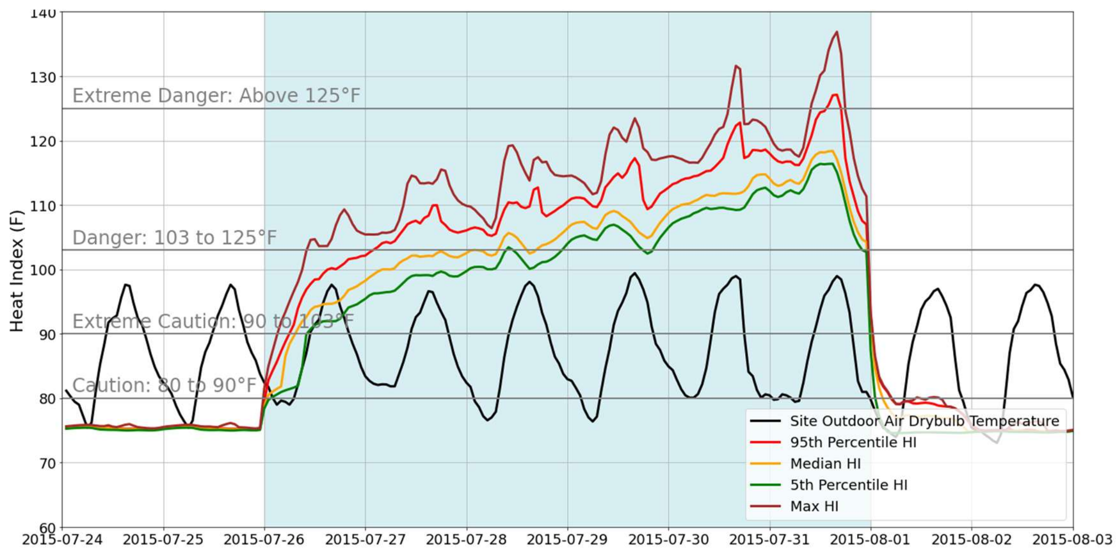


Figure 13. Hourly Heat Index Distribution Among All Bedrooms and Outdoor Air Temperature of the Baseline Assisted Living Facility Model During the 2015 Heatwave

7.2.1 Resilience under 2021 Cold Snap without Power Supply

Using the indoor air temperature (IAT) as the metric, Figure 14 shows the time series of IAT distribution of all the bedrooms for the baseline ALF model in the 2021 snowstorm. The minimum IAT never drops below the Moderate cold stress level of 50°F. The median time for a bedroom to drop the IAT below the Minimum for Vulnerable Population level (64°F) is 27 hours, and 60 hours for the Mild level (60°F). Six bedrooms on the second floor drop their IAT below the Minimum for Vulnerable Population level (64°F) within six hours.

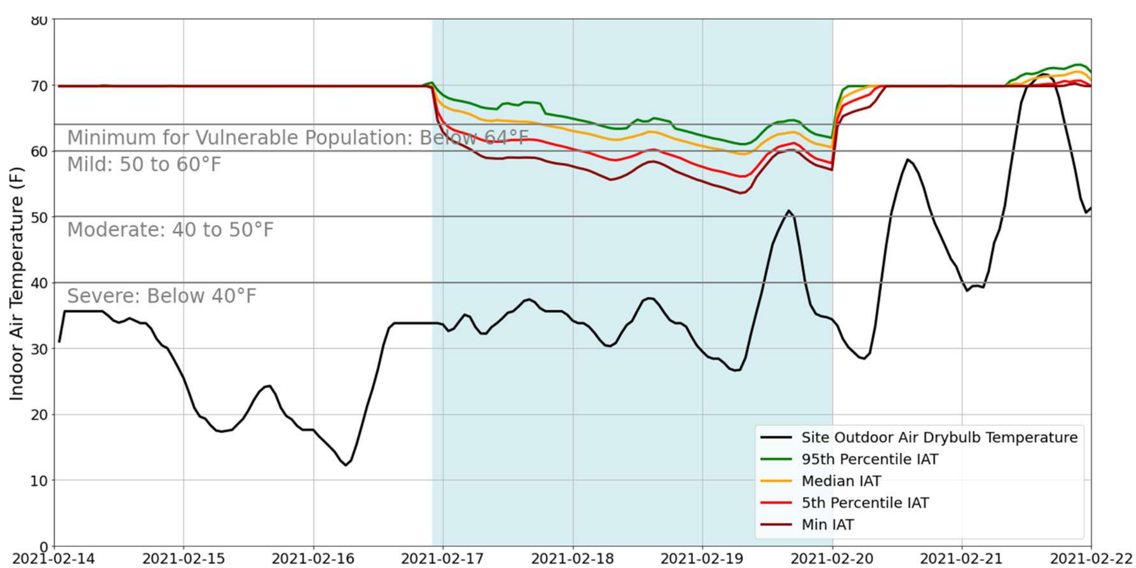


Figure 14. Hourly Indoor Air Temperature Distribution and Outdoor Air Dry-Bulb Temperature of Baseline Assisted Living Facility Model in 2021 Snowstorm

7.2.2 Influences of Mitigation Measures on Resilience Under 2015 Heatwave Without Power Supply

Figure 15 shows the relative reduction of the average SET degree hours above 86°F for the evaluated passive mitigation measures during the 2015 heatwave with power outage. Window solar film, envelope package, and natural ventilation significantly reduce the average SET degree hours above 86°F per bedroom by 27%, 62%, and 32%, respectively. However, the infiltration reduction measure shows a substantial opposite effect by a 20% average increase of SET degree hours. Internal window shade is about twice as effective as the wall and roof insulation and coating measures.

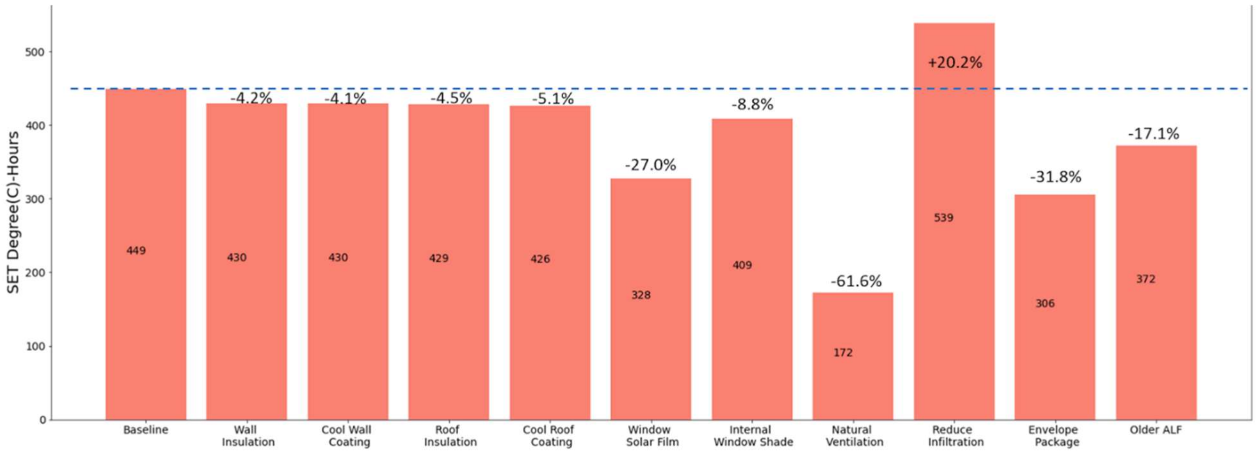


Figure 15. Average SET Degree Hours (above 86°F) of the Baseline and Improved Assisted Living Facility Models with Passive Measures for the 2015 Heatwave

Using the HI hours as the metric, Figure 16 presents the percentage of HI hours 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.

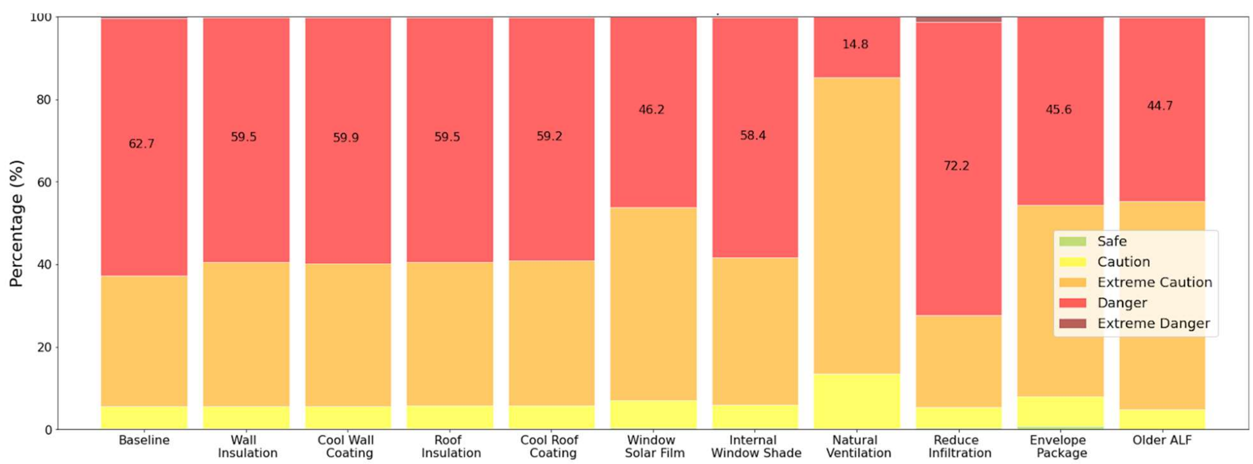


Figure 16. Percentage of Hours at each Heat Index Level of the Baseline and Mitigated Assisted Living Facilities with Passive Measures During the 2015 Heatwave

7.2.3 Influences of Mitigation Measures on Resilience Under 2021 Cold Snap Without Power Supply

Using the cold stress level of IAT as the metric, as Figure 17 shows, IAT never drops below Mild level (60°F) for the baseline and any passive measures. About 80% of the time, IAT stays at the Minimum for Vulnerable Populations level (64°F). Wall and roof insulation both reduce the hours at Mild level, although the improvement of roof insulation is very limited. Cool wall and roof coatings slightly increase the hours at Mild level. With more insulation, the envelope package marginally reduces Mild level hours over the infiltration reduction.

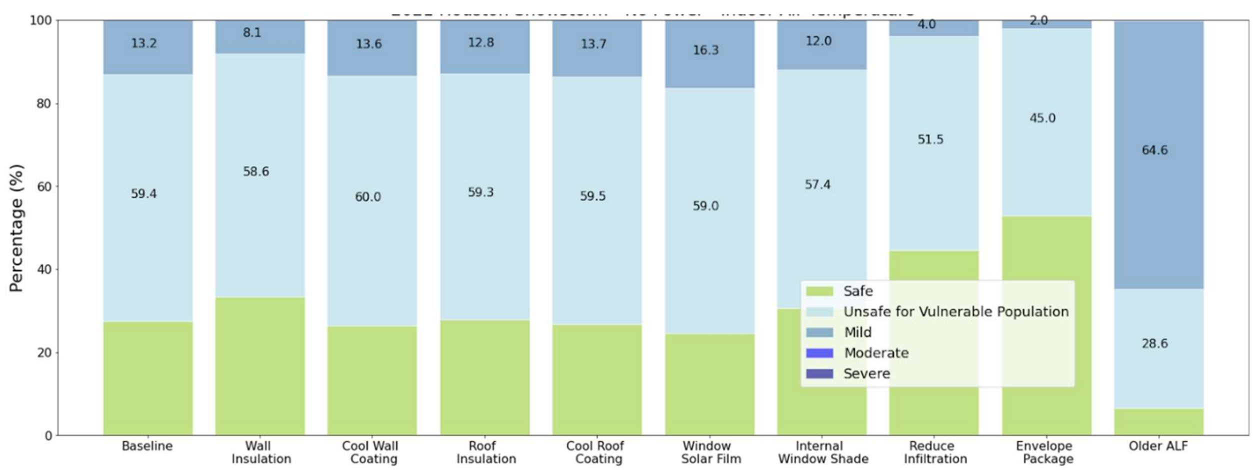


Figure 17. Percentage of Hours at Each Cold Stress Level of the Baseline and Mitigated Assisted Living Facilities with Passive Measures During the 2021 Snowstorm

7.2.4 Influences of Mitigation Measures on Annual Energy Use with Full Power and Typical Meteorological Year 3 Weather Data

Figure 18 shows the annual site energy use intensity (EUI) of the baseline ALF and improved cases with passive and active mitigation measures. The baseline ALF has an EUI of 52 kBtu/ft2. Passive measures, in general, have limited impact on EUI, except the measure to reduce infiltration, which is the most effective with 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, highly efficient direct expansion coil, and plug load controller. The lighting measure can achieve higher savings of 8.6%. For the older ALF, it consumes 19% more in annual site energy than the baseline ALF.

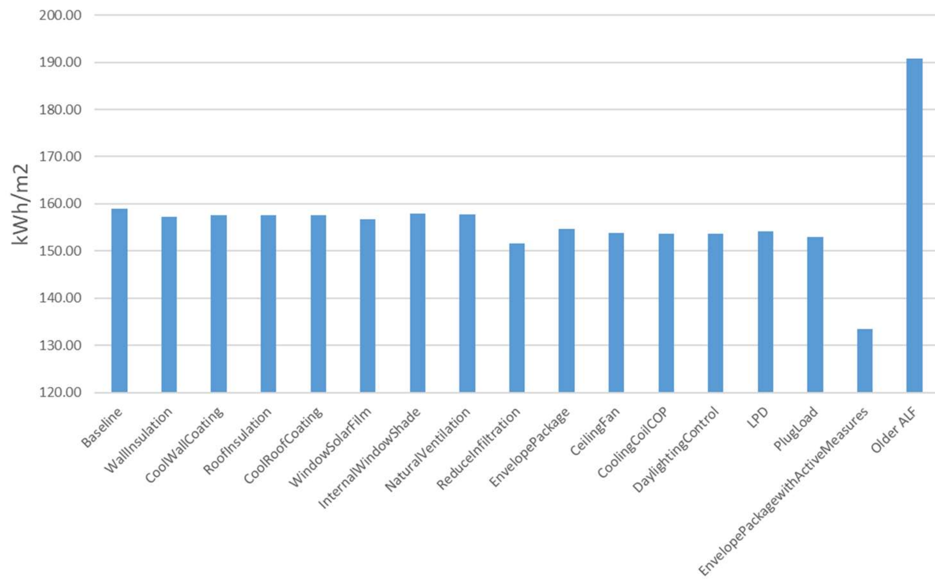


Figure 18. Annual Site EUI of the Baseline and Mitigated Assisted Living Facilities with Passive and Active Measures

7.2.5 Influences of Mitigation Measures on Back-Up Power Capacity to Provide Full Services for 2021 Cold Snap

Figure 19 shows the simulation results of back-up power capacity to meet full services of the ALF. The back-up power system needs to provide 9,828 kWh with a peak demand of 177 kW during the cold snap. Passive measures show limited impacts on back-up power needs with the exterior wall insulation showing about 2% reduction. Cool wall and roof measures reflect more solar, which increases the ALF heating loads and therefore the back-up power needs, although marginal. Active measures show improvements for back-up power, with the lighting measure reducing back-up power capacity by 8%. As the baseline facility is new, opportunities from EEMs can be limited. However, the simulation results for the older ALF (built in the 1990s) show much higher back-up power needs (11,615 kWh), about 28% higher than the baseline ALF.

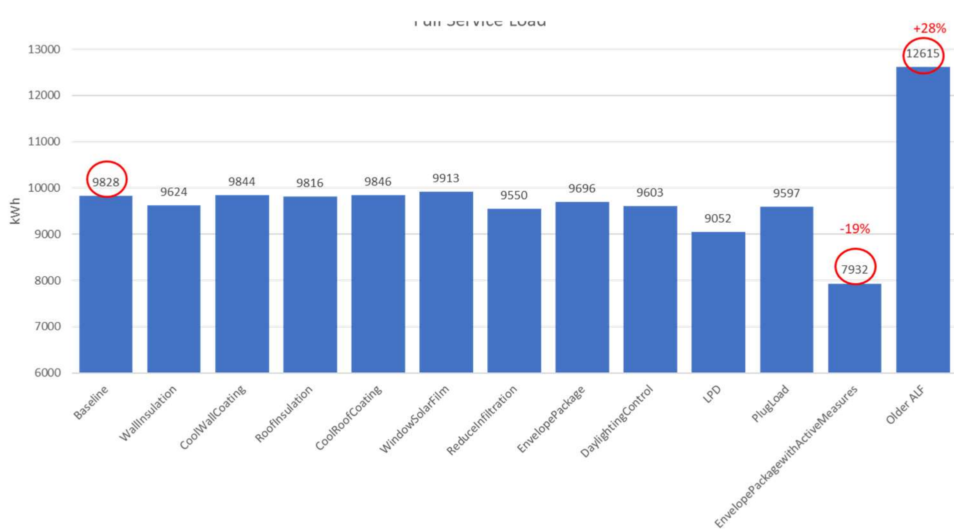


Figure 19. Back-up Power Capacity to Provide Full-service Loads for the 2021 Cold Snap

7.3 Summary and Discussion

For the 6-day heat event in 2015 with power outage, the bedrooms take 2–4 days (average is 3 days) to exceed the 216 SET degree hours, failing to meet the LEED PS criteria of a 7-day period. This indicates that although the baseline ALF is energy efficient, if not incorporated with natural ventilation, the heat may be trapped indoors, leading to excess heat exposure for residents. Depending on the location, orientation, and window area, the bedroom may perform very differently. For example, the top floor west- or east-facing bedrooms with more windows will perform much worse than bedrooms located at the bottom floor, facing north, and with no or fewer windows during the heat event.

For the 3-day cold snap in 2021 without power supply, the baseline ALF performs relatively well with no bedroom having SET temperature below 54°F, the lower threshold of the LEED PS. Only the worst bedroom has SET below 60°F for a few hours. Using the IAT as the metric, no bedroom has IAT below the Moderate cold stress level of 50°F. The average time for a bedroom to drop the IAT below the Minimum for Vulnerable Population level (64°F) is 27 hours, and 60 hours for the Mild level (60°F). 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 (IAT above 60°F) as the metric, the bedrooms have from 9 to 74 hours of safety for residents, showing a wide variation of performance.

The widely 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., portable or ceiling fans) may be essential to avoid deadly heat hazards for residents. Also, residents in those dangerous bedroom conditions can be considered for moving to safer bedrooms.

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

The influences of passive measures on the thermal resilience of the baseline ALF are complex depending on the nature of the individual measure, type of extreme temperature event (cold or heat), and the resilience metric and criteria adopted for the evaluation. For the heatwave without power event, natural ventilation is the most effective passive measure to improve thermal resilience, especially in reducing nighttime temperature which is essential to residents' sleep quality. Window film is the second most effective measure while other passive measures have marginal improvements. The measure to reduce air infiltration has a negative impact on thermal resilience as it prevents heat release from indoor to outdoor when indoor temperature is very high, exposing overheat risk to residents.

For the cold snap without power event, some measures present opposite impacts on thermal resilience. Infiltration reduction, as the most negative measure in the heat event, becomes the most useful passive measure in the cold snap by preventing the heat from escaping the building envelope. Window solar film, although considerably improving heat resilience in the heat event, delivers a negative impact in the cold event because it prevents the heat of incoming solar radiation during the day, which can warm up the IAT. This negative impact is impaired at night not only because there is no solar radiation, but also because the lower U-value of the window solar film helps to trap the heat staying indoors at night. In addition, other measures that reduce solar heat, including the cool wall and roof coating, benefit the heat event but worsen the cold event. Such conflicting influences should be evaluated considering both heat and cold events, especially for CZs with cold winters and hot summers.

Table 22 and Table 23 summarize the relative influences of the mitigation measures (against the baseline settings) on the thermal resilience of the ALF. Some measures have consistent performance in both heat and cold events. The envelope package overall improves thermal resilience in both heat and cold events, as it comprehensively 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 shall not work independently but shall be used coordinately to provide well-balanced thermal resilience. Interior window shades, as a flexible measure that can be controlled manually and when operated with the correct schedule, can prevent heat coming in during the day in heat events and heat escaping at night in cold events.

Table 22. Relative Difference of Heat Index Hours in Danger and Extreme Danger Hazard Levels

During the 6-day Heatwave and in Minimum for Vulnerable Population and Mild Hours During the 3-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
Heatwave	-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%

Table 23. Relative Difference of SET Degree Hours (above 86°F) during 6-day Heatwave

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

SET degree hours (below 54°F) during the 3-day cold snap is 0.

A passive envelope package, active efficient lighting, and plug loads controller can reduce the needed capacity of back-up power of the baseline ALF by 7%, 8%, and 2.5% respectively to meet the full or critical loads during grid power outages. In other words, with the same back-up power capacity, EEMs enable the ALF to operate longer during outages.

The older ALF, depicting code-compliant construction 20 years ago, has a less insulated and leakier envelope compared with the baseline ALF. It performs much worse during the extreme cold event. It also increases indoor heat exposure faster than the baseline ALF during the extreme heat event. However, it performs better after the first day of the heat event because the baseline ALF traps solar heat gain, and the well-insulated and airtight envelope reduces the heat release from indoors to outdoors. The older ALF consumes 6% more annual energy and has 6% higher peak demand than the baseline ALF, as well as requiring 18% more back-up power to meet the full loads or critical loads for the 3-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, keeping in mind the active management of interior window shades and operable windows to enable natural ventilation are two effective resilience improving measures.

ALFs are not currently required to have back-up power. In Texas, ALFs are required to have emergency plans but not generators. In California, a decades-old regulation (22 CCR §72641) requires skilled nursing facilities to have back-up power available for six hours to cover for exceedingly limited functions. Many states are discussing strengthening requirements of back-up power for ALFs 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 back-up power. 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 4.0 incorporated pilot credits for resilience under three groups: Assessment and Planning for Resilience, Designing for Enhanced Resilience, and Passive Survivability and Back-up Power during Disruptions. Occupants of assisted living facilities and nursing homes could greatly benefit from the inclusion of back-up power requirements so that occupants can stay in thermally safe indoor environments with critical services (cooling, heating, refrigeration) provided by the back-up power system during grid power outages.

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 thermal resilience under extreme hot temperature events without power can be quite opposite and negative, as highly insulated and airtight building envelopes trap solar heat gain and prevent nighttime cooling that lead to higher indoor temperatures than outdoors. Such a situation can only be mitigated with natural ventilation, indicating 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.

Certain EEMs, such as making building envelope airtight, may have conflicting influences on building thermal resilience; they are 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 IAT is higher than the outdoors. Also, some passive measures may not show energy saving benefits, but they are critical to improve thermal resilience during extreme temperature events. Benefits of resilience mitigation measures should be evaluated across seasons and under extreme weather conditions. Low-cost and behavior-related measures such as natural ventilation should be encouraged (via awareness, behavior change, training) and enabled (with operable windows) in building designs and operations.

EEMs also reduce the size or capability of back-up power equipment. This benefit should be incorporated in the cost benefit analysis for energy-efficient design or retrofit. Passive measures can improve thermal resilience of ALFs but are not adequate to fully maintain safe conditions for residents, which requires back-up power for running HVAC systems to provide critical cooling or heating service.

In general, the co-benefits between energy efficiency and thermal resilience of ALFs should be considered and addressed through building energy codes and policy as the building industry is moving toward carbon neutrality and climate resilience.

This simulation-based case study has some limitations. Although the facility manager provided valuable information through an interview, necessary assumptions and simplifications in the building modeling and analysis were made. The simulated results were not calibrated due to the lack of utility bill data. The findings from the study are for general reference, while the simulated results are case specific as they can vary due to the actual ALF design and operations as well as actual extreme weather conditions. The 3-day cold event is based on the actual power outage of the ALF during the 2021 Texas snowstorm, while the 6-day heat event in 2015 is selected from the historical extreme high-temperature events; therefore, caution should be used in directly comparing both events and the influences of mitigation measures on thermal resilience of the ALF.

8.0 Discussion

The study develops a methodology to quantify the impact of increased building efficiency on the ability to shelter in place during extreme temperature events. The approach allows resilience benefits to be accounted for in efficiency investment decision-making; however, there are application limitations associated with some of the new, innovative, method components. These component procedures, assumptions, and limitations are outlined in Section 8.1 and discussed in Section 8.2. Section 8.3presents ideas for future work emerging from team and TAG discussions in response to method limitations.

8.1 Resilience Valuation Robustness

A list of the assessment components and their perceived robustness is provided in Table 24. The robustness rating is based on method assumptions, caveats, and limitations presented in Section 4 and summarized in Appendix J. The component rating considers its usage of supporting data aligned with the analysis purpose and scope, industry-defined indicators and thresholds, and published methods for quantifying resilience benefits. The dependence of the component on other assessment components is also considered, including the bias that each value may introduce. For example, the benefit–cost ratio (BCR) values provided in Table 19 (in Section 5.4.5), take into account the stacked benefits associated with improved efficiency that go beyond annual energy use reduction and include resilience benefits. The calculation is dependent on three novel analysis components, including the joint probability (potential overestimate), excess mortality (potential under estimate), and property damage (under estimate). Due to bias and the lower confidence of some calculation methods, the BCR values are considered to have medium robustness and are best used for limited, comparative purposes.

Table 24. Relative Robustness of Resilience Valuation Components

Valuation Component	Data Source or Method	Relative Robustness	Opportunities for Improvement
Extreme temperature event identification	Ouzeau method	Medium	Standardize approach for selecting representative event
Joint probability of event with power outage	OE-417	Medium	Improve outage data assessment
Occupant exposure	SET and HI determined from simulation modeling	High	Correlate metrics to health impacts
Occupant damage	Gasparrini relative rate mortality curves	Medium	Further develop method and perform additional validation checks
Property damage	FEMA NRI data	Low	Base losses on data compiled from recent events
First costs	Energy codes costing algorithms	Medium	Consider existing building first costs as incremental for retrofit-ready projects
Benefit–cost ratio	Net present value	Medium	Improve robustness of input values

A resilience valuation component that has a high confidence is the occupant exposure metrics (e.g., standard effective temperature (SET), SET degree hours, and heat index (HI)). The occupant damage indicator of excess mortality has moderate robustness based on the results of the Houston Winter Storm Case Study, presented in Section 6. Modifications to the applied method for estimating excess death may be warranted though, as discussed in Section 8.2. Metrics considered to have low robustness need further work before they can be meaningfully applied. Medium robust metrics can be used as a rough indicator of resilience trends but should be more fully developed before referencing alongside highly robust metrics.

As an example, Table 25 indicates the relative impact of passive efficiency measures on habitability in terms of SET degree hours for median comfort conditions determined for existing single-family (SF) buildings. The percent improvement of the SET metric, as well as the days of habitability, are indicated for the two improved efficiency cases. The results can be used in combination with mitigation costs to inform measure selection. For example, the current code passive measures might be adopted in Houston instead of beyond-code measures since the two mitigation strategies result in similar occupant exposure and days of habitability. However, in Portland, the beyond-code measures may be deemed worth the extra expense due to the notable improvement in comfort and habitability they provide.

Table 25. Impact of Passive Measures on Habitability in Existing Single- Family Buildings

Data shows the median building in the population sample over a 7-day extreme event.

		SET Degree Hours*					Habitability				
		7-Day Cumulative			Improvement†		Days of Safety (per Event)			Improvement†	
Location (Climate Zone)	Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Cold	749	222	-	70%	100%	3.8	6.9	7	82%	85%
	Heat	600	141	-	76%	100%	4.0	7	7	75%	75%
Atlanta, GA (3A)	Cold	2,558	1,610	200	37%	92%	1.4	2.3	7	64%	409%
	Heat	438	59	-	87%	100%	2.9	7	7	140%	140%
Los Angeles, CA (3B)	Cold	87	-	-	100%	100%	7	7	7	-	-
	Heat	100	-	-	100%	100%	7	7	7	-	-
Portland, OR (4C)	Cold	2,963	1,849	237	38%	92%	1.1	2.4	6.8	123%	523%
	Heat	371	319	-	14%	100%	4.7	5.5	7	16%	49%
Detroit, MI (5A)	Cold	4,248	3,020	1,778	29%	58%	0.9	1.7	2.4	82%	159%
	Heat	223	53	0.3	76%	100%	6.8	7	7	2%	2%
Minneapolis/ St. Paul, MN (6A)	Cold	5,397	3,699	2,190	31%	59%	0.6	1.2	1.8	100%	214%
	Heat	215	66	5	69%	98%	7	7	7	-	-

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Existing Stock

8.2 Application of New Methods

Application considerations for the new procedures incorporated into the efficiency performance assessment to address resilience are presented below. An overview of method assumptions, caveats, and limitations, introduced in Section 4 and reflected in the Table 24 robustness assessment, are summarized in Appendix J for reference.

8.2.1 Occupant Exposure

Three passive survivability (PS) metrics, the SET, SET degree hours, and HI, that measure the ability to shelter in place are used in the study. Each is calculated and reported within the EnergyPlus building simulation engine (version 9.4 and later). The LEED Pilot Credit IPpc100 references the SET degree hour metric and specifies a required threshold value of 216 be met to earn the credit. The cumulative value is based on a 7-day period spanning an extreme temperature power outage event. These PS metric values are available in commonly used simulation programs and are starting to be applied in practice.

To calculate the metrics, the building is simulated using weather data that include an extreme heat or cold event. The events are identified using historical weather data by applying methods defined by Ouzeau et al. (2016). The Ouzeau method has been adopted for use in the International Energy Agency Annex 80 Resilient Cooling project. This demonstrates its acceptance and application in international policy development.

Our application identifies multiple extreme events of varying intensity and duration for each location. These variations across events can impact the resulting PS metric values. For general industry application, the identification, creation, and distribution of representative extreme events for global locations are needed to support standardization of applied methods. Also, extreme events identified from historical weather data may underestimate actual lifecycle cost benefits due to the impacts of climate change. Representative extreme event weather data files based on future weather projections are also needed to inform decision-making.

It may be possible to make comparisons of PS metric values across performance analysis studies, but the same general cautions for making cross-comparisons of building simulation results still apply. Specifically, conclusions drawn from comparing results may be unreliable if the analyses use different simulation engines, software versions, weather data files, modeling assumptions, or passive system characterizations.

8.2.2 Quantifying the Value of Health Impacts

Recent literature identifies a strong correlation between building characteristics and occupant health (Weimer and Nambiar 2022). Building-related causes of health hazards include exposures to dampness and mold, extreme cold or heat, fine particulate matter, and chemicals like radon, lead, and formaldehyde. Indirect health impacts of buildings include cognitive performance, productivity, absenteeism, comfort, and general well-being. Exposure to temperature extremes is associated with hypertension, increased risk of cardiovascular or cerebrovascular events, respiratory stress, hypothermia, hyperthermia, and mortality.

In its 2020 research report (Hayes et al. 2020), the American Council for an Energy Efficiency Economy (ACEEE) monetized health outcomes of energy-efficiency investments on four health threats—asthma, heat-related thermal stress, cold-related thermal stress, and trip-and-fall-injuries. The study focused on building conditions affecting indoor air quality and safety and provided recommended actions for making changes through energy-efficiency programs. The estimated potential benefit associated with reduced heat- and cold-related stress totaled over $11 million on average annually. Based on the total residential building area in the United States, the savings is equivalent to about $0.004/sq. ft,[20] which is low compared to the benefits related to reduced loss of life, energy savings, and greenhouse gas emissions reductions estimated in this study. However, the benefits of air quality and injury hazard mitigation might not be attributed evenly across the building population, which would increase the floor area normalized benefit value since the proposed solutions are intended to target those that would receive the most benefit, which includes economically and socially vulnerable communities.

[20] The normalized benefit value assumes 237.4 billion sq. ft. of U.S. residential floor area (EIA. 2015. Residential Energy Consumption Survey. Table HC10.1, released October 2017).

The methods applied in the Multi-Hazard Mitigation Study (MMC 2018) investigating the cost effectiveness of code adoption as a mitigation measure on four natural hazards (riverine and coastal flooding, hurricanes, earthquakes, and fires at the wildland–urban interface) include the effect of loss of life reduction. To align with that effort, occupant damage expressed in terms of excess death is considered in this study. Human mortality associated with severe temperature is a substantive area of public health research (Weimar and Nambiar 2022). These studies evaluate the exposure and resistance of the population to severe temperatures, both hot and cold. Each climate region and area will differ in its demographic composition based on age, gender, socioeconomic status, and climate adaptation. The literature in a few cases provides the relationship between temperature levels and mortality. To account for mortality in the valuation methodology, the methods outlined by Gasparrini et al. (2015) were used, since they provided adequate information to determine reduction in lives lost for the locations studied. Focusing on lost life is aligned with the study's focus on building efficiency and thermal conditions. A future refinement to the valuation methodology would be to include indoor air quality and safety condition considerations in applicable existing building stock, as addressed in the ACEEE study.

The Gasparrini study provides damage curves, which relate average daily outdoor temperatures and death rates specific to 135 U.S. cities/counties. The model controls for air pollution, humidity trends, and days of the week mean daily temperature. The model also contained a 10-day lag to capture the effects of cold and to remove deaths that were advanced by only a few days. To apply the damage curves in the study, several simplifying assumptions were made:

- Estimates of changes in excess mortality related to efficiency mitigation using average daily indoor temperatures determined from the simulation analysis.
- Mortality impacts analyzed using Gasparrini assume a heat and cold event duration of 7 days.

Regarding the duration assumption, the average duration for long events analyzed in the study equals 10.5 days for both heat and cold events based on the six locations. The joint probability determination is based on data for extreme events that last 5 days or more, although the duration of the associated power outage is not identified in the OE-417 dataset. The number of hours that Texans who lost power during the 2021 winter storm event were without is an average of 42 hours (Watson et al. 2021). Without better information, the researchers opted to use the average daily temperature data associated with the first 7 days of the long heat and cold extreme events that were modeled for each location. However, for the 2021 Houston winter storm case study, the excess death estimate is based on the actual extreme temperature event duration of 12 days. The case study results are 80% of the published excess death value. This indicates that using a 7-day period with the Gasparrini model for our application may markedly underestimate excess deaths and the investment benefit of efficiency. The event duration assumption has a direct impact on excess death reduction and warrants further analysis and application refinement.

8.2.3 Determination of Annualized Benefits and Costs

A common application for building simulation analysis is the determination of energy use impact and cost effectiveness of building efficiency investment, which are assessed based on a typical weather year. These procedures are included as part of the study net present value analysis to account for annual energy cost savings, annual greenhouse gas emissions reduction, the associated societal monetary benefit, and the investment cost. The developed methodology also includes the effect of improved building efficiency on reduction in excess mortality and property damage attributed to extreme heat and cold events. This expanded valuation can be applied in energy codes and standards development and in support of state and local jurisdiction resilience planning.

The expanded cost effectiveness analysis requires annualizing and monetizing excess mortality and property damage attributed to extreme events. As discussed in Section 4, this requires assessing risk probability. For property damage, the published FEMA National Risk Index (NRI) data are annualized values that embed risk probability. For excess mortality, the team assessed occupant exposure using the building performance simulation results to discern the impact of passive efficiency measures. The simulation modeling provides improved resolution compared to the NRI damage data, which is based on historical event data and reflects the collective condition of the existing building stock.

To annualize the reduction in excess mortality, the impact of exposure is determined based on the first 7 days of the long-duration representative extreme temperature events and the coincident extreme temperature–power outage probability factor, with the values indicated in Table 13. The calculation of the coincident probability is a novel component of the methodology, but the supporting data have deficiencies. While the reporting of an electric incident disturbance report using DOE Form OE-417 is mandatory, it is not clear if the geographic area impacted is recorded consistently across incidents. Some entries indicate only the state and not the counties impacted. Also, the records do not consistently indicate outage end times. Further assessment of the NRI data records, other data sources, and potential reporting issues is needed, as well as establishing informational needs to improve data collection. The development of supporting assessment tools would also be helpful to automate cross-referencing the datasets. The tool would make the process more straightforward and improve implementation consistency.

8.2.4 Example Decision Matrix

A key component of resilience valuation is deciding which measures to consider. The decision portfolio provides a format for conducting this assessment. The procedure incorporates results of the mitigation measure evaluations by building type and CZ and supports making comparisons between mitigation options. The assessment involves normalizing the selected metrics then applying user-defined weighting factors. The factor values reflect stakeholder's objectives and are intended to result in the best mitigation solution. A sample decision matrix is provided in Table 26, which uses the analysis results for the existing SF buildings located in Houston.

Table 26. Example Decision Matrix for Existing Single- Family Buildings in Houston (2A)

Metric	Value		Assigned Weights	Normalized	
	Current Code IECC 2021	**Beyond Code** PHIUS		**Current Code** IECC 2021	**Beyond Code** PHIUS
BCR	0.63	<u>0.68</u>	30%	0.92	1.00
Levelized First Costs ($/ft²/year)	<u>0.63</u>	0.77	15%	1.00	0.82
Energy Savings (kWh/ft²/year)	<u>3.1</u>	4.1	15%	1.00	0.76
Lives Saved	62	<u>93</u>	10%	0.66	1.00
SET Degree Hours Saved	985	<u>1348</u>	30%	0.73	1.00
			Weighted Total	**0.86**	**0.94**

Five metrics are considered to evaluate which mitigation package best meets the decision-maker's objectives. The metrics include BCR, first cost, energy savings, total lives saved, and total SET degree hours saved. The values underlined in Table 26 are the best of the two mitigation solutions. Notice that for first costs and energy the lowest value is the best value. Example weighting factors are provided. The weight for BCR was set at 30%, first cost at 15%, energy savings at 15%, lives saved at 10%, and SET degree hours at 30%.

In this example, the low weight for lives saved reflects perceived limitations of the Gasparrini method application. The weights were multiplied by the values in each row and summed across. The highest weighted sum suggests the best alternative for Houston SF retrofits. Given the weights applied, the beyond-code package is the best solution. Of course, other combinations of weighting factors may indicate the IECC 2021 package best meets objectives.

8.3 Future Research

The study explores opportunities for incorporating resilience considerations into building efficiency investment cost effectiveness, with a focus on the resilience benefits of energy code adoption. Throughout the effort, several related research topics were identified but were beyond the scope of the study to address. These potential areas of future research are presented below.

Improve the determination of the joint probability. The joint probability of extreme temperature power outage occurrence is determined from DOE's Office of Cybersecurity, Energy Security and Emergency Response Electrical Emergency Incident and Disturbance data, collected on Form OE-417, which was identified as the best currently available data source. The approach followed may result in an overestimation of outage probability and duration concurrent with extreme hot and cold temperatures. Due to lack of geographic granularity reflected in the outage records, the probability values may be biased upward due to the assumption that all outages reported for the state affected the entire state. Future work should refine the power outage data assessment and perform a more detailed analysis of the temperature and power outage distribution.

Improve the assessment of property damage attributed to extreme temperature. The FEMA NRI property damage data appear to be deficient and underestimate damages when compared to published values for recent U.S. extreme temperature events. Future research should identify other data resources that include recently recorded damage values and use these values to improve the BCR estimate. In addition, the method for assessing the impact of increased efficiency on property damage should be reexamined. For example, instead of using excess mortality reduction to prorate property damage, SET degree hours or days of habitability could be used.

Improve the assessment of excess mortality. The Gasparrini et al. (2015) epidemiology-based relative rate of mortality fragility curves is used in the study to estimate the impact of passive efficiency on indoor space conditions and excess mortality during extreme temperature events. A 7-day period was the basis for monetizing the occupant damage for the BCR calculation. However, based on the Houston case study results, this may markedly underestimate impact. Additional case studies should be conducted to compare published excess death values to modeled values to establish an appropriate time period to use in the analysis.

Create a library of representative extreme temperature data files for resilience analysis. Creating a library of extreme temperature weather data files will improve standardization and analysis consistency. Regressive efficiency-resilience analysis based on historical data can be used to check the results of new methods against published impact data. Predictive analyses based on future extreme temperature conditions could help inform the effective design of resilient new and retrofitted buildings and better address investment cost effectiveness over the measure lifetime.

Standardize procedures followed for thermal resilience calculations. The study followed the uninhabitability temperature ranges and cumulative threshold adopted for the LEED pilot credit for calculating SET degree hours and days of habitability. Obtaining broad industry acceptance of these parameters affecting metric values will help establish standardized procedures. Related considerations include the duration of the extreme event to be used in the analysis. For instance, a key consideration is understanding when it is most appropriate to use a fixed duration, such as 7 days, or the duration of the extreme event. Additionally, procedures can be established to inform energy system sizing based on extreme event data. As part of this, methods to establish the spatial and temporal diversity of loads and occupants at the individual space level can be established. Typical methods currently applied using area averaging or lump assumptions for energy modeling may not be adequate.

Differentiate health damage impacts across different population groups. Another key area for future work is understanding and establishing health metric thresholds that differentiate between healthy and vulnerable populations. The health impacts analyzed in the study are based on the Gasparrini damage models, which indicate aggregated impact across a county. Understanding habitability thresholds for different occupant groups, along with the occupant behaviors that dictate safe or unsafe conditions (e.g., opening windows, being exposed outdoors for longer durations) will help refine methods and improve the analysis of critical facilities.

Evaluate efficiency-resilience impacts for additional building types and locations. Understanding efficiency-resilience opportunities for commercial buildings, new and existing, as well as critical facilities such as hospitals, police stations, and water treatment facilities, could be valuable to emergency and community planners. Similarly, the federal building stock could be analyzed to inform code and standard requirements supporting resilience. The analysis can also be performed in additional locations prioritized by state interest, perceived risk, or to estimate impacts at the national level.

Consider thermal resilience in conjunction with other weather-related hazards. Understanding passive efficiency measure performance during disruptive events coincident with extreme temperature, such as wildfires, air pollution, or flooding, should be considered. For example, if there is frequent occurrence of power outage with extreme heat accompanied by poor air quality, investment in a back-up power system may be warranted to maintain thermal comfort and indoor air quality. In addition, post-incident mitigation efforts resulting from other hazards that affect the building envelope, such as flooding, may provide an opportunity to include passive measures for increased thermal resilience as an incremental cost.

Incorporate thermal resilience metrics natural hazard resilience models, tools, and frameworks. Metrics characterizing the building stock could be integrated into the FEMA NRI assessment framework to connect energy resilience to the built environment within the risk framework. Opportunities with risk-related industries, such as insurance providers or FEMA, should also be explored.

Validate the effectiveness of strategies through field studies. Modeling and simulation results are useful for understanding building design options for improved resilience. Validating the effectiveness of implemented strategies through field studies and performance measurement and verification are effective strategies for encouraging efficiency-resilience strategy adoption and advancement. Opportunities for DOE and its national laboratories to team with organizations that conduct field implementation, such as the General Services Administration's Green Proving Ground Program and the Department of Defense's Environmental Security Technology Certification Program, can be explored.

9.0 Conclusions

The study developed and applied a methodology to assess the value of efficiency for enhancing resilience in new and existing single-family (SF) and multifamily (MF) apartment buildings in six U.S. cities. In nearly every situation, improving passive efficiency in residential buildings to meet or exceed current energy code requirements saves lives during extreme temperature events. Improving passive efficiency in residential buildings to meet or exceed current energy code requirements extends occupant habitability and the ability to shelter in place. The study found that increasing the efficiency of the envelope in existing SF buildings to meet code requirements extends habitability by as much as 120% during extreme cold and by up to 140% during extreme heat. For example, for a SF building in Atlanta during a 7-day cold event, the typical existing building will maintain habitable conditions for 1.4 days, while a building built to the 2021 IECC will maintain habitable conditions for 2.3 days, nearly a full day longer. However, a highly efficient home built to Passive House Standards can maintain temperature within the habitability threshold for the full 7 days, five times as long as the typical existing building. The Atlanta cold event results also show that increasing passive efficiency will save 3.6 and 8.6 lives for the current code and beyond-code cases, respectively.

The BCR calculation includes the stacked benefits associated with efficiency that go beyond energy use reduction. The values indicate that improving the building envelope to meet or beat current code is cost effective for new SF and for most new MF buildings for the locations investigated. For the new buildings, the BCR values range from 4 to 7 for SF and 3 to 14 for MF buildings, making a strong financial case for their implementation. BCR values tend to be lower for the existing buildings due to higher first costs.

The case study of an assisted living facility (ALF) located in Texas shows that the passive measures considered improved its thermal resilience overall. Some measures, such as infiltration reduction and window films, when evaluated individually improved habitability during extreme heat or cold only. This demonstrates the benefit of an integrated design approach and indicates the advantages of flexible operating strategies for controlling solar gains or natural air flow. While the passive measures did improve indoor conditions, they did not result in safe conditions being maintained for the residents. However, the passive measures can reduce back-up power capacity requirements, which should be considered in the evaluation of measure benefits.

The developed methodology lays the foundation for establishing a standardized analysis for quantifying the resilience benefits of improved building efficiency. It expands upon traditional efficiency studies focused on annual energy operating costs to include monetized impact assessments related to greenhouse gas emissions, occupant damages in terms of excess mortality, and property damage. Due to the lack of robustness of some input parameters used in its calculation, the BCR values should be regarded as preliminary. The occupant exposure metrics, including standard effective temperature (SET), SET degree hours and heat index (HI), can be determined with high confidence. These metrics are already incorporated into the EnergyPlus building simulation program. Thus, they can readily be applied in current assessments to demonstrate the impact of building efficiency on extreme temperature resilience.

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Appendix A – Technical Advisory Group

The role of the TAG was to inform analyses and ensure results and visualizations were helpful and relevant. The TAG consisted of 20 members. Meetings were scheduled monthly and held when TAG input was needed, or new results were available. The TAG members are listed in Table A-1. Descriptions of the meeting topics follow the table.

Table A-1. TAG Member List

Sector or Category	Organization	First Name	Last Name
Asset Valuation and Insurance Risk	Insurance Institute for Business & Home Safety (IBHS)	Fred	Malik
	Hartford Steam Boiler	Rick	Jones
Building Codes and Standards	National Institute of Building Sciences (NIBS)	JiQiu (JQ)	Yuan
	International Code Council (ICC) / Alliance for National and Community Resilience (ANCR)	Ryan	Colker
	ASHRAE / NREL	Sheila	Hayter
Building Design & Construction	Resilient Design Institute	Alex	Wilson
Disaster Management (Mitigation, Operations, and Recovery)	FEMA, Building Resilient Infrastructure and Communities (BRIC)	Camille	Crain
	FEMA, Threat and Hazard Identification and Risk Assessment (THIRA)	Daniel	Nyquist
	Cybersecurity & Infrastructure Security Agency (CISA)	Steve	Cauffman
Disaster Recovery and Affordable Housing	Enterprise Community Partners	Laurie	Schoeman
Hazard Assessment/ Extreme Weather Analysis	Federal Emergency Management Agency (FEMA)	Jesse	Rozelle
	National Institute of Standards and Technology (NIST)	Joshua	Kneifel
State and Local Jurisdictions	National Association of State Energy Officials (NASEO)	Ed	Carley
	National Association of State Energy Officials (NASEO)	Rodney	Sobin
Utilities/ ISOs/ RTOs	Synapse Energy Economics	Jenn	Kallay
Vulnerability Indicators and Estimated Losses	University of Washington	Kristie	Ebi
	U.S. Environmental Protection Agency	Colby	Tucker
	Centers for Disease Control and Prevention (CDC)	Paul	Schramm
	Centers for Disease Control and Prevention (CDC)	Shubhayu	Saha
	Centers for Disease Control and Prevention (CDC)	Ambarish	Vaidyanathan

Schedule and topics covered are shown below:

TAG Kick-Off Meeting: 12/10/2020
The kick-off meeting was attended by 17 TAG members, three BTO staff, and representatives from each of the three labs. The objective of the meeting was to introduce the project and set expectations of the TAG and associated meetings.

Methodology Meeting: 1/14/2021
The methodology meeting introduced the tri-lab research project to the TAG through the methodology development process and input was solicited.

Methodology Synopsis and Acceptance Meeting: 2/11/2021
The goal of the meeting was to summarize the methodology and where it had been refined using feedback from the previous TAG meeting, then obtain agreement that the methodology was effective for the project team to deploy.

Valuation Modeling: Metrics and Process Flow: 4/8/2021
The valuation modeling meeting included an overview of the metrics being used in the project, an introduction to the new single-family (SF) modeling (PNNL), existing SF modeling (NREL), and the process workflow.

Passive Survivability in Practice: 5/13/2021
The passive survivability (PS) meeting was intended to provide an opportunity to discuss recent events related to extreme temperature vulnerability (e.g., Winter Storm Uri in Texas in February 2021), review PS analyses of previous historic events using the ResStock model, and revisit thermal performance metrics and their value to different user groups.

Methodology Updates: 9/9/2021
The methodology update meeting was an opportunity to provide TAG members with a progress update on the methodology as it was being applied to the models at the different labs, discuss research priorities for part-power analyses, and provide an open discussion on related topics.

Methodology Update and Initial Modeling Results: 11/18/2021
Discussion topics included building simulation graphics and health damage model analysis results. The objective of the meeting was to share results of the analyses, get feedback on the effectiveness of the graphics, and check that results were consistent with expectations, while acknowledging shortcomings of the analyses.

Analysis Update: 3/10/2022
The analysis update meeting provided TAG members with the latest results from modeling at the three labs and included occupant exposure and damage. The objective was to provide a status update and gain TAG input on the assumptions and results.

Assisted Living Facility Analysis: 4/14/2022:
In lieu of a meeting, the assisted living facility (ALF) case study was emailed to TAG members for their review and comment.

Appendix B – U.S. Climate Zones

The building simulation analysis conducted in this study uses building physics to assess the indoor comfort conditions based on external weather conditions. To assess habitability during extreme heat and cold, the research team identified three U.S. hazard regions and selected two cities in each region to characterize a range of building and weather conditions. Figure B-1 presents the range of CZs by county across the United States. The map shows the hazard regions, cities, and the associated CZs analyzed in the study. The former includes the Gulf Coast, Pacific Coast, and Great Lakes. The locations include Houston (2A), Georgia (3A), Los Angeles (3B), Portland (4C), Detroit (5A), and Minneapolis/St. Paul (6A).

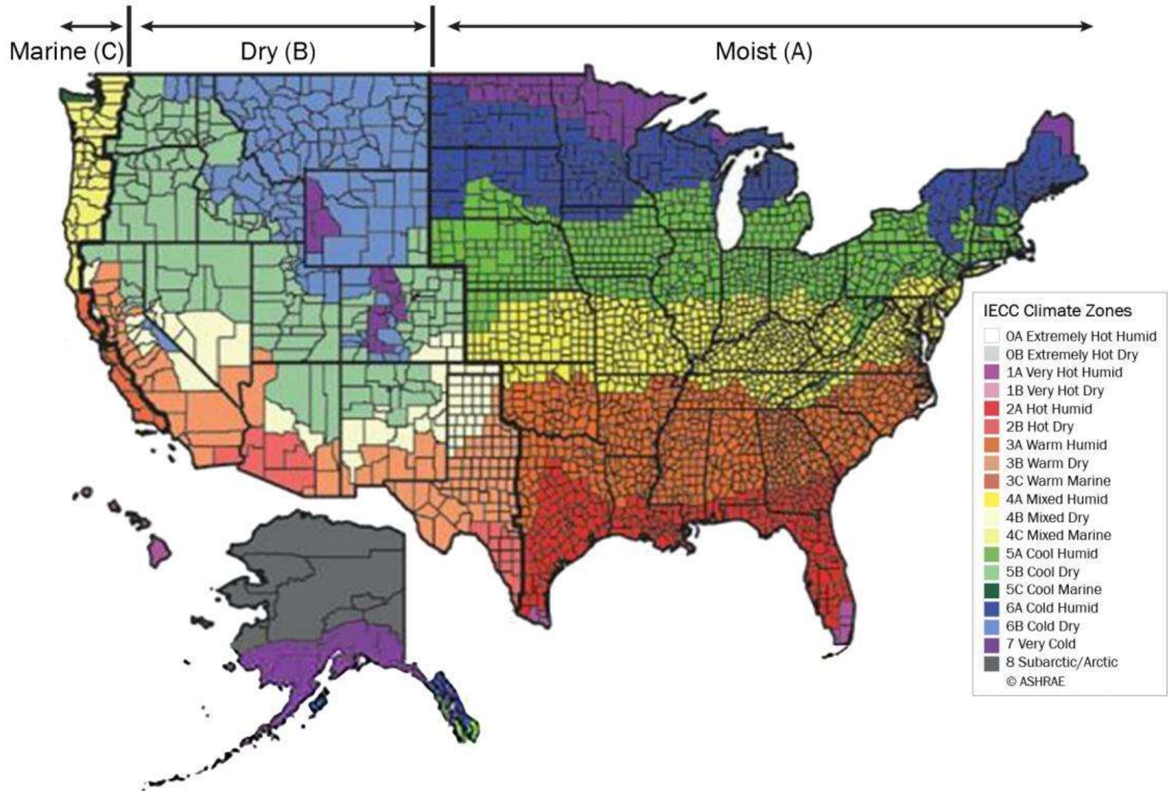


Figure B-1. CZs of the Continental United States (IECC 2021)

Appendix C – Building Base Case Conditions and Efficiency Measures

Three residential building types are included in the analysis. Their characteristics are summarized in Table C-1. They include single-family (SF) and multifamily (MF) buildings. A counterfactual baseline case study analysis is also performed for an existing ALF. The study is included to gain insights on energy resilience as it relates to a vulnerable occupant population.

Based on each building's use type and floor area, design and construction requirements are relegated to comply with either residential or commercial building code. Residential model energy code is recognized as the IECC-R (ICC 2021). The commercial model energy code is recognized as ASHRAE Standard 90.1 (ASHARE 2019), with the current published codes being the 2021 IECC-R and ASHRAE 90.1-2019. The historic code reference for each used in the analysis is the 2006 IECC-R and 90.1-2004.

In the study, building performance analysis is performed using the EnergyPlus simulation engine. The simulation is used to evaluate indoor comfort conditions and building energy use. As identified in Table C-1, the base case and improved conditions depend on the building type and vintage modeled. For new buildings, the conditions characterize historic code, current code, and beyond energy code measures. For existing buildings, the conditions characterize the building stock (determined based on survey data), current energy code, and beyond current code measures. The ALF is characterized based on the as-built construction details of an actual building located near Houston, Texas. The SF and MF buildings are analyzed in each of the six hazard region locations. The ALF is analyzed in Houston.

Table C-1. Building Model Types and Their Characteristics

Building Type	New			Existing		
	Historic Case	Current Code	Beyond Code	Base Case	Current Code	Beyond Code
Single Family	IECC 2006	IECC 2021	2021 IECC plus passive beyond-code measures	ResStock data[21]	Passive measures from IECC 2021	Passive beyond-code measures
Multifamily Apartment	ASHRAE 90.1 2004	ASHRAE 90.1 2019	ASHRAE 90.1 2019 plus passive beyond-code measures	ASHRAE 90.1 2004 plus U.S. survey data	Passive measures from 90.1 2019	Passive beyond-code measures
	Base Case		Older Building		Improved Design	
Assisted Living Facility	As-built construction		Select measures from 90.1 1999		Select beyond-code measures	

C.1 Efficiency Mitigation Measures

EEMs are improvements made to the building design and construction that reduce building energy use while still maintaining or improving building services (e.g., lighting, heating, cooling, ventilation) and occupant needs (e.g., visual acuity, thermal comfort, air quality). In this study,

[21] ResStock couples statistically represent residential household and efficiency characterizations with the OpenStudio building modeling interface, which is powered by the EnergyPlus simulation engine (Langevin 2019).

the base case building condition is improved by upgrading the building as indicted in Table C-1 to assuage the effects of extreme temperature events. For this application, packages of measures were applied to SF and MF buildings to ensure sufficient impact was achieved to discern changes in mortality rate in order to demonstrate the developed building thermal resilience assessment methodology. However, efficiency improvements are analyzed for individual measures and packages of measures in the ALF case study.

The building conditions that reference IECC-R and ASHRAE 90.1 code cycles are based on characteristics captured in the building prototype simulation models published by the DOE Building Energy Codes Program, which are maintained by PNNL.[22] To indicate the benefit of improvements not yet included in energy codes, an advanced measure package is also assessed. The advanced measures amended to the residential building baseline condition reflect requirements for compliance defined by the 2021 Passive House Institute U.S. (PHIUS) Standard (PHIUS 2021). Passive house concepts include superinsulation, airtight envelopes, high-performance windows, and managing solar gain. The approach minimizes energy loads to achieve ambitious yet technically feasible performance targets.

C.2 Resilience Mitigation Measures

Key efficiency attributes of the baseline and mitigation packages for SF and MF buildings affecting their passive resilience are summarized below. The measures applied in the ALF are presented in the Section 7 case study.

Table C-2. New Single Family Base Case Condition and Passive Measure Packages

			Climate Zone					
No.	**Measure**	**Unit**	**2A**	**3A**	**3B**	**4C**	**5A**	**6A**
Base Case Condition: Historic Code IECC 2006								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.087	0.087	0.087	0.064	0.064	0.064
2a	Roof U-Factor	Btu/hr·F·ft²	0.543					
2b	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft²	0.035	0.035	0.035	0.03	0.03	0.026
3	Floor U-Factor	Btu/hr·F·ft²	0.212					
4a	Window U-Factor	Btu/hr·F·ft²	0.751	0.651	0.651	0.35	0.35	0.35
4b	Window SHGC		0.34	0.337	0.337	0.335	0.335	0.335
Current Code Measures: IECC 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.087	0.06	0.06	0.048	0.048	0.048
2a	Roof U-Factor	Btu/hr·F·ft²	0.543					
2b	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft²	0.026	0.026	0.026	0.023	0.023	0.023
3	Floor U-Factor	Btu/hr·F·ft²	0.212					
4a	Window U-Factor	Btu/hr·F·ft²	0.40	0.30	0.30	0.30	0.30	0.30
4b	Window SHGC		0.217	0.217	0.217	0.335	0.335	0.335
Beyond Code Measures: PHIUS 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.048	0.028	0.035	0.026	0.023	0.023
2a	Roof U-Factor	Btu/hr·F·ft²	0.543					
2b	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft²	0.023	0.021	0.021	0.021	0.020	0.020
3	Floor U-Factor	Btu/hr·F·ft²	0.212					
4a	Window U-Factor	Btu/hr·F·ft²	0.40	0.24	0.25	0.26	0.16	0.13
4b	Window SHGC		0.217	0.217	0.217	0.225	0.335	0.335

[22] https://www.energycodes.gov/prototype-building-models

Table C-2 shows the passive measure values for new SF homes. The baseline model uses the 2006 IECC historic code requirements. One of the mitigation measure packages corresponds to requirements specified in the current code, which is the 2021 IECC 2021. The second measure package exceeds current code and is aligned with the PHIUS Standard.

For the existing SF buildings, two scenarios of passive efficiency upgrades from the code baseline conditions are considered and are shown in Table C-3. The existing conditions are based on U.S. survey data. The current code package includes passive measure upgrades based on the 2021 IECC residential code requirements. The beyond code package includes passive measure upgrades aligned with the PHIUS Standard.

Table C-3. Existing Single Family Base Case Condition and Passive Measure Packages

No.	Measure	Unit	Climate Zone 2A	3A	3B	4C	5A	6A
Base Case Condition: Existing Building Stock								
1	Exterior Wall U-Factor	Btu/hr·F·ft^2	0.091	0.091	N/A	0.091	0.143	N/A
2	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft^2	0.033	0.053	0.053	0.026	0.033	0.033
3	Floor U-Factor	Btu/hr·F·ft^2	none					
4a	Window U-Factor	Btu/hr·F·ft^2	0.84	0.76	0.76	0.49	0.49	0.49
4b	Window SHGC		0.63	0.67	0.67	0.56	0.56	0.56
5	Foundation Wall U-Factor	Btu/hr·F·ft^2	none					
6	Slab Edge Insulation	ft^2·hr·F/Btu	none					
Current Code Measures: IECC 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft^2	0.077	0.05	0.05	0.05	0.05	0.033
2	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft^2	0.02	0.02	0.02	0.017	0.017	0.017
3	Floor U-Factor	Btu/hr·F·ft^2	0.077	0.053	0.053	0.033	0.033	0.033
4a	Window U-Factor	Btu/hr·F·ft^2	0.4	0.3	0.3	0.3	0.3	0.3
4b	Window SHGC		0.25	0.25	0.25	0.4	0.4	0.4
5	Foundation Wall U-Factor	Btu/hr·F·ft^2	none	0.2	0.2	0.067	0.067	0.067
6	Slab Edge Insulation	ft^2·hr·F/Btu	none	2ft R-10	2ft R-10	4ft R-10	4ft R-10	4ft R-10
Beyond Code Measures: PHIUS 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft^2	0.037	0.032	0.033	0.029	0.024	0.022
2	Ceiling/Attic Floor U-Factor	Btu/hr·F·ft^2	0.018	0.016	0.017	0.015	0.014	0.013
3	Floor U-Factor	Btu/hr·F·ft^2	0.037	0.032	0.033	0.029	0.024	0.022
4a	Window U-Factor	Btu/hr·F·ft^2	0.28	0.23	0.28	0.24	0.16	0.13
4b	Window SHGC		0.25	0.25	0.25	0.4	0.4	0.4
5	Foundation Wall U-Factor	Btu/hr·F·ft^2	0.1	0.077	0.071	0.063	0.048	0.042
6	Slab Edge Insulation	ft^2·hr·F/Btu	2ft R-13	2ft R-13	2ft R-14	2ft R-16	2ft R-21	2ft R-24

Table C-4 shows the passive measure values for new MF. The baseline model is based on historical code requirements of ASHRAE 90.1-2004. A measure package is considered for meeting current code requirements in accordance with ASHRAE 90.1-2019. The beyond code package amends the 90.1-2019 requirements with passive measures aligned in PHIUS 2021.

Table C-4. New Multifamily Base Case Condition and Passive Measure Packages

No.	Measure	Unit	Climate Zone					
			2A	3A	3B	4C	5A	6A
Base Case Condition: Historic Code ASHRAE 90.1 2004								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.124	0.084	0.084	0.064	0.064	0.064
2	Roof U-Factor	Btu/hr·F·ft²	0.063					
3	Floor F-Factor	Btu/hr·F·ft²	0.730					
4a	Window U-Factor	Btu/hr·F·ft²	1.232	0.595	0.595	0.595	0.595	0.595
4b	Window SHGC		0.250	0.610	0.610	0.390	0.390	0.390
Current Code Measures: ASHRAE 90.1 2019								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.064	0.064	0.064	0.064	0.055	0.049
2	Roof U-Factor	Btu/hr·F·ft²	0.039	0.039	0.039	0.032	0.032	0.032
3	Floor F-Factor	Btu/hr·F·ft²	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft²	0.487	0.450	0.450	0.382	0.382	0.360
4b	Window SHGC		0.245	0.245	0.245	0.353	0.368	0.370
Beyond Code Measures: PHIUS 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.034	0.030	0.035	0.028	0.023	0.021
2	Roof U-Factor	Btu/hr·F·ft²	0.017	0.016	0.017	0.016	0.014	0.013
3	Floor F-Factor	Btu/hr·F·ft²	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft²	0.290	0.240	0.460	0.250	0.170	0.130
4b	Window SHGC		0.250	0.250	0.250	0.353	0.368	0.370

Passive measures values for existing MF buildings are listed in Table C-5. The base case condition is based on ASHRAE 90.1-2004 with conditions modified to be consistent with existing conditions for passive measures indicated by survey data describing the U.S. MF building stock. The two mitigation measure packages correspond to passive measure requirements specified in current code, which is ASHRAE 90.1-2019, and beyond-code passive measures aligned with the PHIUS Standard.

Table C-5. Existing Multifamily Base Case Condition and Passive Measure Packages

No.	Measure	Unit	Climate Zon					
			2A	3A	3B	4C	5A	6A
Base Case Condition: Historic Code ASHRAE 90.1 2004 plus Survey Data								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.261	0.261	0.261	0.261	0.257	0.254
2	Roof U-Factor	Btu/hr·F·ft²	0.467	0.467	0.467	0.464	0.464	0.464
3	Floor F-Factor	Btu/hr·F·ft²	0.730	0.635	0.635	0.625	0.620	0.582
4a	Window U-Factor	Btu/hr·F·ft²	0.860	0.835	0.835	0.800	0.500	0.490
4b	Window SHGC		0.393	0.428	0.428	0.446	0.389	0.390
Current Code Measures: ASHRAE 90.1 2019								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.064	0.064	0.064	0.064	0.055	0.049
2	Roof U-Factor	Btu/hr·F·ft²	0.039	0.039	0.039	0.032	0.032	0.032
3	Floor F-Factor	Btu/hr·F·ft²	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft²	0.487	0.450	0.450	0.382	0.382	0.360
4b	Window SHGC		0.245	0.245	0.245	0.353	0.368	0.370
Beyond Code Measures: PHIUS 2021								
1	Exterior Wall U-Factor	Btu/hr·F·ft²	0.034	0.030	0.035	0.028	0.023	0.021
2	Roof U-Factor	Btu/hr·F·ft²	0.017	0.016	0.017	0.016	0.014	0.013
3	Floor F-Factor	Btu/hr·F·ft²	0.730	0.540	0.540	0.520	0.510	0.434
4a	Window U-Factor	Btu/hr·F·ft²	0.290	0.240	0.460	0.250	0.170	0.130
4b	Window SHGC		0.250	0.250	0.250	0.353	0.368	0.370

Appendix D – Building Simulation Modeling

This appendix provides additional information on the building energy models and tools used in this project.

D.1 ResStock

The ResStock methodology is summarized below. For further details see Wilson (2017).

Stock characterization: Conditional probability distributions for building stock characteristics are queried from published data sources (e.g., the U.S. Energy Information Administration [EIA] Residential Energy Consumption Survey [RECS]). Parameters common across data sources, such as geographic location, building type, and vintage, are used to combine and map between the disparate data sources. Geographic resolution for queried distributions varies in scale—for example, from counties (~3,000) to CZs (16)—so various geospatial data sources are used to map between geographic resolutions. The conditional probability distributions take the form of a hierarchical tree of dependencies.

Sampling: The parameter space defined by the conditional probability distributions is sampled, meaning ResStock currently uses deterministic quota sampling, with probabilistic combination of non-correlated parameters. At the U.S. national scale, ResStock typically uses 550,000 samples to represent 133,172,057 dwelling units (approximately 1:242). The appropriate ratio of samples to buildings or dwelling units was initially determined through convergence testing for national-scale applications (Wilson 2017); however, the appropriate ratio for different applications and scales is the subject of ongoing research.

Physics simulation: The samples are used to construct physics-simulation models using a simulation engine of choice. NREL typically uses the EnergyPlus simulation engine for this purpose, as is the case for this research. Model construction and articulation is facilitated by the OpenStudio software development kit and associated residential modeling workflows.

Calibration and validation: ResStock went through an initial calibration/validation process in 2015. Annual electricity and natural gas consumption were validated against the 2009 EIA RECS data for various cohorts of single-family (SF) detached homes. Calibration involved numerous improvements to model input data and refinement of probability distribution dependencies. ResStock validation, with a focus on end-use load profiles, is ongoing under the DOE project “End-Use Load Profiles for the U.S. Building Stock” (Mims Frick et al. 2019).

Model outputs and post-processing: Model outputs include both annual and hourly or sub-hourly timeseries energy use outputs for each sample for major and minor end uses (e.g., electricity and on-site natural gas, propane, and fuel oil use). Outputs for each sample also include HVAC system capacities and hours the heating and cooling setpoints were not met. For this project, key outputs also include timeseries indoor zone dry-bulb temperature, mean radiant temperature, relative humidity, and derivative outputs specific to passive survivability (PS) such as standard effective temperature (SET) and heat index (HI).

Upgrades: The physics simulation allows us to consider what-if scenarios: What if homes with no wall insulation were retrofitted with dense-packed cellulose? What if homes built before the 1950s and with high air leakage (measured by ACH50) were retrofitted with air sealing? What if homes with electric resistance heating replaced those heaters with heat pumps? ResStock can model upgrade scenarios for any home that meets the conditions chosen. Similar to baseline runs, outputs of upgrade runs include annual and sub-hourly energy use (and home conditions such as indoor/outdoor temperature and humidity) for the baseline home and the hypothetical upgraded home.

D.2 Code Prototype Models

Residential and commercial building prototype models are maintained by PNNL to support the advancement of national building energy codes. PNNL-developed prototypes represent a suite of EnergyPlus building simulation models intended to represent typical buildings. The prototypes are used to simulate building energy performance and associated energy costs in 16 cities representing U.S. CZs. The prototypes currently include 32 residential[23] and 16 commercial building models, which are listed in Table D-1 along with their floor areas and contribution to total new construction floor area.

Table D-1. Residential and Commercial Code Prototype Building Model Characteristics

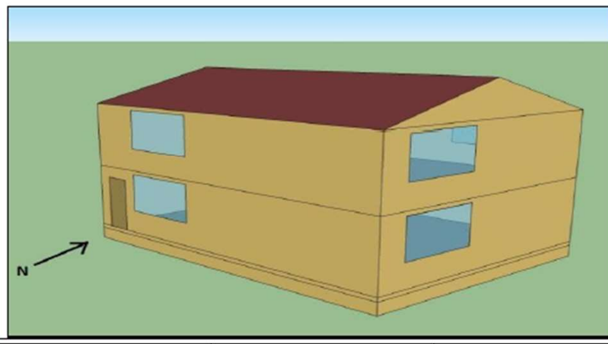
Building Category	Building Type	Floor Area (ft^2)	Floors	Average New Construction Floor Area (% or ft^2/year)
Residential	Single Family	2,377	2	80%
	Lowrise Multifamily	21,610	3	20%
		Residential Total:		**2,768,857,300**
Commercial	Apartment Highrise	84,352	10	7.2%
	Apartment Midrise	33,741	4	10.3%
	Hospital	241,501	5	3.4%
	Hotel Large	122,120	6	3.2%
	Hotel Small	43,202	4	1.2%
	Office Large	498,588	12	2.9%
	Office Medium	53,628	3	3.8%
	Office Small	5,502	1	2.8%
	Out-Patient Healthcare	40,946	3	2.6%
	Restaurant Fast Food	2,501	1	0.2%
	Restaurant Sit Down	5,502	1	0.7%
	Retail Standalone	24,692	1	8.2%
	Retail Strip Mall	22,500	1	2.8%
	School Primary	73,959	1	3.6%
	School Secondary	210,887	2	8.2%
	Warehouse	52,045	1	13.9%
	Not represented			25.0%
		Commercial Total:		**1,287,090,200**

[23] The two core residential building types, SF and lowrise MF buildings, form the basis for 32 variations that account for different heating systems and foundation types typically found in residential new construction.

The prototypes represent code-compliant buildings as characterized by model code that is published every three years. Model codes as recognized by DOE include the IECC for residential buildings and ASHRAE Standard 90.1 for commercial buildings. The PNNL code prototype modeling framework supports modeling the most recently published code (IECC-R 2021 and ASHRAE 90.1-2019). It also supports modeling past code cycles, including each cycle since 2006 for the IECC-R and 2004 for ASHRAE Standard 90.1. For the resilience study, two code prototypes were used, residential single-family (SF) and commercial midrise apartment. The efficiency requirements for the latter are dictated by commercial code requirements because its height is greater than three floors. An overview of the SF and midrise apartment prototype buildings used in the study, including schedules, form, envelope, occupancy, HVAC requirements, water heating, lighting, plug, and process loads, are provided in Table D-2 and Table D-3, respectively. Additional information describing the prototypes is provided by Thornton (Thornton et al. 2010) and Goel (Goel et al. 2014). All energy code prototype buildings are available for download from the DOE Building Energy Code Program website.[24]

[24] Available at https://www.energycodes.gov/prototype-building-models

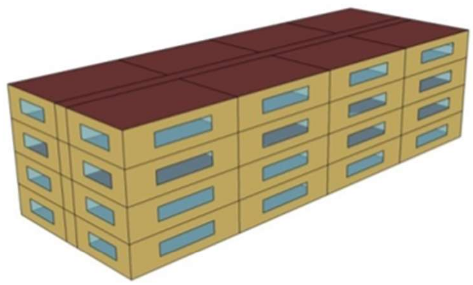
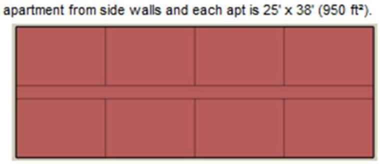
Table D-2. Single-Family Prototype Building Details

	Item	Description	Data Source
General			
	Vintage	New Construction	
	Locations	See under Section 1.42.2	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Available fuel types	Natural Gas/Electricity/Fuel Oil	
	Building Type (Principal Building Function)	Residential	
	Building Prototype	Single-family Detached	
Form			
	Total Floor Area (sq. feet)	2,400 (30' x 40' x 2 stories)	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Building shape		
	Aspect Ratio	1.33	
	Number of Floors	2	
	Window Fraction (Window-to-Floor Ratio)	Average Total: 15.0% divided equally among all facades	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Window Locations	All facades	
	Shading Geometry	none	
	Orientation	Back of the house faces North (see image)	
	Thermal Zoning	The house is divided into three thermal zones: 'living space', 'attic' and 'crawlspace', 'heated basement', 'unheated basement' when applicable.	
	Floor to ceiling height	8.5'	
Architecture			
	Exterior walls		
	Construction	Wood-Frame Walls (2x4 16" O.C. or 2x6 24" O.C.) 1" Stucco + Building Paper Felt + Insulating Sheathing (if applicable) + 5/8" Oriented Strand Board + Wall Insulation + 1/2" Drywall	
	U-factor (Btu / h * ft^2 * °F) and/or R-value (h * ft^2 * °F / Btu)	IECC Requirements Residential; Walls, above grade, Wood Frame	IECC
	Dimensions	based on floor area and aspect ratio	
	Tilts and orientations	Vertical	
	Roof		
	Construction	Asphalt Shingles	

	U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	IECC Requirements Residential; Roofs, Insulation entirely above deck	IECC
	Tilts and orientations	Gabled Roof with a Slope of 4/12	
	Window		
	Dimensions	based on window fraction, location, floor area and aspect ratio	
	Glass-Type and frame	Hypothetical window with the exact U-factor and SHGC shown below	
	U-factor (Btu / h * ft² * °F)	IECC Requirements Residential; Glazing	IECC
	SHGC (all)		
	Operable area	100%	
	Skylight		
	Dimensions	Not Modeled	
	Glass-Type and frame	NA	
	U-factor (Btu / h * ft² * °F)		
	SHGC (all)		
	Visible transmittance		
	Foundation		
	Foundation Type	Four Foundation Types are Modeled- i. Slab-on Grade ii. Vented Crawlspace Depth 2' iii. Heated Basement - Depth 7' iv. Unheated Basement- Depth 7'	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Insulation level	IECC Requirements for floors and basement walls	IECC
	Dimensions	based on floor area and aspect ratio	
	Internal Mass	8 lb/ft² of floor area	IECC 2015 Section 404
	Infiltration (ACH)	2006 IECC: 8 Air Changes/Hour at 50 Pa (8 ACH50) 2009 IECC: 7 Air Changes/Hour at 50 Pa (7 ACH50) 2012 IECC: 5 or 3 Air Changes/Hour at 50 Pa (5 or 3 ACH50) depending on climate zone	
HVAC			
	System Type		
	Heating type	Four Heating System Types are Modeled- i. Gas Furnace ii. Oil Furnace iii. Electric Furnace iv. Heat Pump	Reference: Methodology for Evaluating Cost Effectiveness of Residential Energy Code Changes
	Cooling type	Central DX Air-Conditioner/Heat Pump	
	HVAC Sizing		
	Cooling	autosized to design day	
	Heating	autosized to design day	
	HVAC Efficiency		
	Air Conditioning	SEER 13	Federal minimum efficiency
	Heating	AFUE 78% / HSPF 7.7	Federal minimum efficiency
	HVAC Control		

	Thermostat Setpoint	75°F Cooling/72°F Heating	
	Thermostat Setback	No setback	
	Supply air temperature	Maximum 110 F, Minimum 52 F	
	Ventilation	60 CFM Outdoor Air; Continuous Supply	2015 IRC
	Supply Fan		
	Fan schedules	See Appendix A.3	
	Supply Fan Total Efficiency (%)	Depending on the fan motor size	Residential Furnaces and Centralized Air Conditioners and Heat Pumps Direct Final Rule Technical Support Document.[1]
	Supply Fan Pressure Drop	Depending on the fan supply air cfm	
	Domestic Hot Water		
	DHW type	Individual Residential Water Heater with Storage Tank	
	Fuel type	Natural Gas/Electricity	
	Thermal efficiency (%)	EF = 0.59 for Gas-fired Water Heaters EF = 0.917 for Electric Water Heaters	Federal minimum efficiency
	Tank Volume (gal)	40 for Gas-fired Water Heaters 52 for Electric Water Heaters	Reference: Building America Research Benchmark
	Water temperature setpoint	120 F	
	Schedules	See Appendix A.2	
Internal Loads & Schedules			
	Lighting		
	Average interior power density (W/ft^2)	Living space: Lighting Power Density is 0.68 W/sq.ft.(For interior lighting) Lighting loads for Garage and Exterior Lighting have also been included	Reference: 2014 Building America House Simulation Protocols
	Interior Lighting Schedule	See Appendix A.3	
	Internal Gains		
	Load (Btu/day)	17,900 + 23.8 x CFA + 4104 x Nbr See Appendix A.4 for the detailed calculations	Reference: IECC 2015 and Building America Research Benchmark
	Internal gains Schedule(s)	See Appendix A.3	
	Occupancy		
	Average people	800 ft2/per person for conditional total and 1601 ft2/per person for total	
	Occupancy Schedule	See Appendix A.3	

Table D-3. Midrise Apartment Prototype Building Details (Multifamily)

Item	Descriptions	Data Source
Program		
Vintage	**NEW CONSTRUCTION**	
Location (Representing 8 Climate Zones)	Zone 1A: Honolulu, Hawaii (very hot, humid) Zone 1B: New Delhi, India (very hot, dry) Zone 2A: Tampa, Florida (hot, humid) Zone 2B: Tucson, Arizona (hot, dry) Zone 3A: Atlanta, Georgia (warm, humid) Zone 3B: El Paso, Texas (warm, dry) Zone 3C: San Diego, California (warm, marine) Zone 4A: New York, New York (mixed, humid) Zone 4B: Albuquerque, New Mexico (mixed, dry) Zone 4C: Seattle, Washington (mixed, marine) Zone 5A: Buffalo, NY (cool, humid) Zone 5B: Denver, Colorado (cool, dry) Zone 5C: Port Angeles, Washington (cool, marine) Zone 6A: Rochester, Minnesota (cold, humid) Zone 6B: Great Falls, Montana (cold, dry) Zone 7: International Falls, Minnesota (very cold) Zone 8: Fairbanks, Alaska (subarctic	Selection of representative climates based on ASHRAE Standard 169-2013
Available fuel types	Gas, electricity	
Building Type (Principal Building Function)	**Multifamily**	
Building Prototype	**Mid-Rise Apartment**	
Form		
Total Floor Area (sq feet)	33,700 (152 ft x 55.5 ft)	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*
Building shape		
Aspect Ratio	2.74	
Number of Floors	4	90.1 Envelope Subcommittee
Window Fraction (Window-to-Wall Ratio)	South: 20.0%, East: 20.0%, North: 20.0%, West: 20.0% Average Total: 20.0%	Reference: Based on feedback from the National Multi-family Housing Council (NMHC)
Window Locations	See image	
Shading Geometry	None	
Azimuth	Non-directional	
Thermal Zoning	Each floor has 8 apartments except ground floor (7 apartments and 1 office with equivalent apartment area) Total 8 apartments per floor with corridor in center. Zone depth is 25 ft for each apartment from side walls and each apt is 25' x 38' (950 ft²). 	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*
Floor to floor height (ft)	10	
Floor to ceiling height (ft)	10 (No drop-in ceiling plenum is modeled)	
Glazing sill height (ft)	3 ft (4 ft high windows)	
Architecture		
Exterior walls		
Construction	Steel-frame walls (2X4 16IN o.c.) 0.4 in. stucco+5/8 in. gypsum board + wall Insulation+5/8 in. gypsum board	Reference: PNNL-16770: *Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York*. Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Vertical	
Roof		
Construction	Built-up roof: roof membrane+roof insulation+metal decking	Reference: PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards Residential; roofs, insulation entirely above deck	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Horizontal	

Roof		
Construction	Built-up roof: roof membrane+roof insulation+metal decking	Reference: PNNL-16770: Analysis of Energy Saving Impacts of ASHRAE 90.1-2004 for the State of New York Base Assembly from 90.1 Appendix A.
U-factor (Btu / h * ft² * °F) and/or R-value (h * ft² * °F / Btu)	Requirements in codes or standards Residential; roofs, insulation entirely above deck	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Tilts and orientations	Horizontal	
Window		
Dimensions	Based on window fraction, location, glazing sill height, floor area and aspect ratio	
Glass-Type and frame	Hypothetical window with a weighted U-factor and SHGC	
U-factor (Btu / h * ft² * °F)	Requirements in codes or standards	Applicable codes or standards
SHGC (all)	Residential; vertical glazing	
Visible transmittance		
Operable area	100%	
Skylight		
Dimensions	Not Modeled	
Glass-Type and frame	NA	
U-factor (Btu / h * ft² * °F)		
SHGC (all)		
Visible transmittance		
Foundation		
Foundation Type	Slab-on-grade floors (unheated)	
Construction	8" concrete slab poured directly on to the earth	
Slab on grade floor insulation level	Requirements in codes or standards	Applicable codes or standards
Dimensions	Based on floor area and aspect ratio	
Interior Partitions		
Construction	2 x 4 uninsulated stud wall	
Dimensions	Based on floor plan and floor-to-floor height	
Internal Mass	8 lbs/ft2 of floor area	Reference: Building America Research Benchmark
Air Barrier System		
Infiltration (ACH)	Peak infiltration: 0.2016 cfm/sf of above grade exterior wall surface area, adjusted by wind Additional infiltration through building entrance	Reference: PNNL-18898. *Infiltration Modeling Guidelines for Commercial Building Energy*
HVAC		
System Type		
Heating type	Gas furnace	90.1 Mechanical Subcommittee
Cooling type	Split system DX (1 per apt)	
Distribution and terminal units	Constant volume	
HVAC Sizing		
Air Conditioning	Autosized to design day	
Heating	Autosized to design day	
HVAC Efficiency		
Air Conditioning	Requirements in codes or standards Minimum equipment efficiency for electrically operated unitary and applied heat pumps	Applicable codes or standards
Heating		
HVAC Control		
Thermostat Setpoint	75°F Cooling/70°F Heating	
Thermostat Setback	No setback for apartments	
Supply air temperature	Maximum 113F, Minimum 55F	
Economizers	Requirements in codes or standards	Applicable codes or standards
Ventilation	ASHRAE Standard 62.1 or International Mechanical Code See under **Outdoor Air**	Applicable codes or standards
Demand Control Ventilation	Requirements in codes or standards	Applicable codes or standards
Energy Recovery	Requirements in codes or standards	Applicable codes or standards
Supply Fan		
Fan schedules	See under **Schedules**	
Supply Fan Total Efficiency (%)	Depending on the fan motor size	Requirements in applicable codes or standards for motor efficiency
Supply Fan Pressure Drop	Depending on the fan supply air cfm	
Service Water		
SWH type	Individual residential water heater with storage tank	
Fuel type	Electricity	Reference: RECS 2005
Thermal efficiency (%)	Requirements in codes or standards	Applicable codes or standards
Tank Volume (gal)	50	Reference: *PNNL-23269 Enhancements to ASHRAE Standard 90.1 Prototype Building Models*
Water temperature setpoint	140 F	
Water consumption	See under **Schedules**	Reference: Building America Research Benchmark

Internal Loads & Schedules		
Lighting		
Average power density (W/ft²)	Apartment units: See under **Lighting Load** for the detailed calculations. Corridor: 0.5 W/ft². When applicable, the power density is based on requirements in codes or standards.	Apartment: Building America Research Benchmark and applicable codes or standards
Schedule	See under **Schedules**	Reference: Building America Research Benchmark
Daylighting Controls	Requirements in codes or standards	Applicable codes or standards
Occupancy Sensors	Requirements in codes or standards	Applicable codes or standards
Plug load		
Average power density (W/ft²)	0.62 W/ft² daily peak per apartment, including all the home appliances See under **Plug Load** for the detailed calculations	Reference: Building America Research Benchmark
Schedule	See under **Schedules**	
Occupancy		
Average people	See under **Zone Summary**	Reference: Building America Research Benchmark
Schedule	See under **Schedules**	
Misc.		
Elevator		
Quantity	1	Reference: DOE Commercial Reference Building Models of the National Building Stock
Motor type	hydraulic	
Peak Motor Power (watts/elevator)	16,055	
Heat Gain to Building	Interior	
Peak Fan/lights Power (watts/elevator)	161.9	90.1 Mechanical Subcommittee, Elevator Working Group
Motor and fan/lights Schedules	See under **Schedules**	Reference: DOE Commercial Reference Building Models of the National
Exterior Lighting		
Peak Power (W)	Based on design assumptions for façade, parking lot, entrance, etc. and requirements in codes or standards	Applicable codes or standards
Schedule	See under **Schedules** and control requirements in codes or standards	Applicable codes or standards

Refer to https://www.energycodes.gov/prototype-building-models for further details.

D.2.1 Existing Multifamily Modeling

For modeling existing multifamily (MF) apartment buildings, PNNL used the midrise apartment DOE commercial building code prototype model, which represents an ASHRAE 90.1-2019 code-compliant building; however, the prototype is used as a template to capture representative sample of the existing building stock in order to analyze their range of performance and impact of resilience and efficiency measures. The prototype characteristics, outlined in Table D-3, provided a starting place for identifying model input values to vary as part of the stock characterization. Based on the list, the selected parameters excluded: (1) parameters not required by building energy codes (e.g., building geometry and operation schedules), (2) parameters less impactful on apartment energy use as indicated by published research (e.g., building foundation measures such as slab-on-grade floor insulation level), and (3) advanced control strategies (e.g., daylighting control and occupancy sensors). Excluding these categories of parameters resulted in eight input variables being selected, including: exterior wall and roof (R-value); windows (U-value and SHGC); air barrier system impacting infiltration rate, HVAC system efficiency; and lighting (average power density).

After identifying the analysis input variables, uncertainties were identified consisting of minimum and maximum values, and their anticipated distribution curve. The sources used to identify uncertainty include the 2015 RECS, ASHRAE Standard 90.1, DOE's Commercial Reference Building Models of the National Building Stock, Infiltration Modeling Guidelines for Commercial Building Energy Analysis, and ResStock. Also, the distribution of the value ranges for a given variable was based on RECS 2015 data if displayed. Otherwise, a normal distribution was assumed. Table D-4 provides the uncertainties of selected input variables for existing MF.

Table D-4. Uncertainties of Selected Input Variables for Existing Multifamily

No.	Item	Unit	CZ 2A (Houston, TX and Tampa, FL)			CZ 6A (Minneapolis, MN)		
			Min.	Max.	Dist.	Min.	Max.	Dist.
1	Exterior walls—Insulation R-value	h-ft2-F/Btu	0.000	13.446	Normal	0.000	18.229	Normal
2	Roof—Insulation R-value	h-ft2-F/Btu	0.000	24.524	Normal	0.000	30.133	Normal
3	Window—U-factor	Btu/h-ft2-F	0.487	1.232	Uniform	0.360	0.620	Uniform
4	Window—SHGC (all)	-	0.245	0.540	Uniform	0.370	0.410	Uniform
5	Air Barrier System—Infiltration	cfm/ft2	0.009	0.202	Uniform	0.009	0.202	Uniform
6	HVAC Efficiency—Air Conditioning	-	2.867	4.311	Uniform	2.867	4.311	Uniform
7	HVAC Efficiency—Heating	-	0.780	0.810	Uniform	0.780	0.810	Uniform
8	Lighting—Average Power Density	W/ft2	0.706	2.344	Uniform	0.706	2.344	Uniform

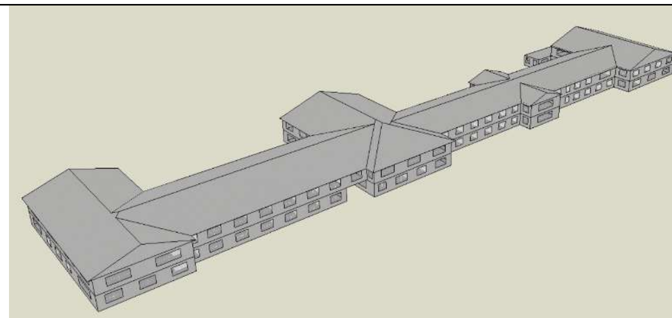
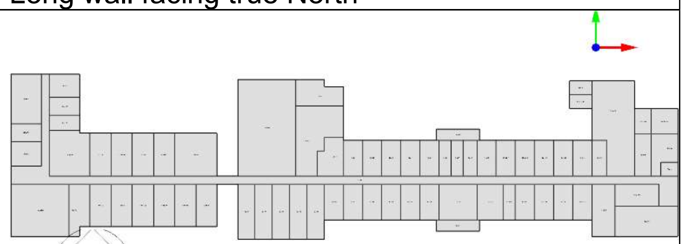
D.2.2 Existing Assisted Living Facility Modeling

The assisted living facility (ALF) case study is based on the real story of an ALF in Houston. The actual ALF was built in 2018, and during the 2021 Houston snowstorm, 40 residents were evacuated due to the power loss and the lack of on-site generators. The ALF model geometry was first created and modified in DesignBuilder, an advanced user interface to EnergyPlus that provides access to most required simulation functions, including building fabric, thermal mass, glazing, shading, renewables, HVAC, and financial analysis. It contains default envelope constructions, occupancy, and internal loads that meet the selected energy codes and standards. The model was then outputted to EnergyPlus 9.6 for further fine tuning and adjustments. EnergyPlus is a free, open-source whole-building simulation program that can model not only energy and water use of the building, but other resilience performance as well.

Since the building footprint and drawings are not available, Lawrence Berkeley National Laboratory adopted a previous Florida nursing home model, adjusted the geometry to match the ALF total floor area, and changed the baseline input according to ASHRAE 91.1 2013, CZ 2A. The detailed inputs are listed in Table D-5.

Table D-5. ALF Building Details

	Item	Description	Data Source
GENERAL			
	Vintage	2018	Building Manager
	Location	Houston	
	Available Fuel Types	Electricity, Natural Gas	
	Building Type	Commercial, ALF	
	Building Prototype	Nursing home	
FORM			
	Total Floor Area (sqft)	116,134	Building Manager

	Building Shape		
	Number of Floors	2	Building Manager
	Window Fraction	27.2% on all facades	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Window Location	All facades	
	Shading Geometry	None	
	Orientation	Long wall facing true North	
	Thermal Zoning		
	Floor-to-Floor Height (ft)	9	
	Floor to Ceiling Height (ft)	9	
	Glazing Sill Height (ft)	2.7	
ARCHITECTURE			
	Exterior Wall		
	Construction	Steel-framed, non-residential wall, R-13+R-3.8 c.i.	DesignBuilder
	U-Factor (Btu/h-ft2-F)	0.084	ASHRAE 90.1-2013, CZ2A
	Dimension	Based on floor area and aspect ratio	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Tilt and Orientation	Vertical	
	Roof		
	Construction	Semi-exterior, insulation entirely above deck, R-38	DesignBuilder
	U-Factor (Btu/h-ft2-F)	0.053	ASHRAE 90.1-2013, CZ2A

	Dimension	Based on floor area and aspect ratio	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Tilts and Orientations	30 ° slope	
	Window		
	Dimensions	Based on window fraction, location, glazing sill height	
	Glass Type and Frame	Metal framing	
	U-Factor (Btu/h-ft2-F)	0.751	ASHRAE 90.1-2013, CZ 2A
	SHGC	0.25	
	Visible Transmittance	0.564	
	Operable Area	100%	
	Foundation		
	Foundation Type	Slab-on-grade, unheated	DesignBuilder
	Construction	8” concrete slab poured directly on earth	
	Insulation Level	F-factor=0.73 Btu/h-ft2-F	ASHRAE 90.1-2013, CZ2A
	Dimension	Based on floor area and aspect ratio	
	Interior Partition		
	Construction	2*1 in. gypsum plasterboard with 4 in. cavity	DesignBuilder
	Dimension	Based on floor plan and floor-to-floor height	
	Air Barrier System		
	Infiltration	0.32 ACH	ASHRAE 90.1-2013, CZ2A
HVAC			
	System Type		
	Heating Type	Gas boiler	Building Manager
	Cooling Type	PTAC for bedrooms, electric chiller for common areas	
	Distribution and Terminal Units	PTAC for bedrooms, single duct VAV reheat for common areas	
	HVAC Sizing		
	Air Conditioning	Autosized to design day	
	Heating		
	HVAC Efficiency		
	Air Conditioning	Requirements in codes or standards	ASHRAE 90.1-2013, CZ2A
	Heating		
	HVAC Control		

	Thermostat Setpoint	Cooling 70F, heating 75F	Building Manager
	Thermostat Setback	No setbacks	
	Economizers	None	
	Ventilation	ASHRAE 62.1 or International Mechanical Code	
	Demand Control Ventilation	None	Building Manager
	Energy Recovery	None	
	Supply Fan		
	Fan Schedules	On 24/7	Building Manager
	Supply Fan Total Efficiency	0.7	Reference: K. Sun et al., Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home, 2020
	Supply Fan Pressure Drop	0.4 inH2O	
INTERNAL LOADS			
	Lighting		
	Average power density (W/ft2)	0.88	Building Manager
	Schedule	ASHRAE 90.1 prototype schedules	
	Daylighting Control	None	
	Occupancy Sensor	None	
	Plug Load		
	Average power density (W/ft2)	1.13 for bedrooms; other based on ASHRAE 90.1 default loads, depends on space use	DesignBuilder, ASHRAE 90.1-2013, CZ2A
	Schedule	ASHRAE 90.1 prototype schedules	
	Occupancy		
	Average People	0.006 for bedrooms; other based on ASHRAE 90.1 default people, depends on space use	DesignBuilder, ASHRAE 90.1-2013, CZ2A
	Schedule	ASHRAE 90.1 prototype schedules	

Since the utility bill was not available for the real building, the annual on-site EUI of the baseline model was benchmarked with the Building Performance Database. According to the database, the median annual site EUI of nursing homes in Houston built after 2016 is 54 kBtu/sqft, and the baseline model of this new ALF has an annual on-site EUI of 50 kBtu/sqft, which is in a reasonable range. One building from the database with a similar floor area, around 116,000 sqft, has an annual site EUI of 44 kBtu/sqft, further confirming the credibility of the baseline model.

Appendix E – Existing Single Family Stock Characterization

The research team used the NREL ResStock tool to characterize and analyze the existing, detached single-family (SF) housing stock for the study. ResStock is a physics-simulation type of generating statistically representative households (Langevin et al., 2019). The tool considers the diversity in the age, size, construction practices, installed equipment, appliances, and resident behavior of the housing stock across U.S. geographic regions. ResStock enables a new approach to large-scale residential energy analysis by combining large public and private data sources, statistical sampling, and detailed sub-hourly building simulations. The tool generates a group of statistically representative building simulation models from a housing parameter space derived from existing residential stock data. For each of the six locations considered in the study, 1,000 building simulations are generated using this methodology.

Model outputs include both annual and hourly or sub-hourly timeseries energy use, including electricity and on-site natural gas, propane, and fuel oil use, as well as HVAC system capacities and the hours the heating and cooling setpoints are not met. For this project, outputs also include timeseries indoor zone dry-bulb temperature, mean radiant temperature, relative humidity, and derivative outputs specific to passive survivability (PS), such as standard effective temperature (SET) and heat index (HI).

The building simulations use actual meteorological year weather data as inputs into the EnergyPlus model to reflect the extreme weather events in this study. Figure E-1 shows a violin plot of the electricity consumption distribution for each building from each city generated by the ResStock analysis tool over a month in the wintertime broken down by southern cities (Atlanta, Houston, and Los Angeles) and northern cities (Portland, Minneapolis/St. Paul, and Detroit). Note that all cities have high-consuming houses that stretch the neck of the violin plot to relatively large consumption values. However, these are outliers in the building simulation set because they are outside of the lower and upper hinges of the boxplot within the violins. The lower and upper hinges reflect the first and third quartile values of electricity consumption within each city's set of building simulations.

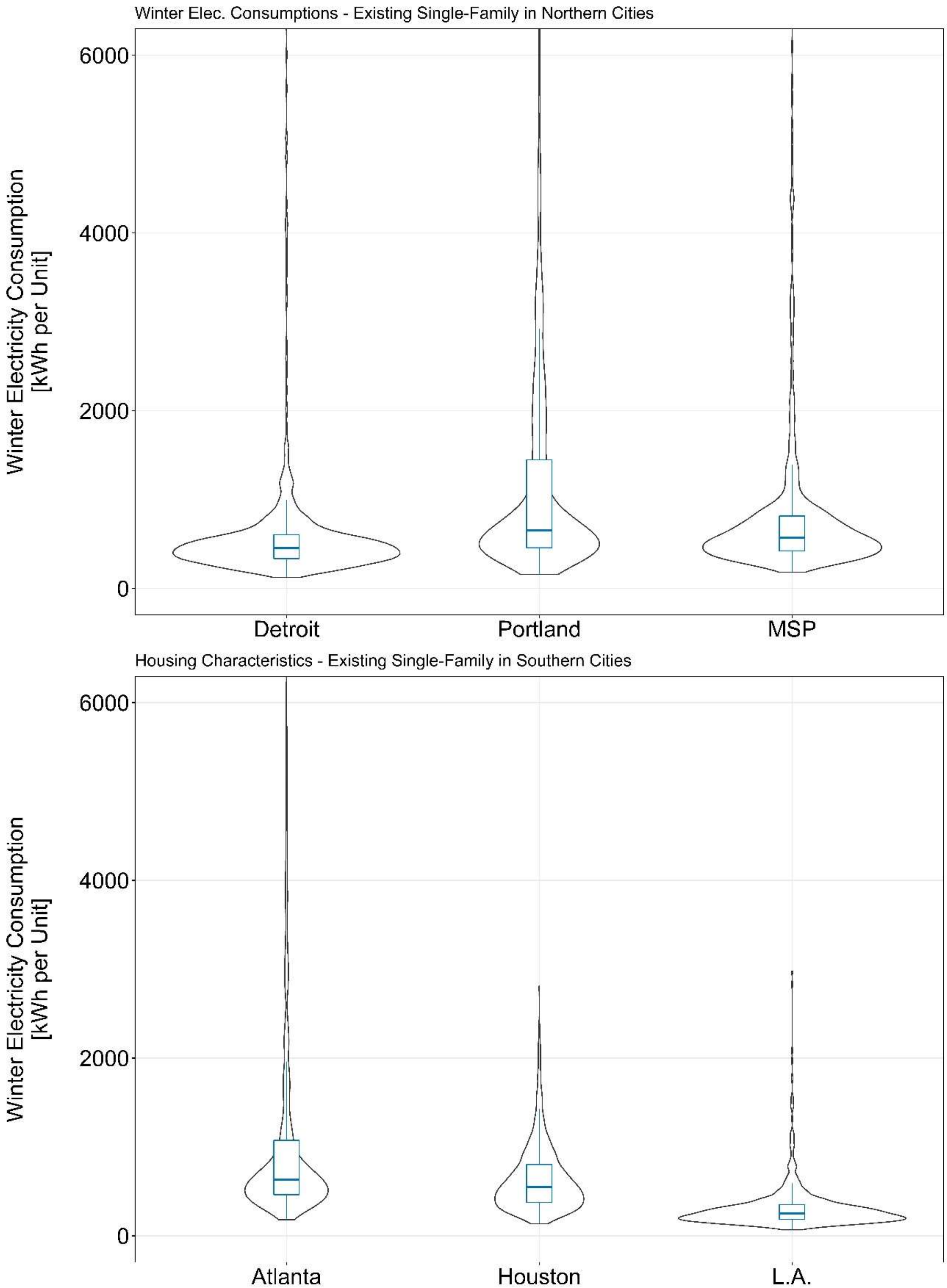


Figure E-1. Violin and Boxplots for Winter Electricity Consumption of the Six Locations in this Study

All cities have high-consuming houses that stretch the neck of the violin plot to relatively large consumption values. However, these are outliers in the building simulation set because they are outside of the lower and upper hinges of the boxplot within the violins. The lower and upper hinges reflect the first and third quartile values of electricity consumption within each city's set of building simulations. The horizontal bar within the boxplots reflects the median consumption building. The y-axis is limited to 6,000 kWh to better show the behavior of the vast majority of buildings, compared to a few outliers with consumption > 6,000 kWh.

Outages for the existing SF household analysis occur at midnight of the start of the outage and run for 48 hours for short duration events and 168 hours (7 days) for long-duration events. During the outage electricity and other fuels (e.g., fuel oil, natural gas, etc.) are not consumed. During the outage, resilience metrics like SET, SET degree hours, HI, and indoor temperature are calculated analyses, only the critical loads of HVAC systems and refrigeration were allowed to consume energy. During these partial outages, temperature setpoints of buildings were offset by 5°F (i.e., temperature setpoints were increased by 5°F during heat events and decreased by 5°F during cold events) by the energy models. During partial outage

E.1 Results and Analysis

Results are provided for mitigation measures of existing SF building stock based on the analysis conducted using ResStock.

E.1.1 Mitigation Measures of Existing Single-Family Households

For existing SF households, two mitigation measures were applied to all 1,000 buildings in each location and separately simulated. These two mitigation measures reflect the current 2021 IECC building code and 2021 Passive House Institute U.S. (PHIUS) requirements. Information about which energy-efficiency improvements these mitigation measures entail can be found in Appendix C.

To realize how these mitigation measures affect overall energy consumption, Figure E-2 shows the same violin plot for Atlanta seen in Figure E-1 but with the addition of violin plots for the buildings after the application of the 2021 IECC and PHIUS mitigation measures. Note the reduction in outlying, high-consuming households, and the decrease in the median household consumption across both mitigation measures as well as the decrease in whisker length.

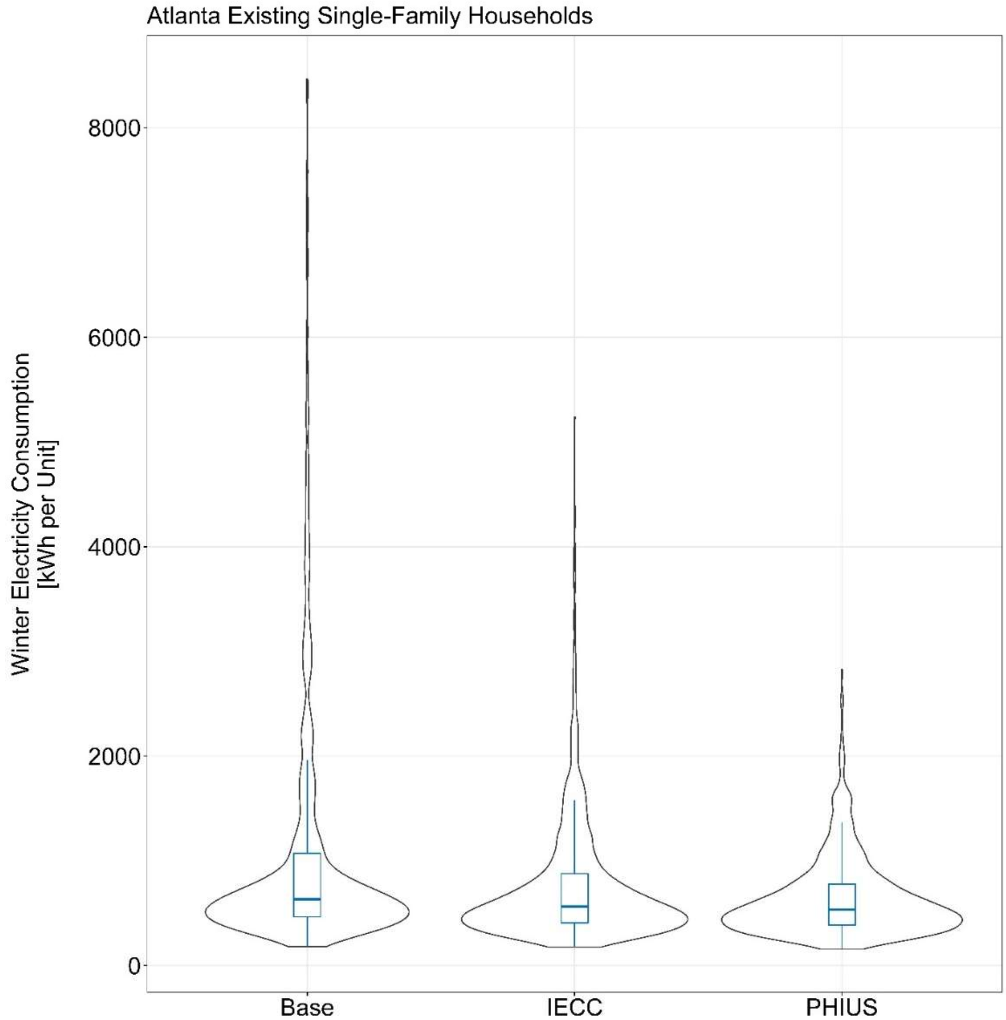


Figure E-2. Violin and Boxplot for Atlanta Households in the Winter for Base Case and two Mitigation Measures

The following results are based on a statistical sample of 1,000 SF homes for each city. Figure E-3 displays the average degree hours outside of SET per day for each city, event, and upgrade. The comfort boundaries are 50°F for cold events and 86°F for heat events. Cold events have a much higher number of hours outside of SET due to the much larger difference between ambient temperature and the SET threshold during cold events than during heat events.

Significant variability in exposure and vulnerability exists between locations. For example, due to their warmer climates, Houston and Los Angeles have a significantly lower number of hours outside of safe temperatures during cold events than other cities in this study. Older homes are more likely to experience unsafe temperatures than more modern homes, while upgraded or retrofitted homes are less likely to experience unsafe temperatures than baseline homes. Cities that are less likely to experience extreme cold or heat may be less prepared for such events, which increases their vulnerability. As the 2021 winter storm tragically demonstrated however, warm-climate cities like Houston can still experience considerable costs from extreme temperatures coinciding with power outages.

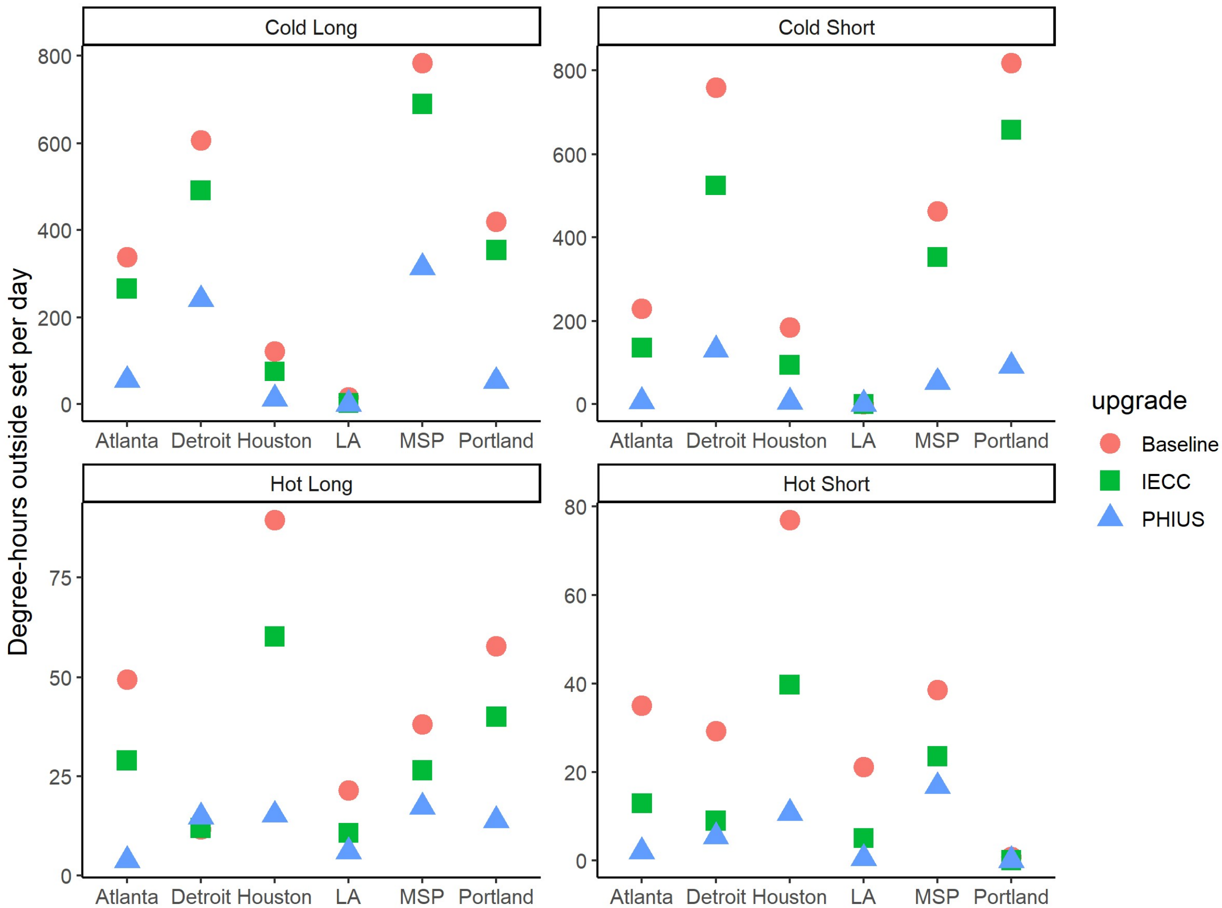


Figure E-3. Average Degree Hours Outside SET per Day

Figure E-4 displays the average number of hours the indoor HI is in each threshold category, averaged across all buildings, during a heatwave that coincides with a one-week outage. Building upgrades have a significant impact on reducing ‘extreme caution’ and ‘danger hours’, particularly in locations such as Houston where extreme temperatures are more likely.

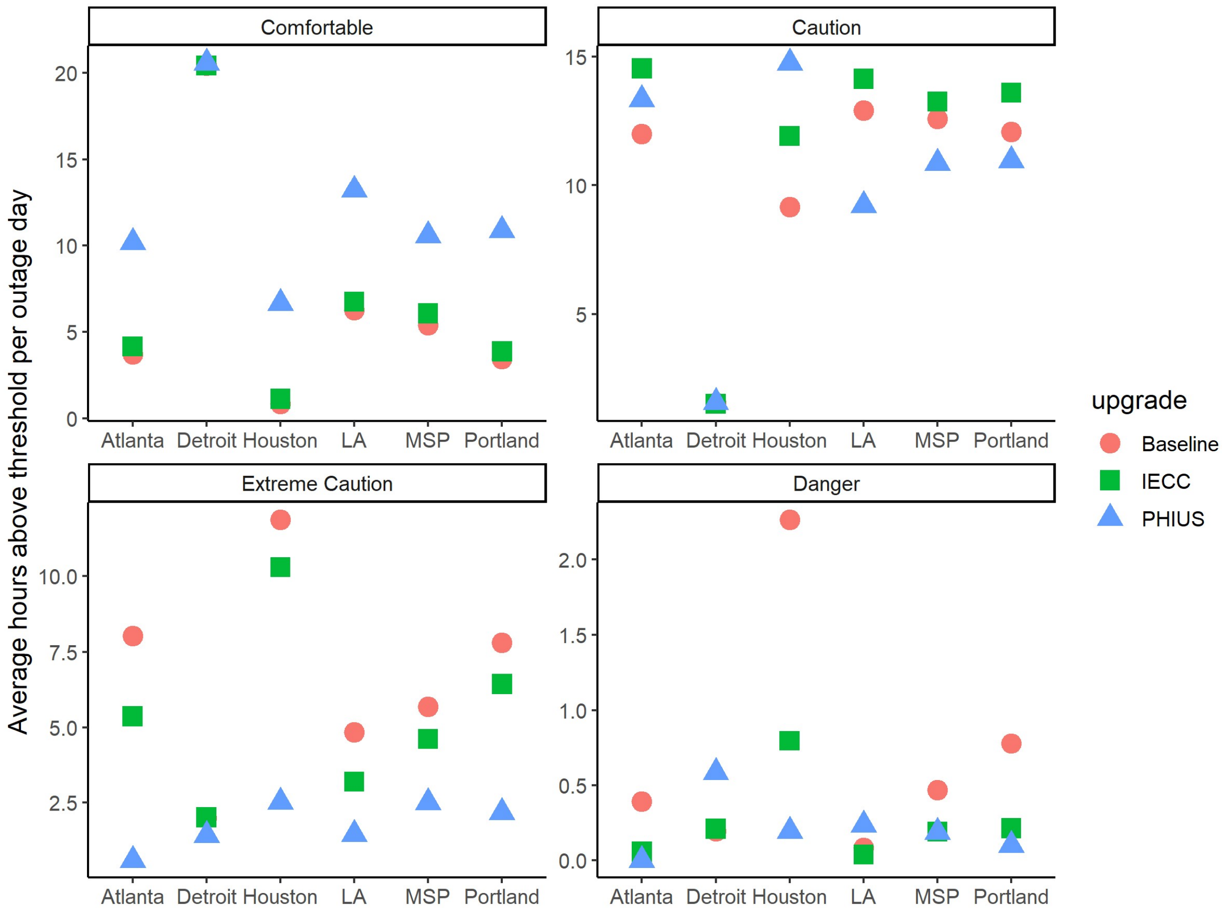


Figure E-4. Long Outage Average Hours Above Thresholds per Outage Day

Figure E-5 displays the average daily degree hours above the SET temperature threshold of 86°F SET during a one-week heatwave in Minneapolis/St. Paul. LEED certifies a building as providing for PS if the temperature does not exceed 216 SET hours above 86°F SET over a week-long outage, which averages to a threshold of 30.9 SET hours per day. On average, older vintages do not meet PS with IECC upgrades and newer vintages meet the threshold without upgrades. Vintages between 1960-1980 do benefit from IECC upgrades in terms of meeting the PS threshold. PHIUS upgrades meet the PS criteria regardless of during heatwaves.

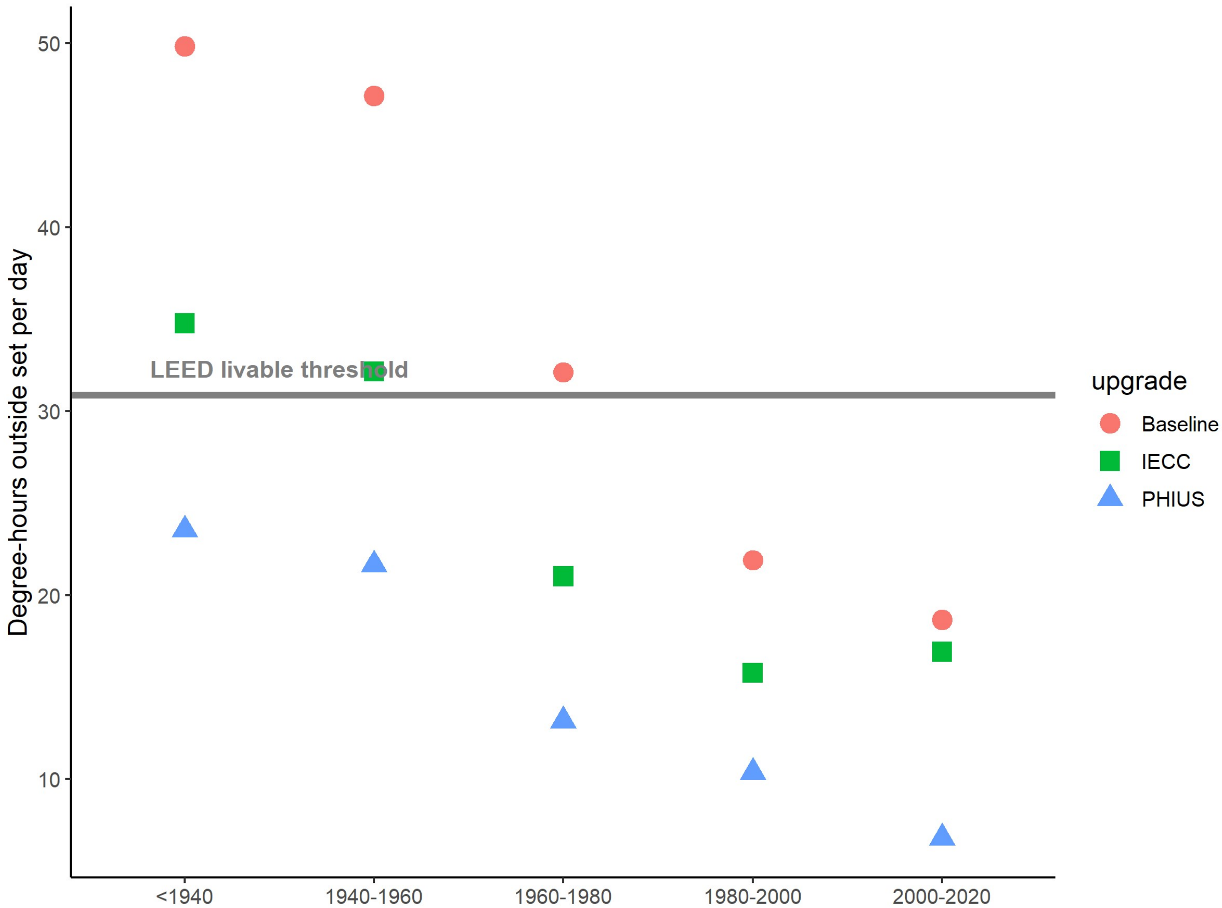


Figure E-5. Average Daily Degree Hours Above the Temperature Threshold of 86°F SET During a One-Week Heatwave in Minneapolis-Saint Paul

These results indicate that PS during heatwaves is strongly influenced by vintage and upgrade types. The optimal upgrade in one location and with one building type may be insufficient or excessive in another location. Identifying which upgrades are necessary to provide sufficient resilience for each building can maximize the impacts of building upgrades given a limited budget.

Figure E-6 and Figure E-7 display the HI for the 7-day heatwave and outage for Atlanta and Portland. The bold lines represent the average value by vintage and upgrade while the shaded area denotes the 10% and 90% confidence interval. Without upgrades, indoor temperatures can spike to dangerous levels for some hours in some buildings. IECC upgrades remove almost all dangerous outage hours and significantly reduce temperature variability for many building types, but temperatures still reach unsafe levels (extreme caution) for many hours during the event. The PHIUS upgrade significantly reduces, and for some buildings eliminates, hours of danger or extreme caution. When considering building upgrades, planners may want to weigh the value of decreasing dangerous temperatures versus reducing temperatures that are uncomfortable but less dangerous.

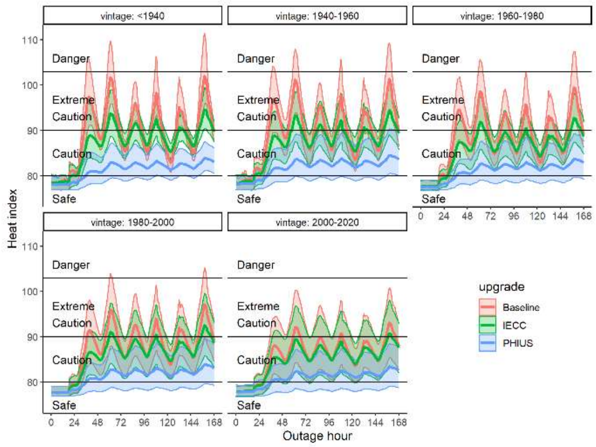


Figure E-6. HI for Atlanta including 10-90 CI

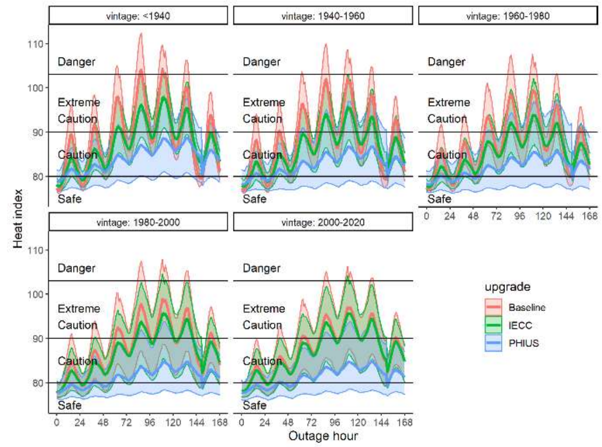


Figure E-7. HI for Portland including 10-90 CI

E.1.2 Cold Event Results

Figure E-8 shows the number of hours per event day, averaged over all buildings, that the temperature falls below specified thresholds. The IECC upgrade significantly reduces the chance of exceeding the extreme pipe freeing threshold for cold locations, while the more extensive PHIUS upgrade significantly reduces the chance of temperatures falling below freezing, which in turn significantly reduces the chance of building damage.

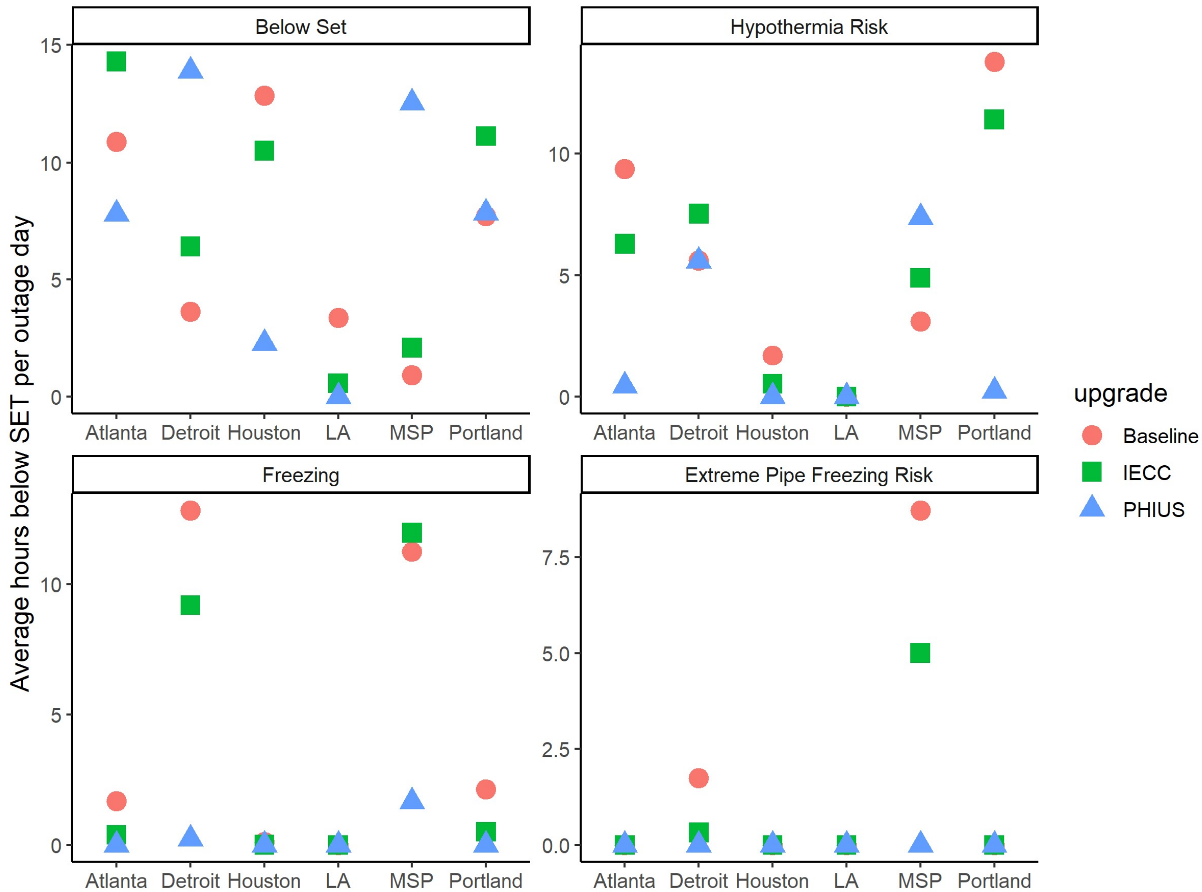


Figure E-8. Number of Hours Per Event Day, Averaged Over All Buildings, that the Temperature Falls Below Specified Thresholds

Figure E-9 and Figure E-9 display a long-duration (e.g., 7 days) cold event in Houston and Minneapolis, respectively. The bold line indicates average hourly temperature by vintage with the shaded region indicating the 10-90% confidence interval. Many homes in Houston cross the hypothermia risk threshold and some older vintage homes cross the freezing risk threshold toward the end of the event, which exposes them to the risk of burst pipes. While newer homes are less likely to drop below hypothermia risk or freezing during the outage, newer homes with less insulation are still at risk. IECC upgrades significantly reduces the chance of indoor temperatures falling below the level of hypothermia risk while PHIUS upgrades eliminates this chance.

In Minneapolis, significantly colder temperatures lead to indoor temperatures falling below freezing for all baseline buildings. IECC upgrades extend the time to freezing for older buildings but seem to have little impact on newer vintages. PHIUS significantly extends the time to freezing and can prevent freezing altogether for some buildings. Though building upgrades may not prevent a building from freezing during extended outages, increasing the time to freezing has significant risk reduction benefits during most outage events.

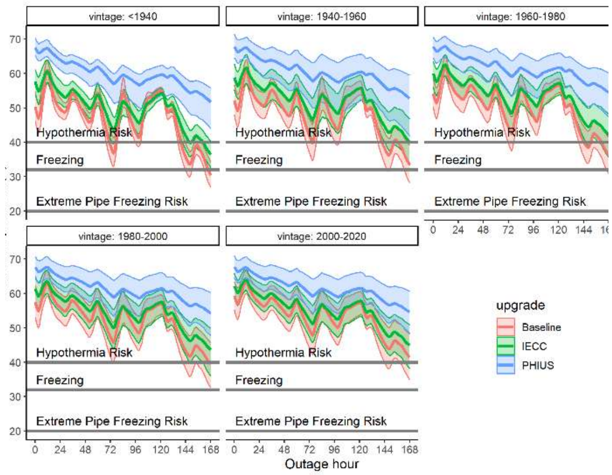


Figure E-9. 7-day Cold Event, Houston

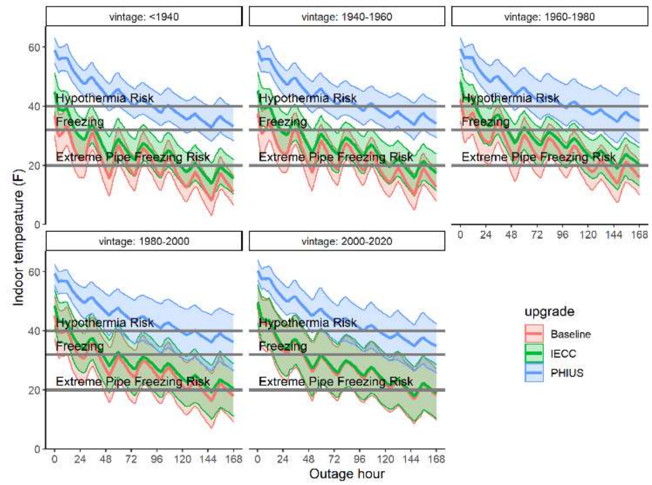


Figure E-10. 7-day Cold Event, Minneapolis/St. Paul

E.2 Summary and Discussion of Results

IECC upgrades significantly reduce extreme pipe freezing, while more extensive PHIUS upgrades reduce potential building damages. Older vintage homes provide a greater opportunity for thermal resilience and passive resilience incorporation through building code improvements and upgrades. Focusing on upgrading R-values and U-values in home built prior to 1940 will provide the greatest energy efficiency and resilience benefits to end users and communities with older building stock.

The case study using ResStock revealed a few opportunities for incorporating thermal resilience and PS. The IECC upgrade significantly reduces the chance of exceeding the extreme pipe freeing threshold for cold locations, while the more extensive PHIUS upgrade significantly reduces the chance of temperatures falling below freezing, which in turn significantly reduces the chance of building damage. Older vintage homes generally have less insulation in the building envelope and a leakier envelope compared to newer (2000-2020) vintage homes. Older vintage homes consume more energy annually for heating and cooling, therefore focusing on upgrading R-values and U-values in the building envelope of older homes (i.e., <1940) will be beneficial for end users in terms of reducing energy consumption, but also enhancing indoor SET during extreme events. Although the energy-efficiency requirements of newer building energy codes have many benefits, retrofitting older vintage homes will have the greatest benefit. Retrofitting older homes to newer codes and standards for resilience purposes only may not have the return on investment that homeowners and communities require (i.e., the costs will outweigh the benefits). Understanding the role that energy efficiency plays in PS and sheltering in place, however, could allow community planners, the Department of Housing and Urban Development, and other agencies to focus on making improvements in older vintage homes to enhance resilience in homes at greatest risk. Similar to the results of the ALF case study, certain EEMs, such as making building envelope airtight, may have conflicting impacts on building thermal resilience (e.g., reduces heat loss during cold weather but prevents heat loss from buildings during hot weather without power). 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 extreme weather conditions. Low-cost and behavioral related measures such as natural ventilation should be encouraged (e.g., awareness, behavior change, training) and enabled through operable windows, shading, etc. in the building design and occupant behavior. This is an area needing further research. In general, the co-benefits between energy efficiency and thermal resilience of SF homes should be considered and addressed through building energy codes and policy as the building industry is moving toward carbon neutrality and climate resilience.

Appendix F – Occupant Exposure Results

Table F-1. SET Degree Hours during Extreme Events in New Single-Family Buildings

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours* Historic Code IECC 2006	SET Degree Hours* Current Code IECC 2021	SET Degree Hours* Beyond Code PHIUS
Houston, TX (2A)	Long Cold	371	363	347
	Short Cold	228	230	227
	Long Heat	451	290	197
	Short Heat	228	182	155
Atlanta, GA (3A)	Long Cold	1,572	1,536	1,509
	Short Cold	270	232	213
	Long Heat	328	132	50
	Short Heat	92	46	25
Los Angeles, CA (3B)	Long Cold	90	70	54
	Short Cold	-	-	-
	Long Heat	34	1.7	-
	Short Heat	20	2.2	-
Portland, OR (4C)	Long Cold	1,366	1,328	1,289
	Short Cold	1.3	0.4	-
	Long Heat	195	149	101
	Short Heat	-	-	-
Detroit, MI (5A)	Long Cold	1,544	1,430	1,212
	Short Cold	706	650	538
	Long Heat	90	69	44
	Short Heat	55	44	34
Minneapolis/ St. Paul, MN (6A)	Long Cold	2,049	1,895	1,594
	Short Cold	487	467	418
	Long Heat	206	180	136
	Short Heat	90	84	71

* Cooling hours > 86°F, Heating hours < 54°F

Table F-2. SET Degree Hours during Extreme Events in Existing Single-Family Buildings

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours*								
		Existing Stock			Current Code IECC 2021			Beyond Code PHIUS		
		5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	Long Cold	1,571	749	136	1,139	222	0.3	634	-	-
	Short Cold	632	295	28	302	32	-	52	-	-
	Long Heat	1,188	600	56	896	141	-	651	-	-
	Short Heat	323	120	0.03	144	7	-	47	-	-
Atlanta, GA (3A)	Long Cold	3,468	2,558	1,047	2,754	1,610	112	1,720	200	-
	Short Cold	714	410	56	309	94	-	61	-	-
	Long Heat	981	438	1.4	696	59	-	308	-	-
	Short Heat	206	36	-	36	-	-	0.8	-	-
Los Angeles, CA (3B)	Long Cold	360	87	-	20	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	423	100	-	349	-	-	95	-	-
	Short Heat	127	25	-	31	-	-	-	-	-
Portland, OR (4C)	Long Cold	3,687	2,963	1,692	2,492	1,849	379	1,234	237	-
	Short Cold	598	366	77	222	89	-	35	-	-
	Long Heat	857	371	3	1,014	319	-	569	-	-
	Short Heat	11	-	-	-	-	-	-	-	-
Detroit, MI (5A)	Long Cold	5,227	4,248	2,547	4,479	3,020	1,484	2,589	1,778	637
	Short Cold	1,671	1,291	637	1,142	670	300	358	211	30
	Long Heat	687	223	-	686	53	-	670	0.3	-
	Short Heat	168	30	-	127	0.9	-	53	-	-
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,746	5,397	3,575	5,094	3,699	1,967	3,228	2,190	912
	Short Cold	1,151	802	384	503	293	110	203	61	-
	Long Heat	714	215	-	681	66	-	609	5	-
	Short Heat	247	40	-	255	0.2	-	209	-	-

* Cooling hours > 86°F, Heating hours < 54°F

Table F-3. SET Degree Hours during Extreme Events in New Multifamily Buildings

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours*								
		Middle Floor Zones			Top Floor Zones			Combined Floor Zones		
		Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	-	-	-	483	273	84	483	273	84
	Short Cold	-	-	-	207	80	-	207	80	-
	Long Heat	197	133	110	613	509	500	810	642	609
	Short Heat	-	-	-	206	126	83	206	126	83
Atlanta, GA (3A)	Long Cold	98	57	-	2,164	1,964	1,203	2,262	2,020	1,203
	Short Cold	-	-	-	209	126	0.1	209	126	0.1
	Long Heat	-	-	-	355	169	98	355	169	98
	Short Heat	-	-	-	79	30	16	79	30	16
Los Angeles, CA (3B)	Long Cold	-	-	-	-	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	-	-	-	61	9.4	3.3	61	9.4	3.3
	Short Heat	-	-	-	11	0.7	-	11	0.7	-
Portland, OR (4C)	Long Cold	255	95	-	2,282	1,850	1,177	2,537	1,945	1,177
	Short Cold	-	-	-	53	3.7	-	53	3.7	-
	Long Heat	-	-	-	276	212	154	276	212	154
	Short Heat	-	-	-	-	-	-	-	-	-
Detroit, MI (5A)	Long Cold	573	288	-	3,297	2,599	1,524	3,870	2,887	1,524
	Short Cold	45	1.3	-	982	673	290	1,027	674	290
	Long Heat	-	-	-	126	105	99	126	105	99
	Short Heat	-	-	-	54	36	26	54	36	26
Minneapolis/ St. Paul, MN (6A)	Long Cold	802	412	0.4	4,719	3,731	2,178	5,521	4,142	2,178
	Short Cold	-	-	-	485	274	33	485	274	33
	Long Heat	21	19	16	290	255	232	311	274	248
	Short Heat	-	-	-	89	66	45	89	66	45

* Cooling hours > 86°F, Heating hours < 54°F

Table F-4. SET Degree Hours during Extreme Events in the Middle Floor Zones of Existing Multifamily Buildings

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours*								
		Middle Floor Zones								
		Historic Code 90.1 2004			Current Code 90.1 2019			Beyond Code PHIUS		
		5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	Long Cold	-	-	-	-	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	254	347	430	127	132	139	108	113	119
	Short Heat	-	1.3	9	-	-	-	-	-	-
Atlanta, GA (3A)	Long Cold	132	23	0.02	4.8	2.7	1.0	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	0.4	15	49	-	-	-	-	-	-
	Short Heat	-	-	-	-	-	-	-	-	-
Los Angeles, CA (3B)	Long Cold	-	-	-	-	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	-	-	-	-	-	-	-	-	-
	Short Heat	-	-	-	-	-	-	-	-	-
Portland, OR (4C)	Long Cold	293	186	68	3.4	1.6	0.2	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	-	2.1	10	-	-	-	-	-	-
	Short Heat	-	-	-	-	-	-	-	-	-
Detroit, MI (5A)	Long Cold	917	705	445	154	142	131	-	-	-
	Short Cold	67	21	1.6	-	-	-	-	-	-
	Long Heat	-	-	-	-	-	-	-	-	-
	Short Heat	-	-	-	-	-	-	-	-	-
Minneapolis/ St. Paul, MN (6A)	Long Cold	1,126	885	577	247	236	222	10	6	3
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	35	54	72	17.5	17.9	18.4	14.4	14.7	15.0
	Short Heat	-	-	-	-	-	-	-	-	-

* Cooling hours > 86°F, Heating hours < 54°F

Table F-5. SET Degree Hours during Extreme Events in the Top Floor Zones of Existing Multifamily Buildings

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours*								
		Top Floor Zones								
		Historic Code 90.1 2004			Current Code 90.1 2019			Beyond Code PHIUS		
		5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	Long Cold	972	829	619	204	200	179	88	85	64
	Short Cold	387	316	226	32	24	13	-	-	-
	Long Heat	893	1,123	1,309	598	601	611	533	535	545
	Short Heat	346	416	463	151	155	159	97	102	106
Atlanta, GA (3A)	Long Cold	2,843	2,609	2,287	1,701	1,688	1,597	1,216	1,197	1,057
	Short Cold	575	498	377	76	71	54	1.04	0.20	-
	Long Heat	654	855	989	216	217	220	116	117	119
	Short Heat	176	245	292	39	40	42	19	20	21
Los Angeles, CA (3B)	Long Cold	253	169	57	-	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	241	402	532	20	21	23	5.25	5.32	5.52
	Short Heat	76	134	180	2.24	2.30	2.38	-	-	-
Portland, OR (4C)	Long Cold	3,118	2,940	2,627	1,642	1,627	1,521	1,237	1,219	1,076
	Short Cold	461	385	253	1.06	0.59	0.02	-	-	-
	Long Heat	539	708	840	211	212	213	149	150	150
	Short Heat	23	56	88	-	-	-	-	-	-
Detroit, MI (5A)	Long Cold	4,612	4,397	4,004	2,492	2,476	2,400	1,623	1,602	1,489
	Short Cold	1,627	1,490	1,245	531	521	465	304	292	229
	Long Heat	371	560	696	107	108	113	85	88	94
	Short Heat	147	210	254	34.5	35.2	36.1	24.2	25.0	25.9
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,247	5,984	5,515	3,552	3,533	3,425	2,328	2,298	2,131
	Short Cold	1,011	905	722	216	210	187	51	43	21
	Long Heat	552	750	893	256	257	261	225	226	230
	Short Heat	199	263	308	64.6	66.1	67.5	42.3	44.1	46.1

* Cooling hours > 86°F, Heating hours < 54°F

Table F-6. SET Degree Hours during Extreme Events in Existing Multifamily Buildings (Combined Middle and Top Floor Zones)

Values shaded in yellow are above the 216-day habitability threshold.

Location (Climate Zone)	Event	SET Degree Hours*								
		Combined Middle and Top Floor Zones								
		Historic Code 90.1 2004			Current Code 90.1 2019			Beyond Code PHIUS		
		5%	Median	95%	5%	Median	95%	5%	Median	95%
Houston, TX (2A)	Long Cold	972	829	619	204	200	179	88	85	64
	Short Cold	387	316	226	32	24	13	-	-	-
	Long Heat	1,147	1,470	1,740	725	733	749	640	648	664
	Short Heat	346	417	472	151	155	159	97	102	106
Atlanta, GA (3A)	Long Cold	2,975	2,632	2,287	1,705.7	1,690	1,598	1,216	1,197	1,057
	Short Cold	575	498	377	76	71	54	1.04	0.20	-
	Long Heat	655	870	1,038	216	217	220	116	117	119
	Short Heat	176	245	292	39	40	42	19	20	21
Los Angeles, CA (3B)	Long Cold	253	169	57	-	-	-	-	-	-
	Short Cold	-	-	-	-	-	-	-	-	-
	Long Heat	241	402	532	20	21	23	5.25	5.32	5.52
	Short Heat	76	134	180	2.24	2.30	2.38	-	-	-
Portland, OR (4C)	Long Cold	3,411	3,126	2,695	1,645	1,629	1,521	1,237	1,219	1,076
	Short Cold	461	385	253	1.06	0.59	0.02	-	-	-
	Long Heat	539	710	850	211	212	213	149	150	150
	Short Heat	23	56	88	-	-	-	-	-	-
Detroit, MI (5A)	Long Cold	5,529	5,102	4,450	2,646	2,618	2,530	1,623	1,602	1,489
	Short Cold	1,694	1,511	1,247	531	521	465	304	292	229
	Long Heat	371	560	696	107	108	113	85	88	94
	Short Heat	147	210	254	34.5	35.2	36.1	24.2	25.0	25.9
Minneapolis/ St. Paul, MN (6A)	Long Cold	7,373	6,869	6,092	3,799	3,768	3,647	2,338	2,304	2,134
	Short Cold	1,011	905	722	216	210	187	51	43	21
	Long Heat	587	804	966	273	275	279	239	240	245
	Short Heat	199	263	308	64.6	66.1	67.5	42.3	44.1	46.1

* Cooling hours > 86°F, Heating hours < 54°F

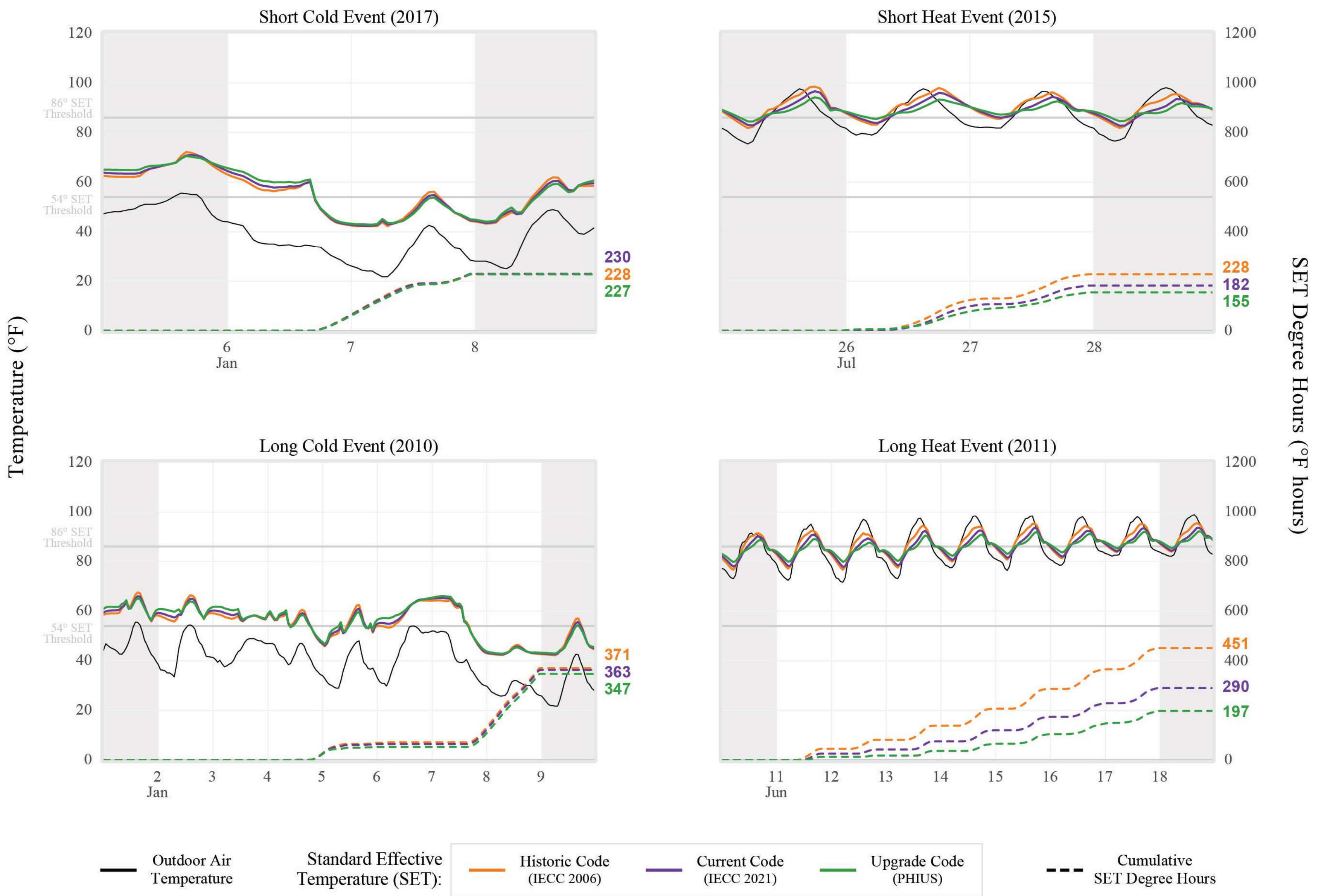


Figure F-1. New Single Family: Houston, TX (2A)

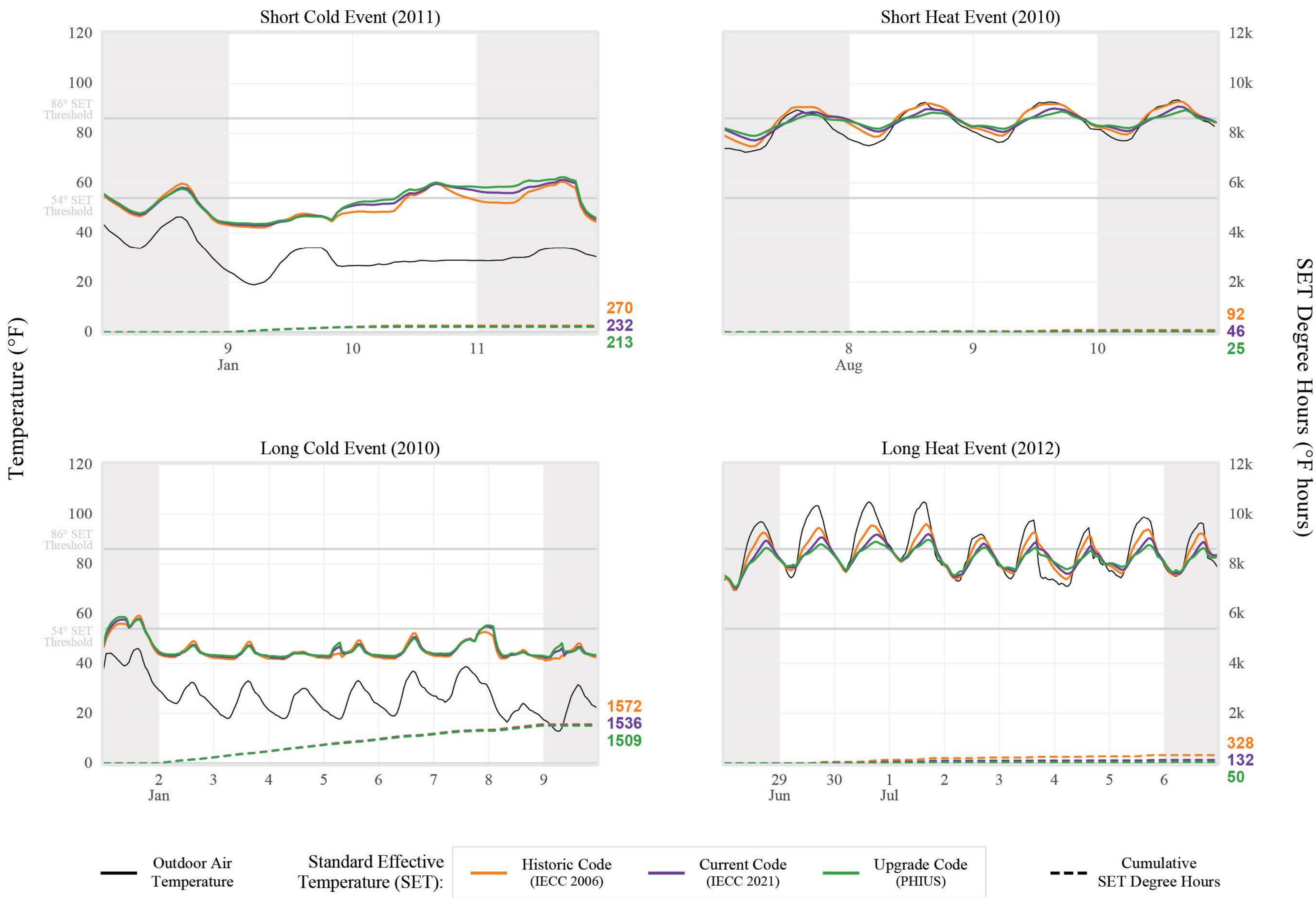


Figure F-2. New Single Family: Atlanta, GA (3A)

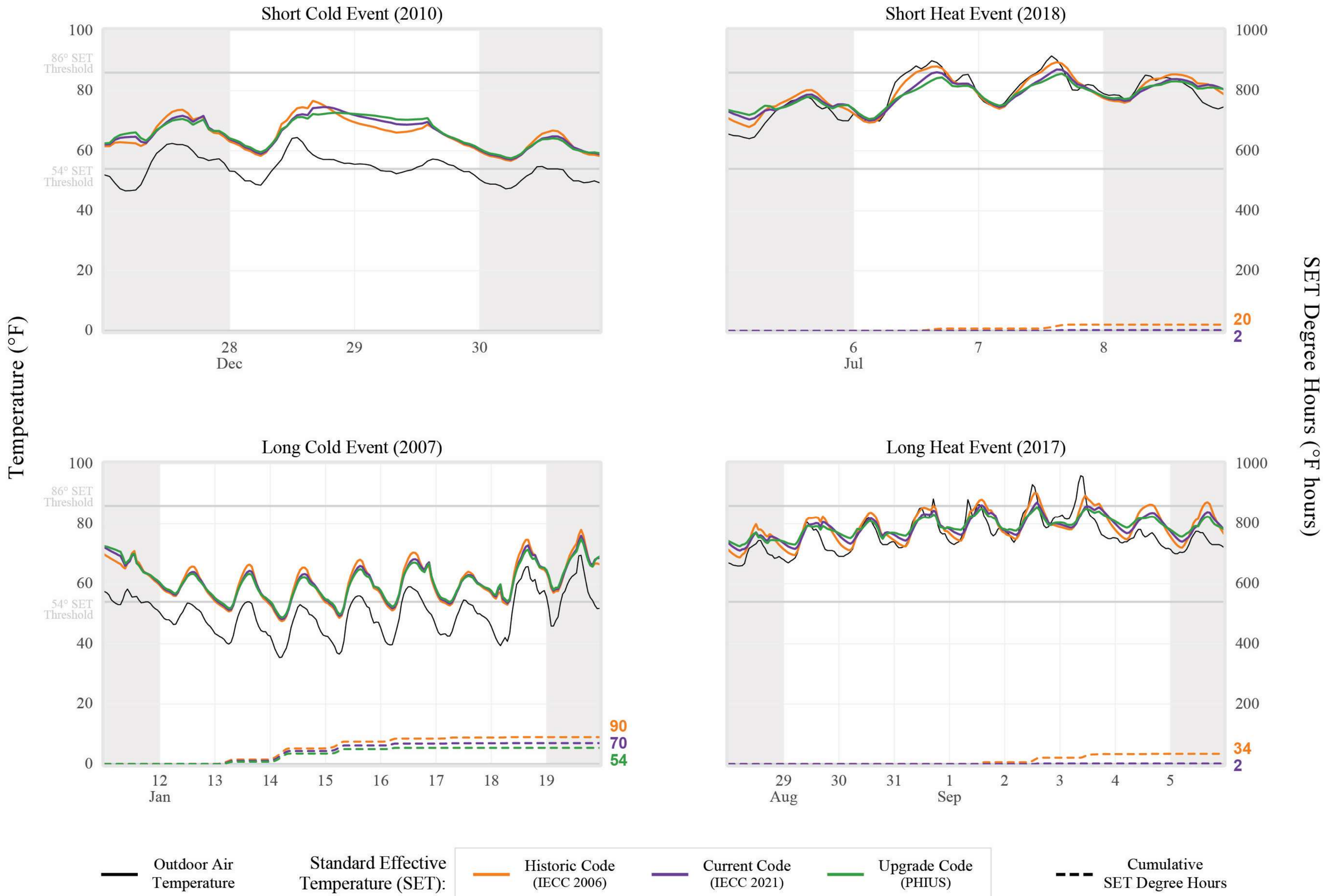


Figure F-3. New Single Family: Los Angeles, CA (3B)

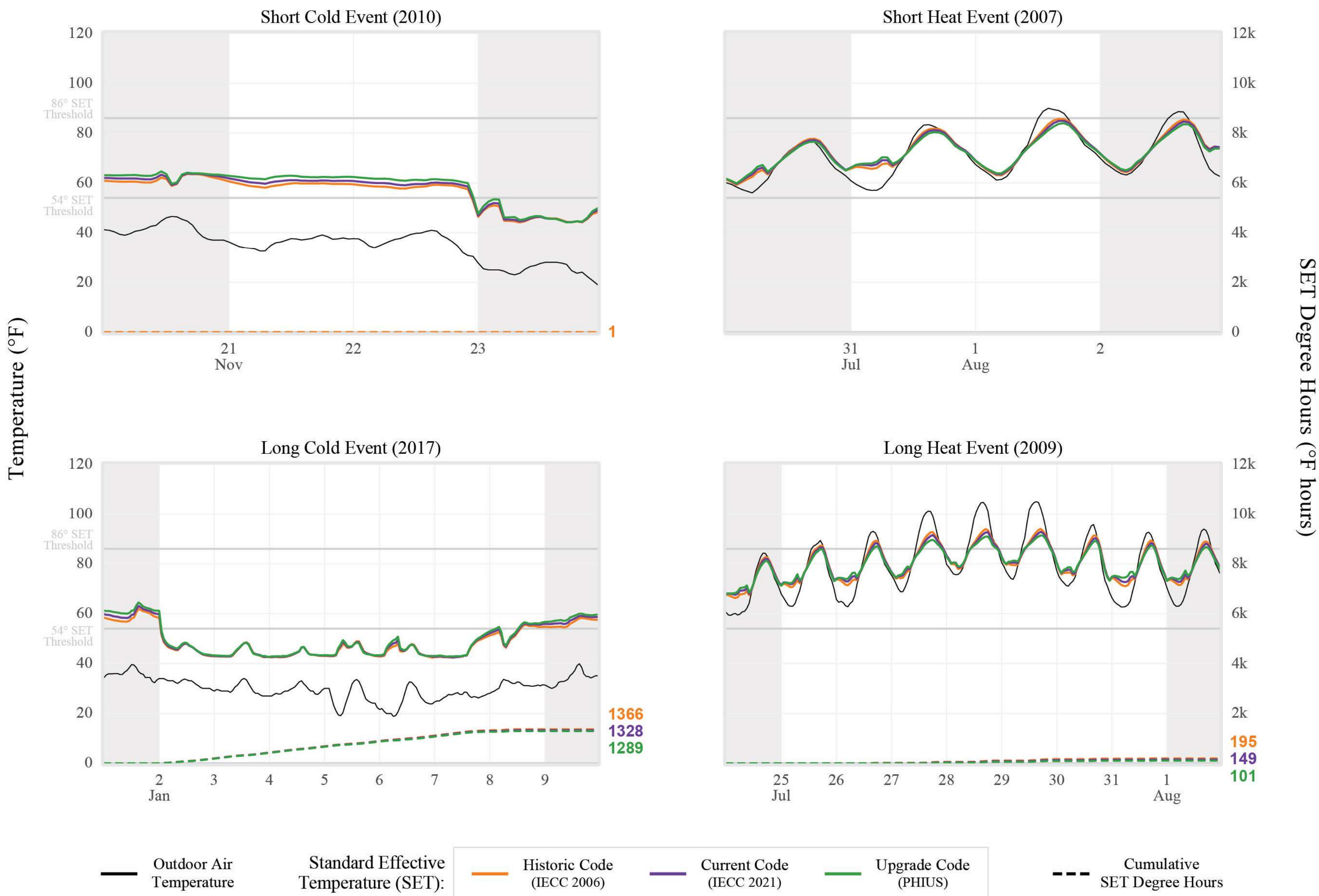


Figure F-4. New Single Family: Portland, OR (4C)

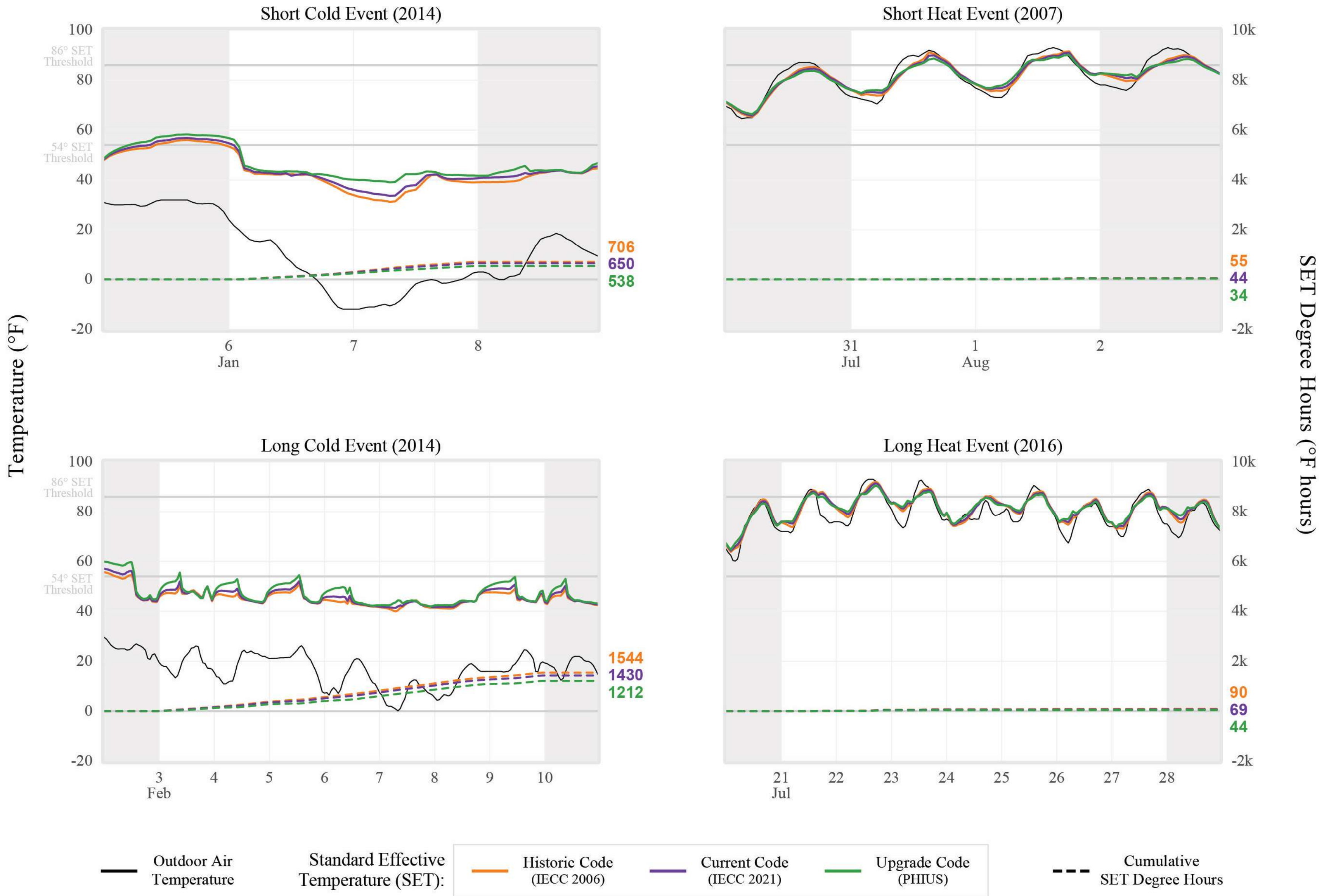


Figure F-5. New Single Family: Detroit, MI (5A)

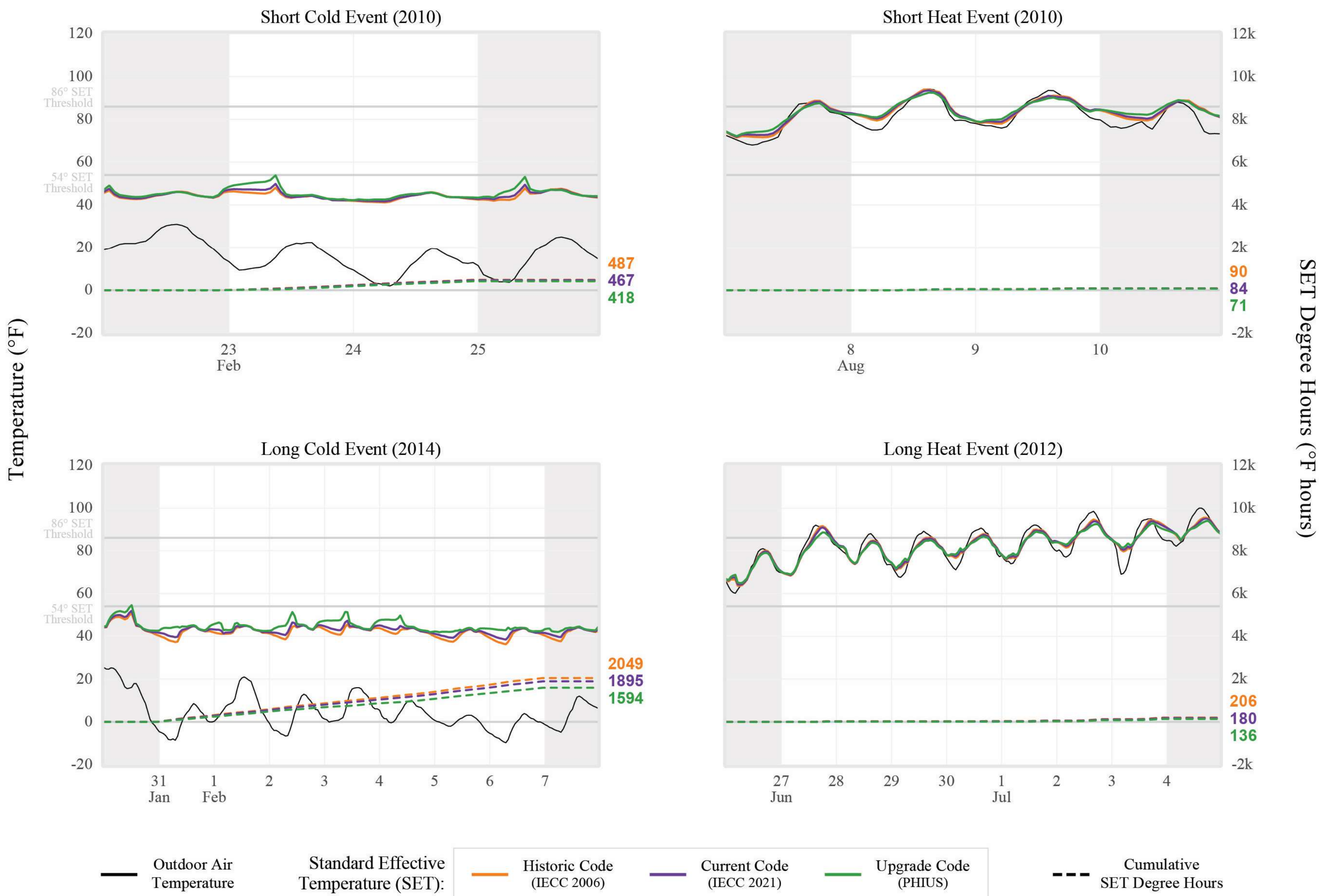


Figure F-6. New Single Family: Minneapolis/St. Paul, MN (6A)

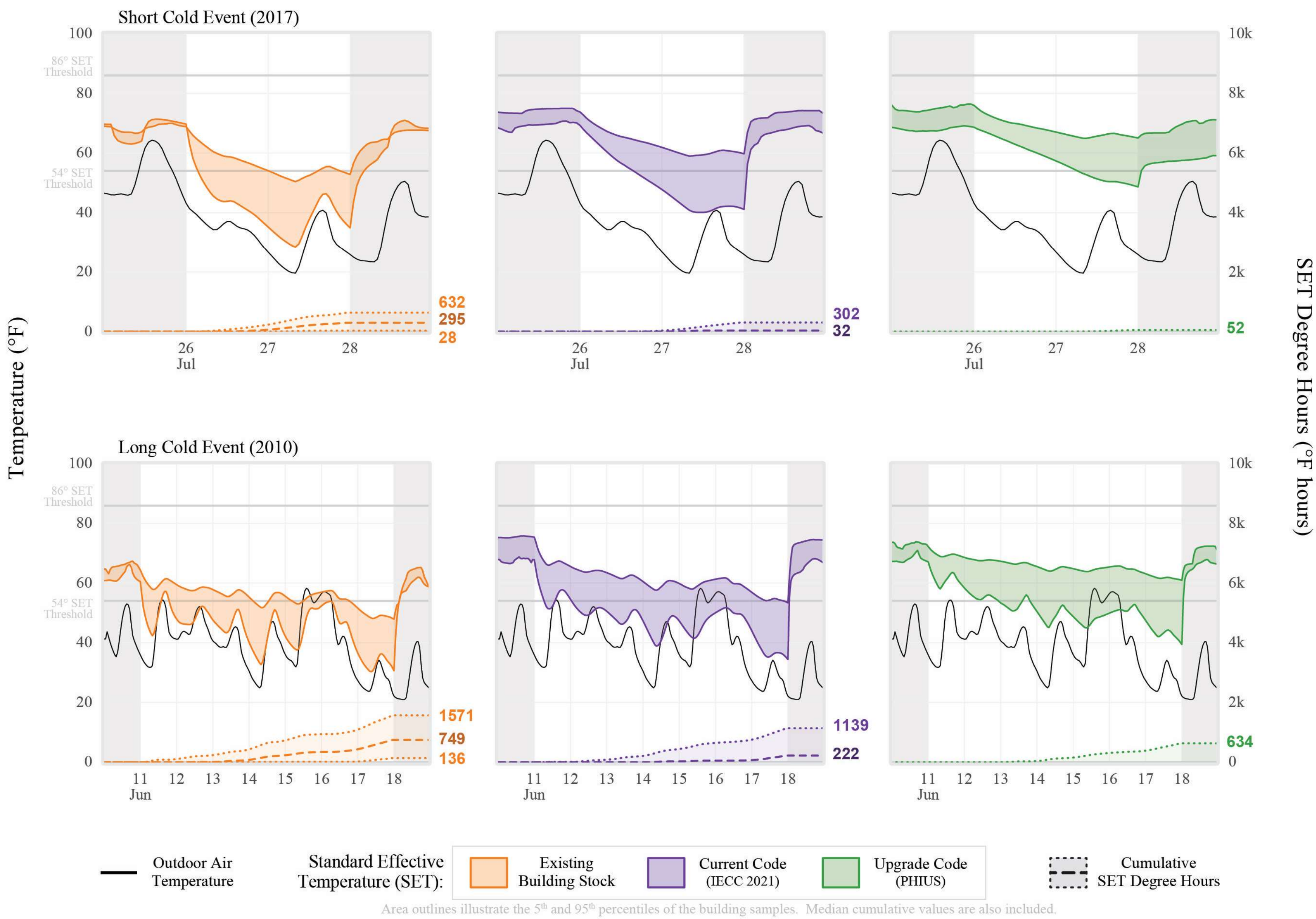


Figure F-7. Existing Single Family: Houston, TX (2A) – Cold Events

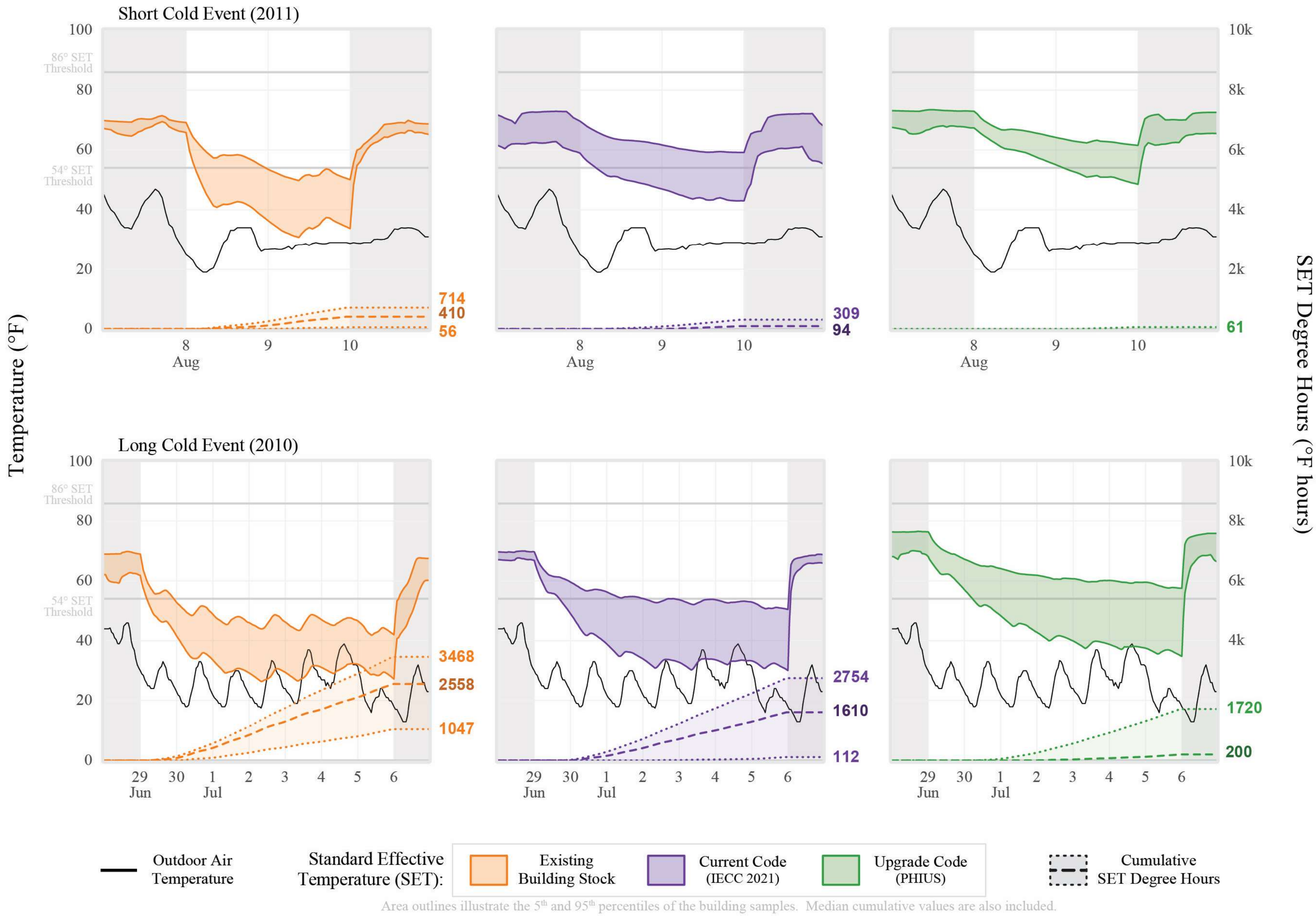


Figure F-8. Existing Single Family: Atlanta, GA (3A) – Cold Events

Figure F-9. Existing Single Family: Los Angeles, CA (3B) – Cold Events

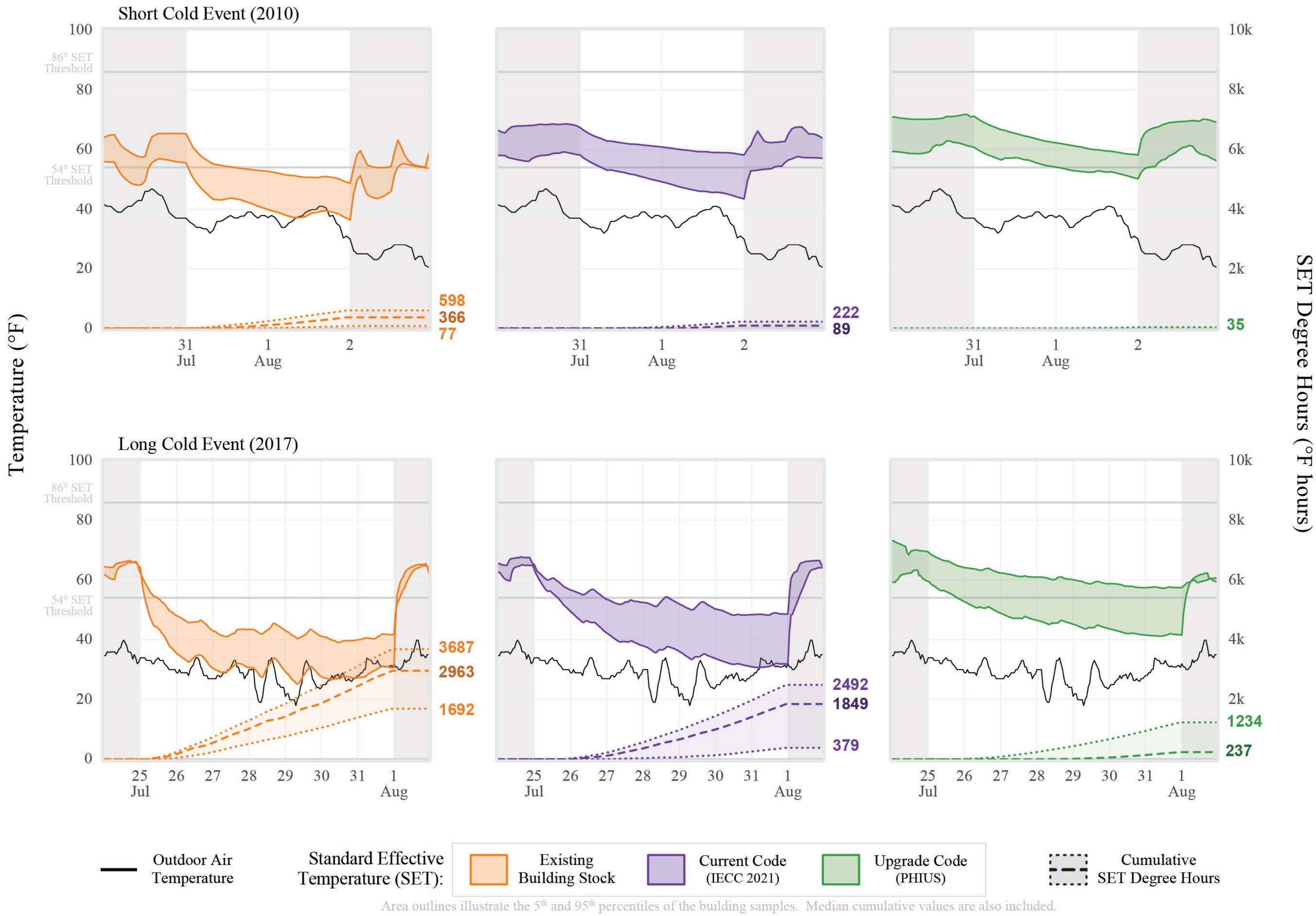


Figure F-10. Existing Single Family: Portland, OR (4C) – Cold Events

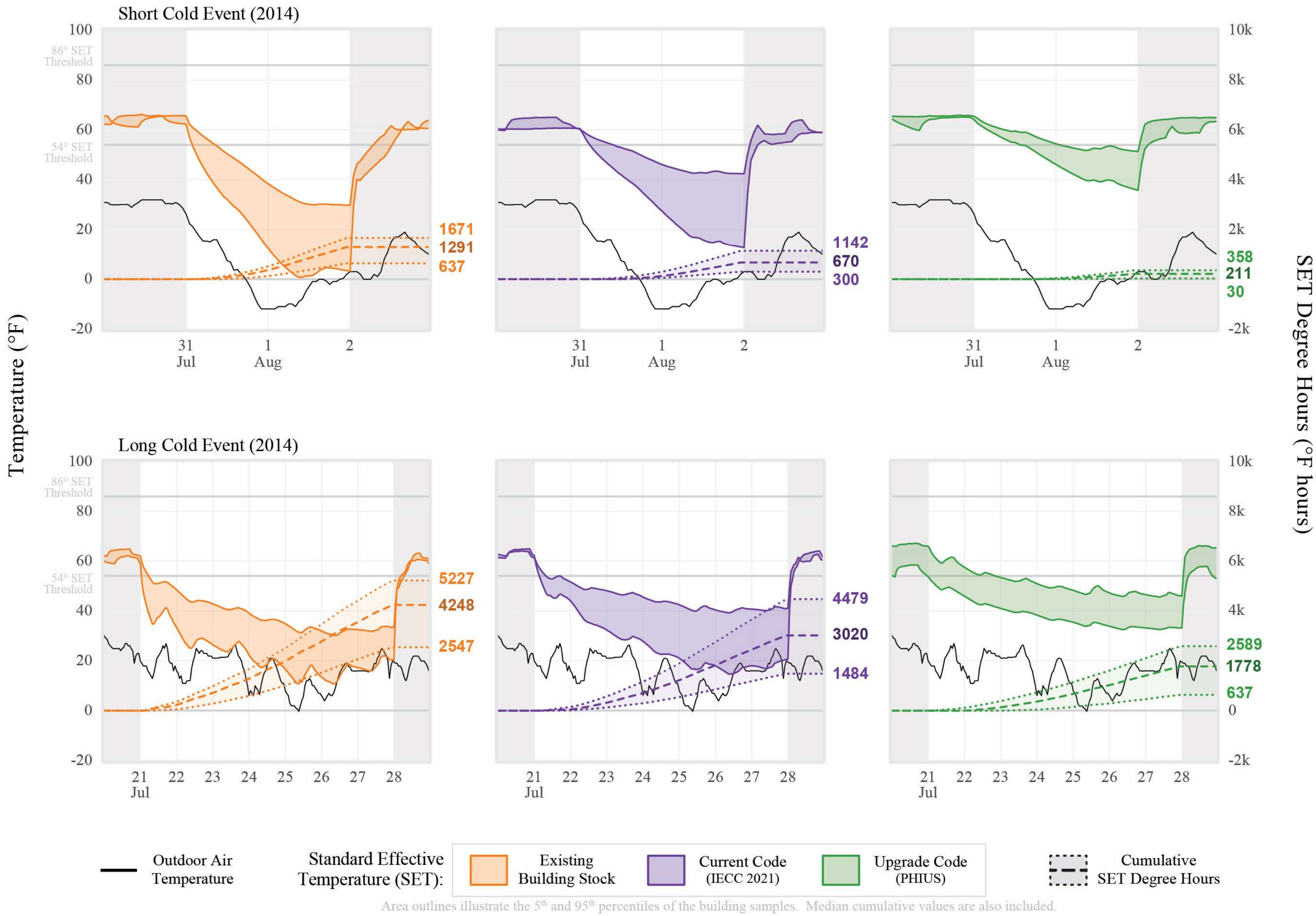


Figure F-11. Existing Single Family: Detroit, MI (5A) – Cold Events

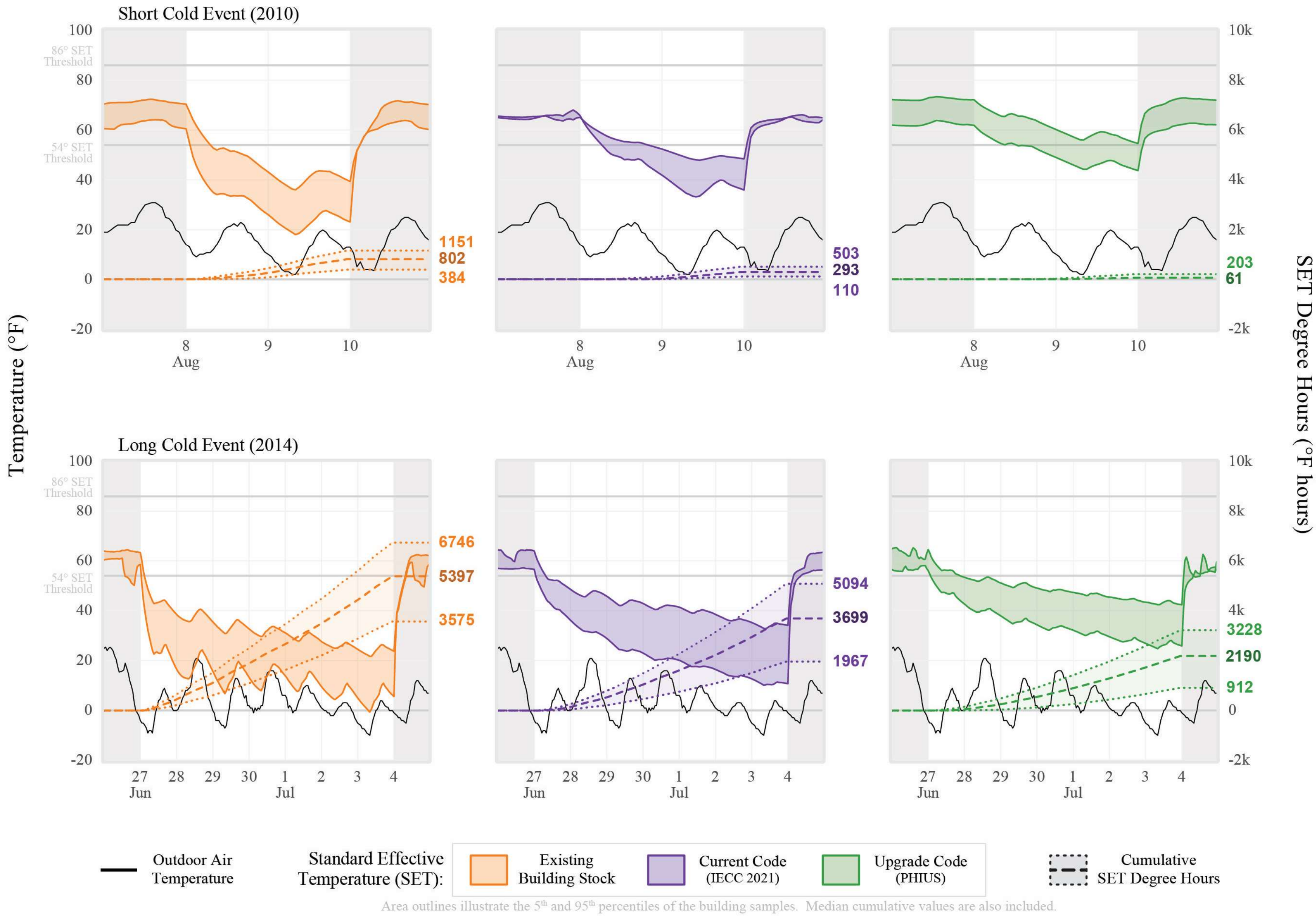


Figure F-12. Existing Single Family: Minneapolis/St. Paul, MN (6A) – Cold Events

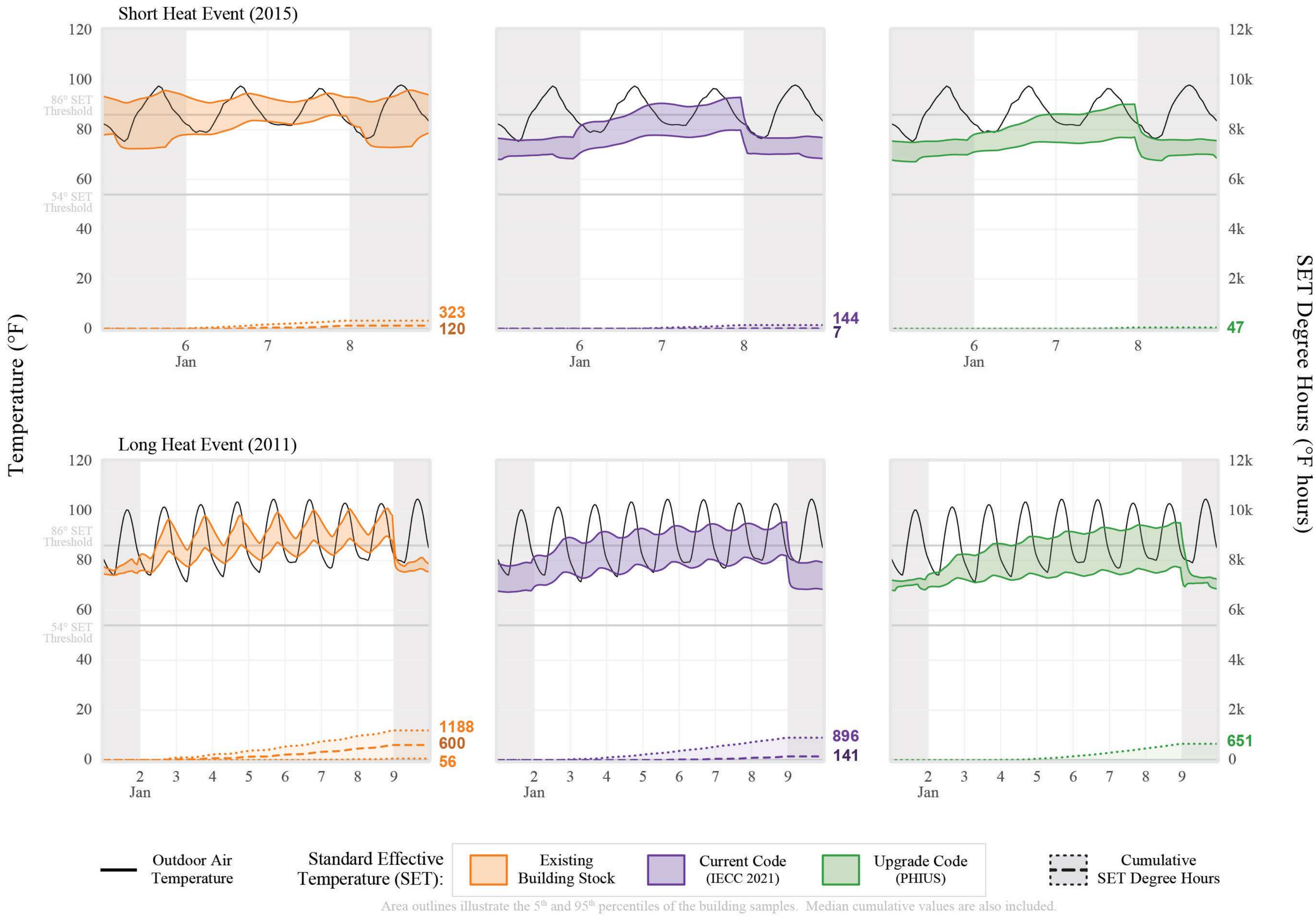


Figure F-13. Existing Single Family: Houston, TX (2A) – Heat Events

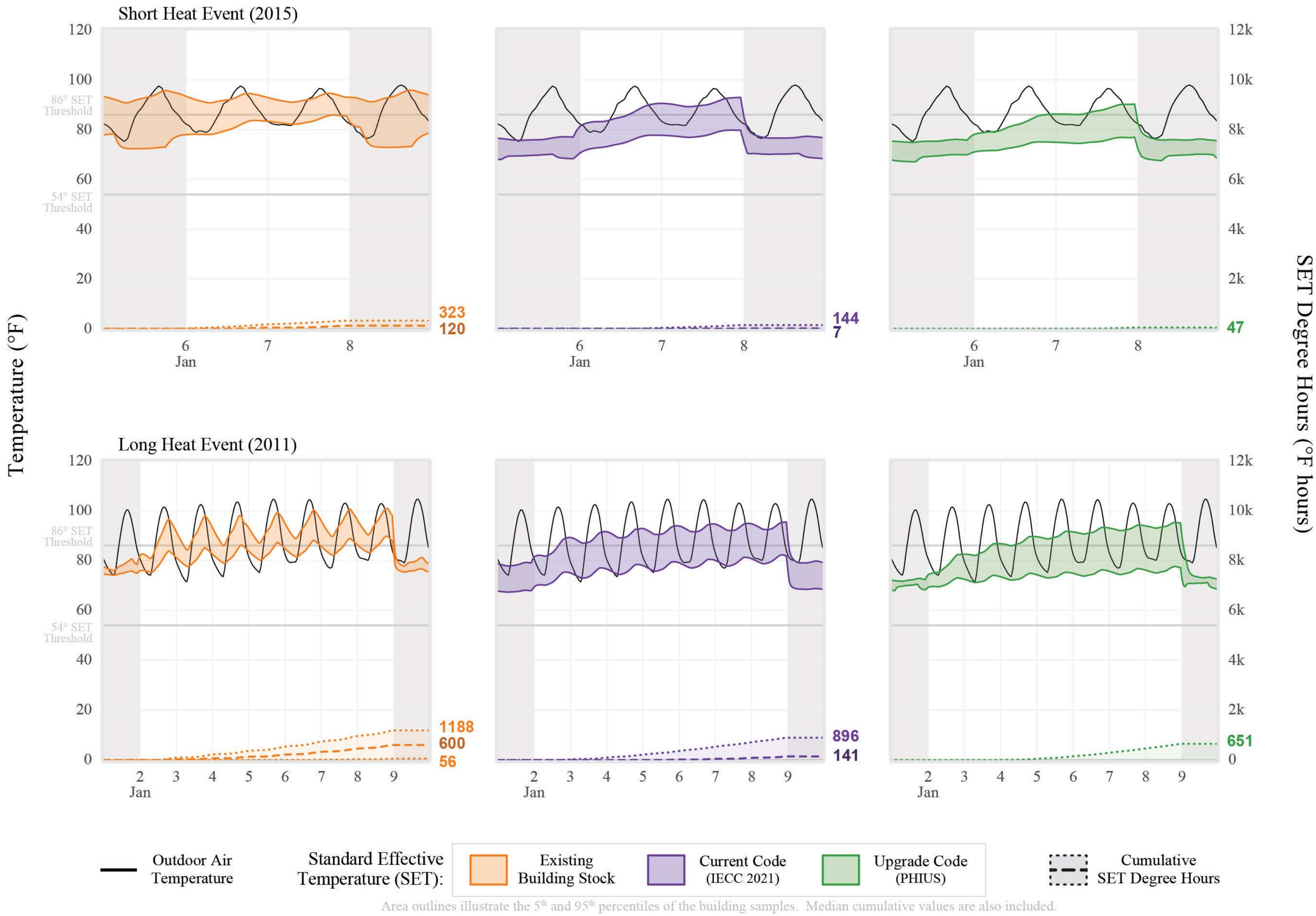


Figure F-14. Existing Single Family: Atlanta, GA (3A) – Heat Events

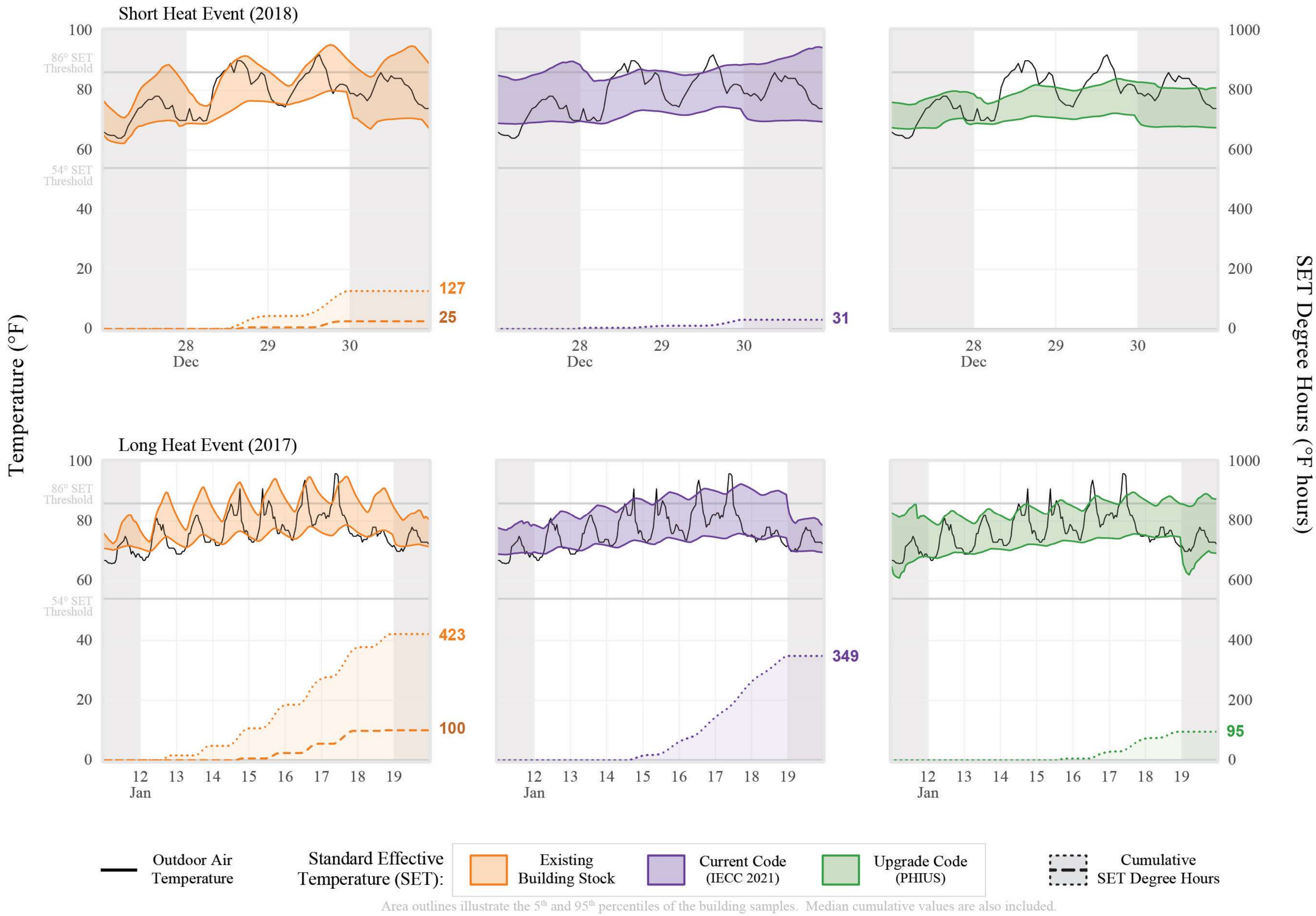


Figure F-15. Existing Single Family: Los Angeles, CA (3B) – Heat Events

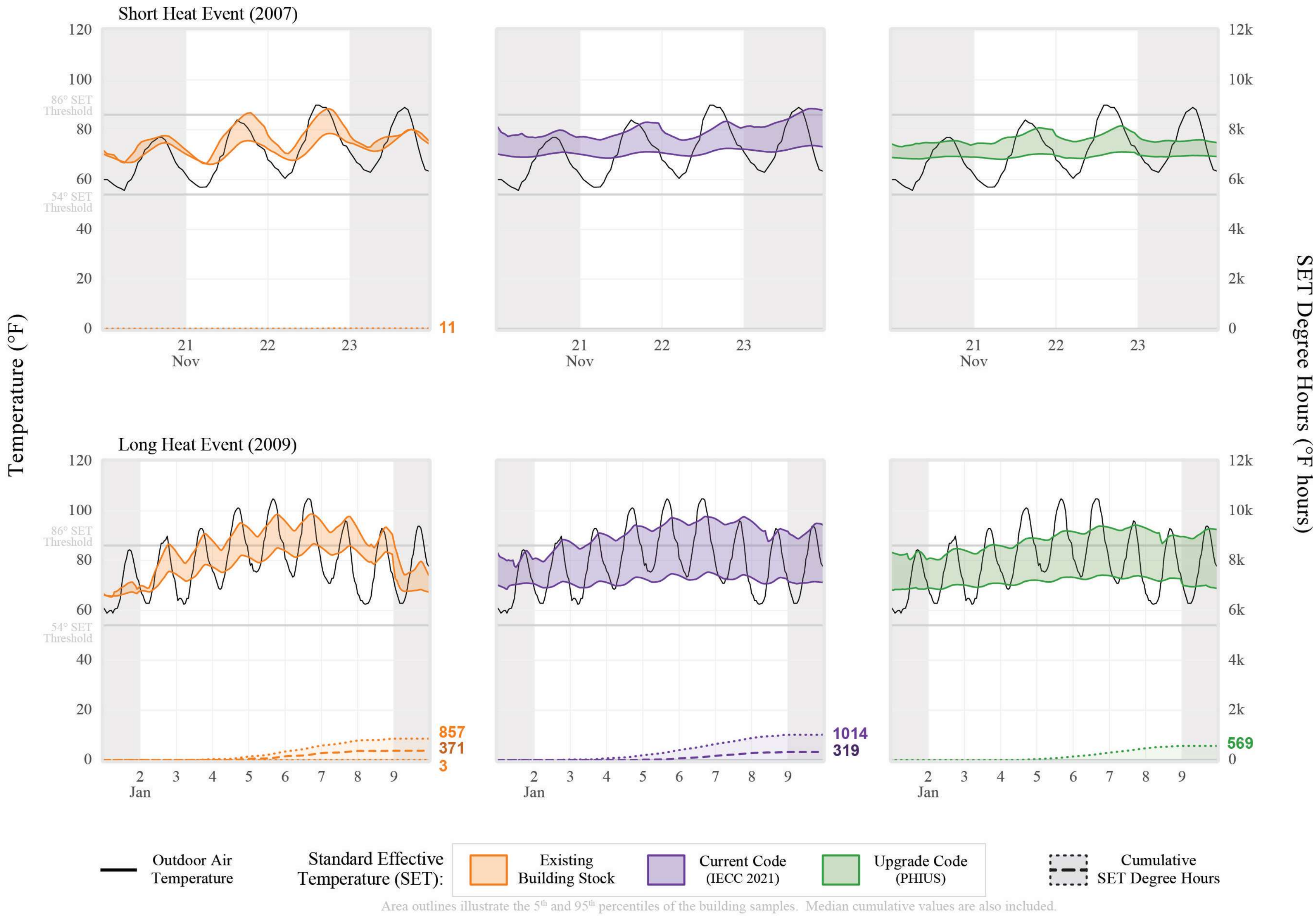


Figure F-16. Existing Single Family: Portland, OR (4C) – Heat Events

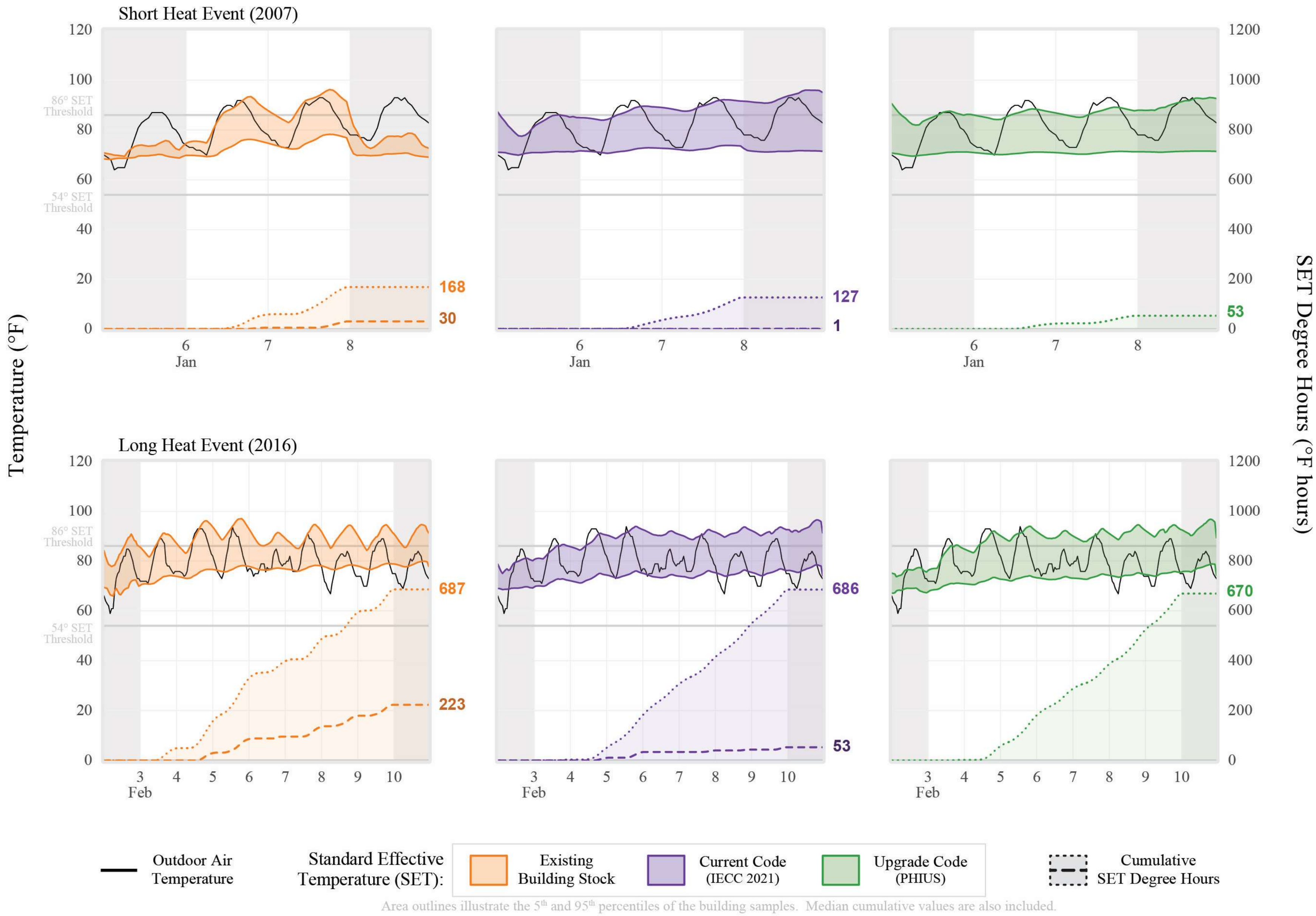


Figure F-17. Existing Single Family: Detroit, MI (5A) – Heat Events

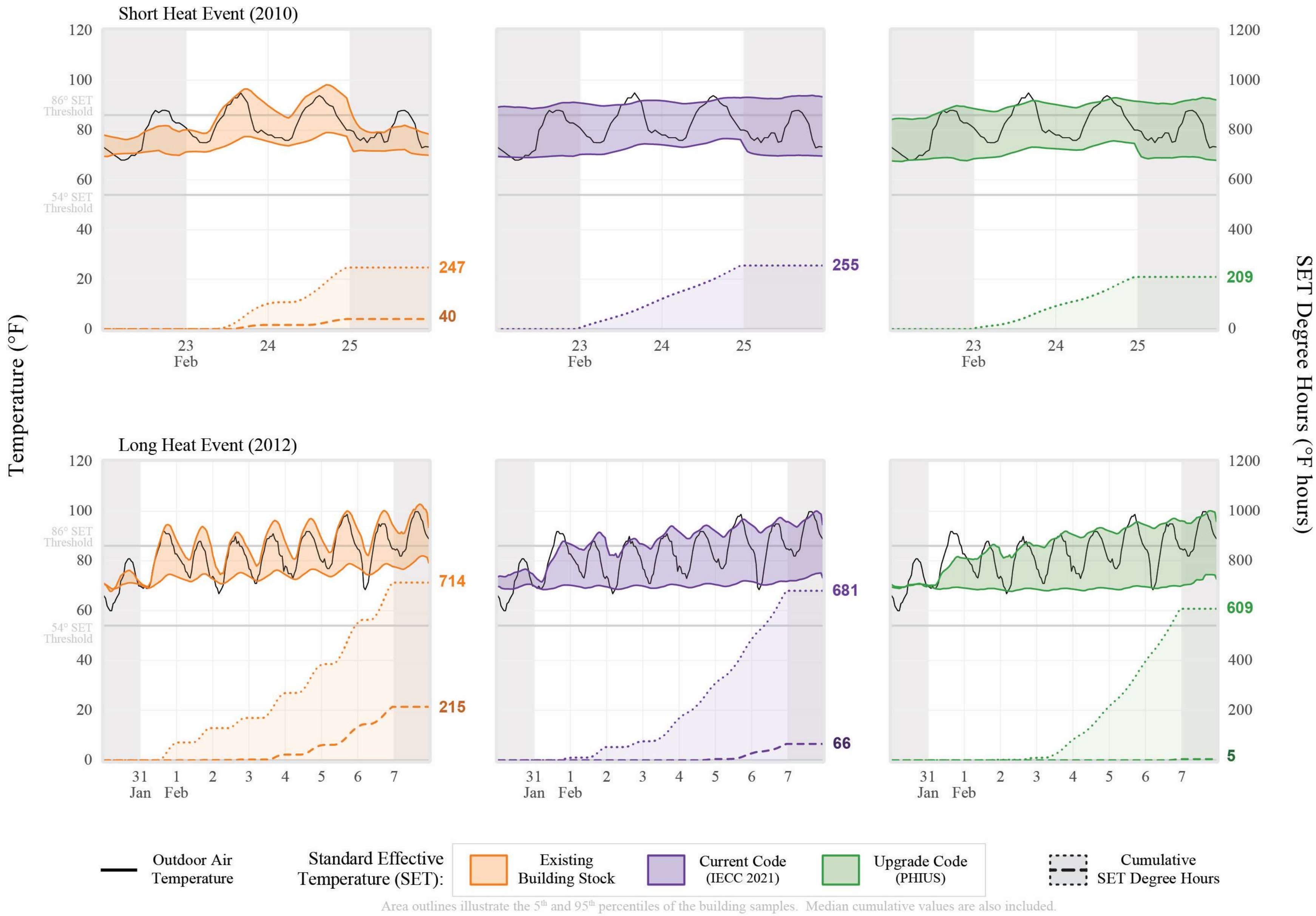


Figure F-18. Existing Single Family: Minneapolis/St. Paul, MN (6A) – Heat Events

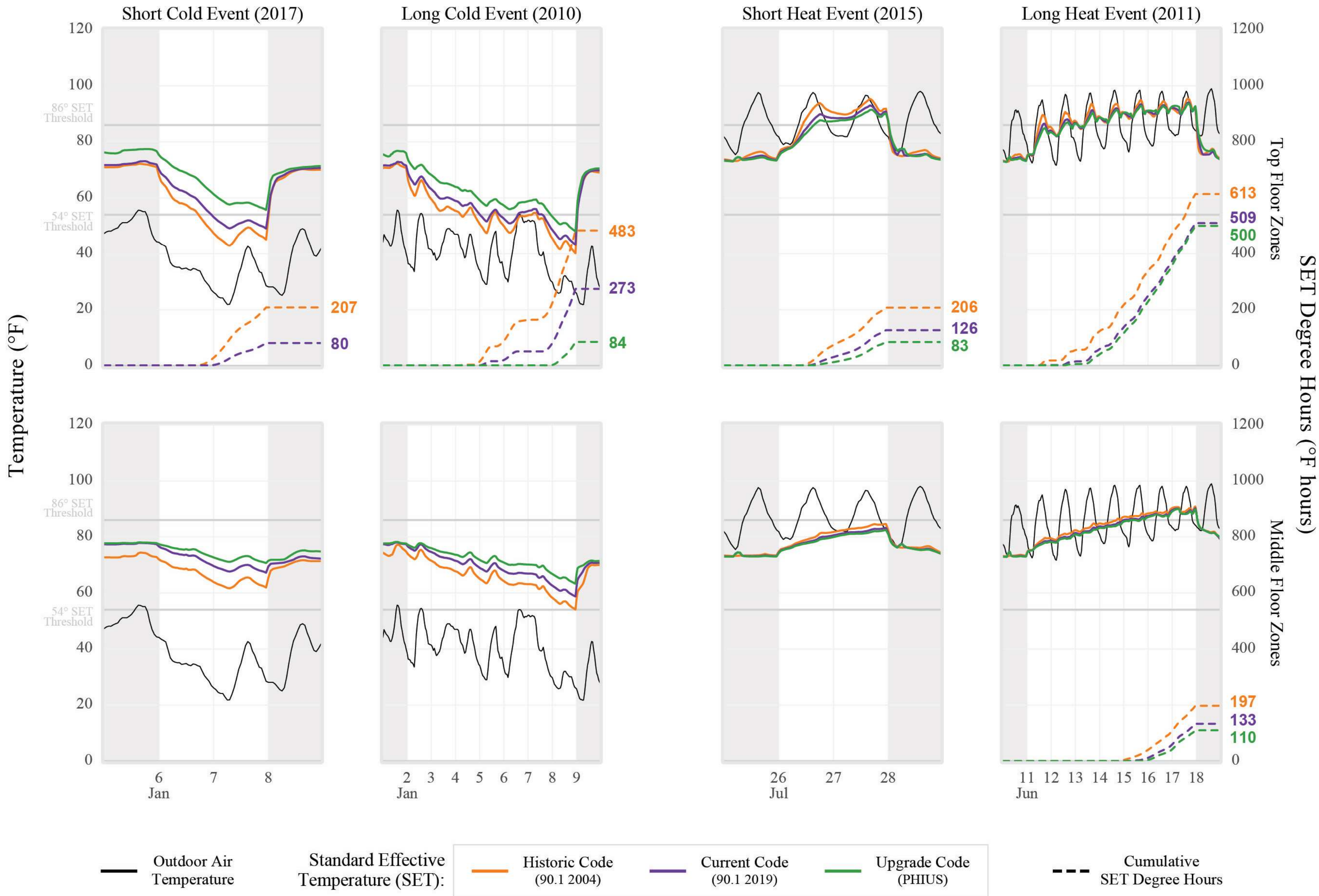


Figure F-19. New Multifamily: Houston, TX (2A)

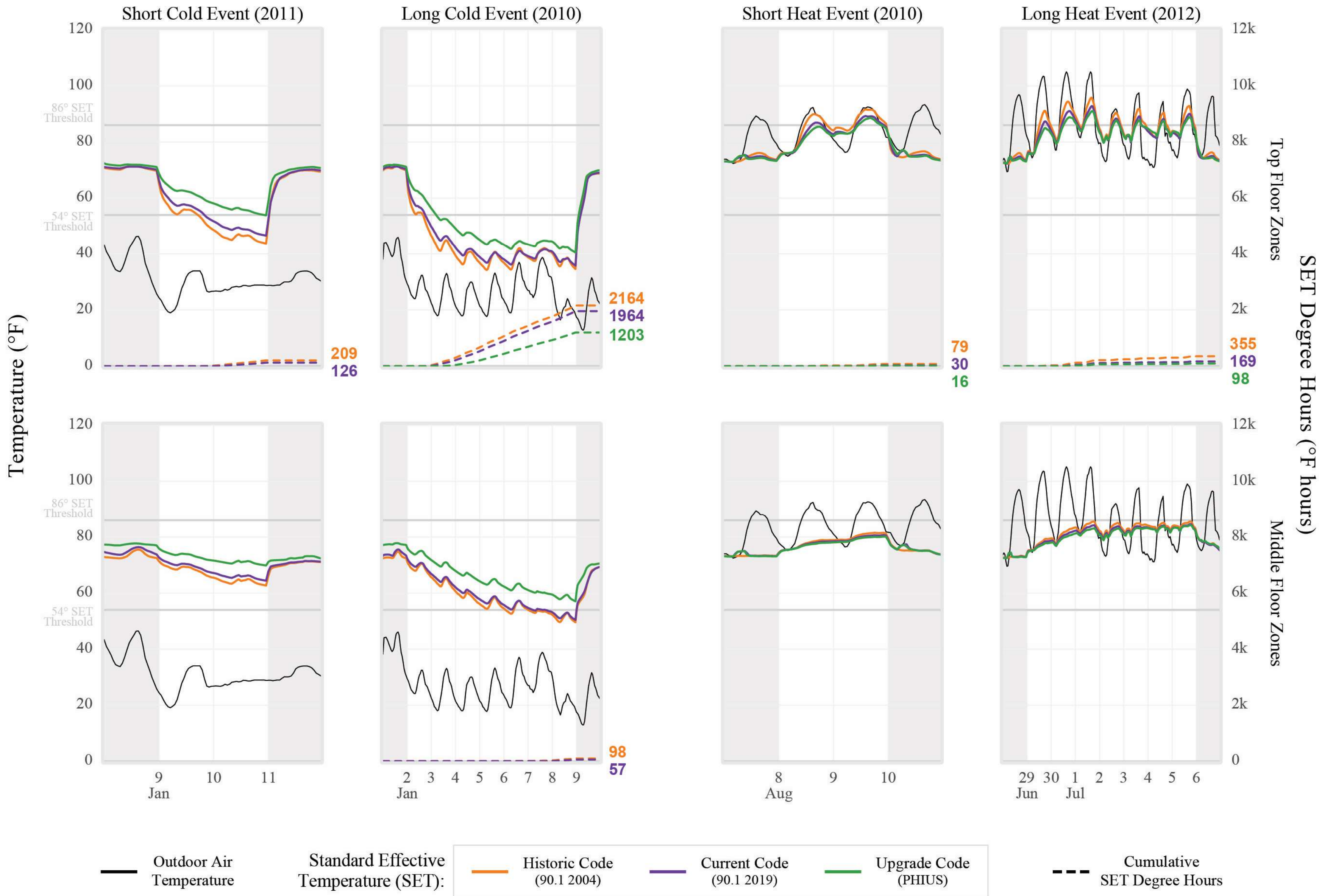


Figure F-20. New Multifamily: Atlanta, GA (3A)

Figure F-21. New Multifamily: Los Angeles, CA (3B)

Figure F-22. New Multifamily: Portland, OR (4C)

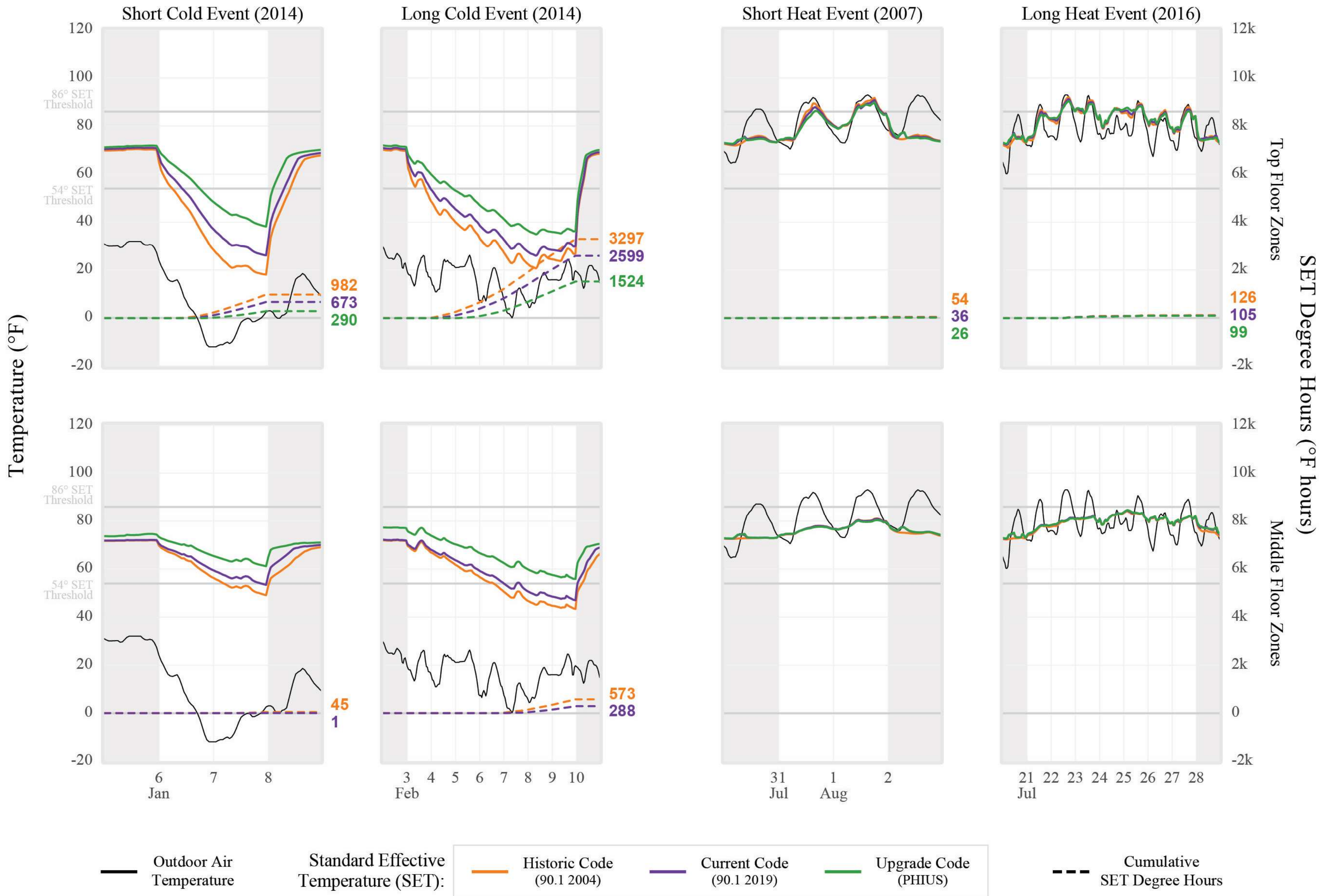


Figure F-23. New Multifamily: Detroit, MI (5A)

Figure F-24. New Multifamily: Minneapolis/St. Paul, MN (6A)

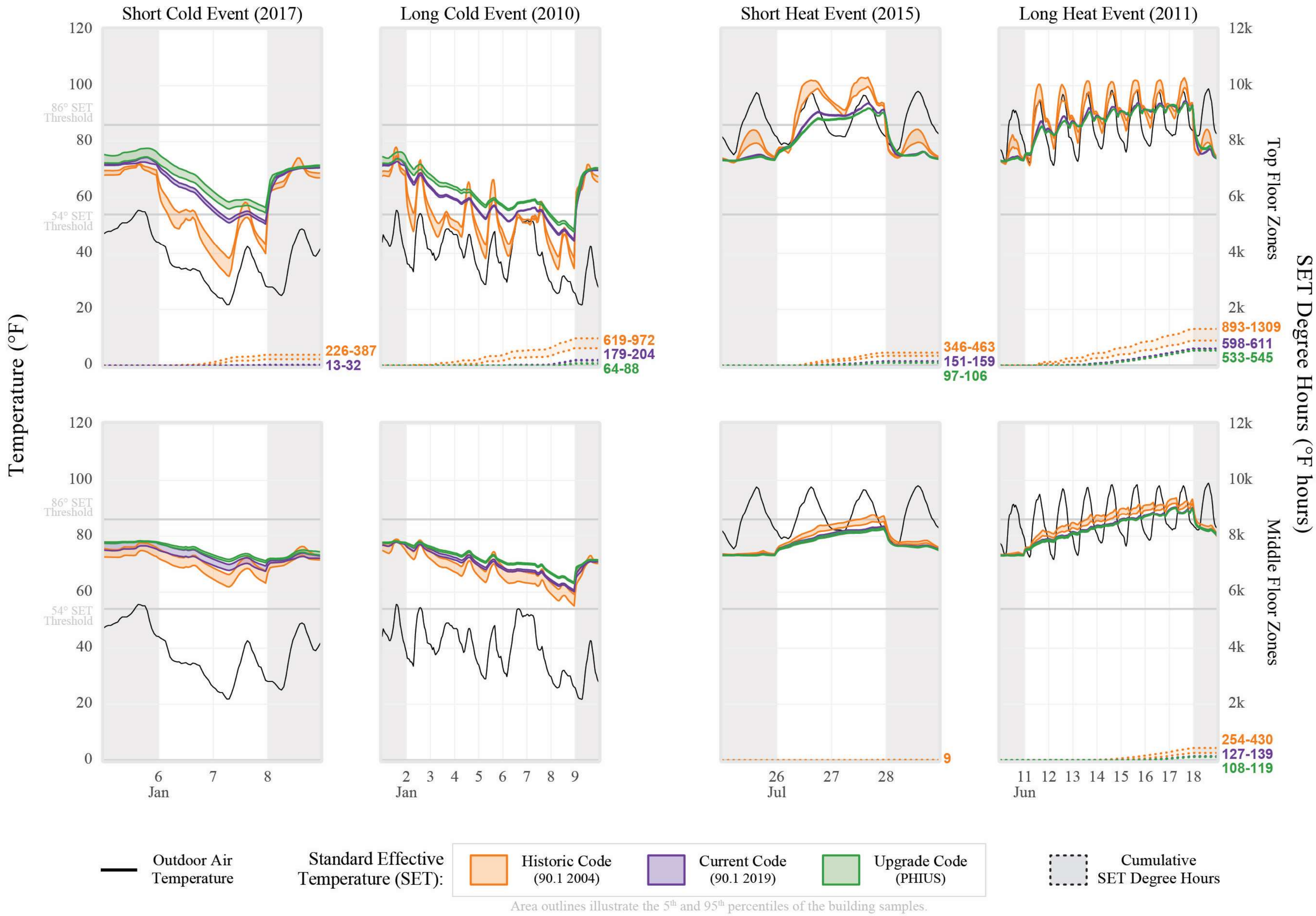


Figure F-25. Existing Multifamily: Houston, TX (2A)

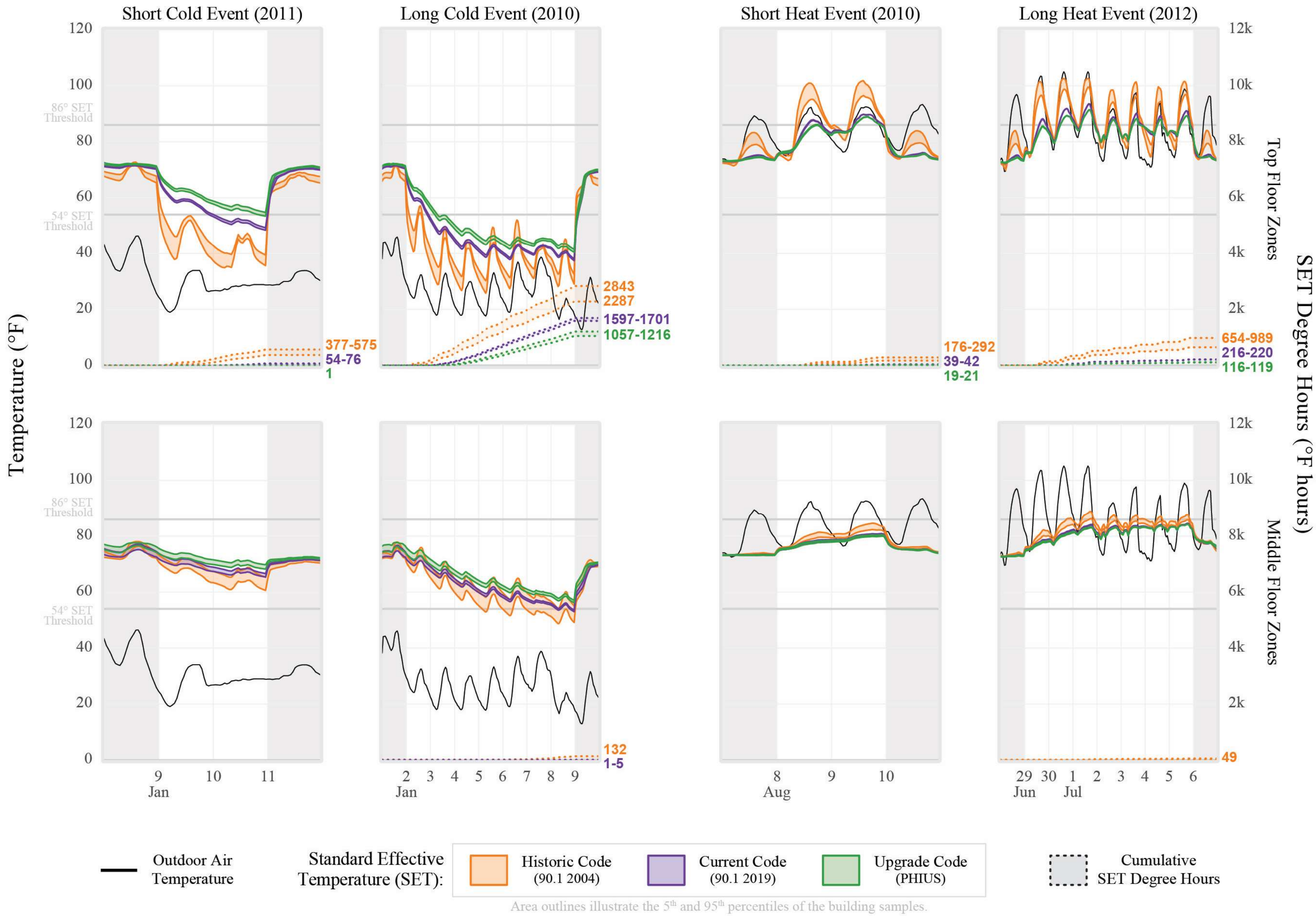


Figure F-26. Existing Multifamily: Atlanta, GA (3A)

Figure F-27. Existing Multifamily: Los Angeles, CA (3B)

Figure F-28. Existing Multifamily: Portland, OR (4C)

Figure F-29. Existing Multifamily: Detroit, MI (5A)

Figure F-30. Existing Multifamily: Minneapolis/St. Paul, MN (6A)

Appendix G – Occupant Damage Assessment

In developing the damage assessment method, several caveats for using health studies on human mortality and morbidity became apparent. They relate to whether the studies accounted for indoor versus outdoor exposure, the impact of severe cold exposure on mortality, when cold exposures occur, whether it is appropriate to include both cold and heat exposures in the same study, and the impact of air conditioning on reducing the adaptive capacity of humans to heatwave exposure when power outages occur. Power outages eliminate the protection to heat associated with air conditioning of living spaces.

The primary problem in applying the Gasparrini et al. (2015) dataset is that the mortality correlations are based on outside temperatures without accommodating for air conditioning and the location of exposure (indoors vs. outdoors). This study, however, calculates mortality based on changes in indoor temperature that result from the implementation of mitigation measures. Thus, there could be significant misclassification issues that both overestimate and underestimate the number of indoor deaths associated with cold and heat deaths. Both cold and heat-related deaths are unknown for their exposure location.

Anecdotal evidence indicates that about 66–69% of heat-related deaths could be due to indoor exposure, and only about 25–33% of cold-related deaths are believed to be indoors. This would mean the Gasparrini analyses both overestimates heat- and cold-related deaths. More appropriate studies would be those that evaluate where exposure occurred and analyzed indoor temperatures rather than outdoor temperatures. There are only a few studies that evaluate indoor temperature impacts on human health. One California study evaluated human vulnerability to indoor temperatures. Most research focuses on outdoor temperatures.

The Gasparrini study was the most recent study that analyzed data by city for several U.S. cities for heat and cold temperatures while the California study did not cover the different CZs and cities that this study includes. Most mortality occurs in the winter; however, that does not mean these deaths are due to cold temperatures. Most winter season deaths are due to cardiovascular and pulmonary diseases. Cholesterol increases, and the blood thickens during the colder months which may contribute to these deaths. Questions remain about the extent to which colder temperatures in the winter cause higher mortality. Deaths from hypothermia are only a fraction of winter mortality; in fact, many deaths from hypothermia occur at other times of the year.

There is no robust justification for including cold and hot temperature analyses in the same model. The lag between exposure and mortality significantly differs between cold and hot temperatures. Questions remain about the extent to which Gasparrini, and colleagues adequately controlled for the different lag structures.

U.S. households have a significant penetration of air conditioning that would tend to depress heat-related deaths. This would mean that Gasparrini’s results could underestimate the mortality associated with a heat event and an electrical outage. Some of the anecdotal evidence indicates that some heat-related deaths are due to outside exposure. But the actual understanding of location of exposure is not yet quantified in many locations. In Phoenix, most deaths are in the unhoused. Some of the deaths occurred in houses with air conditioning but they were not turned on. This variable has not been quantified.

The Gasparrini et al. (2015) occupant damage models were deemed appropriate and the best available for the study application because they addressed temperature–mortality tradeoffs for the cities in the hazard areas studied. The Gasparrini study evaluated the temperature impacts based on average temperatures in 272 locations around the world. The study provided a diversity of U.S. cities (135) to evaluate which met the study's needs in terms of providing alternative cities in the different CZs under investigation. It also provided both heat and cold statistics and fragility curves for understanding the impact of the severe temperature on the population.

Caveats:

- The Gasparrini et al. (2015) study became the human health study used to evaluate the impact of efficiency measures on improving human mortality during severe heat and cold waves. During the study period several caveats for using health studies on human mortality and morbidity became apparent. They related to whether the studies accounted for indoor versus outdoor exposure, the impact of severe cold exposure on mortality, when cold exposures occur, whether it is appropriate to include both cold and heat exposures in the same study, and the impact of air conditioning on reducing the adaptive capacity of humans to heatwave exposure when power outages occur. Power outages eliminate the protection to heat associated with air conditioning of living spaces.
- The primary problem for using the Gasparrini et al. (2015) analyses is that the study is for outside temperatures without accommodating for air conditioning and the location of exposure (indoors vs. outdoors). This study, however, is calculating mortality based on changes in indoor temperature between current standards and new measures designed to improve resistance to severe temperatures. Thus, there could be significant misclassification issues that both overestimate and underestimate the number of indoor deaths associated with cold and heat deaths. Both cold and heat-related deaths are unknown for their exposure location. Anecdotal evidence indicates that about 66–69% of heat-related deaths could be due to indoor exposure, and only about 25–33% of cold-related deaths are believed to be indoors. This would mean the Gasparrini analyses both overestimates heat- and cold-related deaths. More appropriate studies would be those that evaluated where exposure occurred and analyzed indoor temperatures rather than outdoor temperatures. There are only a few studies that evaluate indoor temperature impacts on human health. One a California study that evaluated human vulnerability to indoor temperatures. Most research focuses on outdoor temperatures. The Gasparrini study was the most recent study that analyzed data by city for several U.S. cities for heat and cold temperatures while the California study did not cover the different CZs and cities that this study includes. Most mortality occurs in the winter; however, that does not mean these deaths are due to cold temperatures. Most winter season deaths are due to cardiovascular and pulmonary diseases. Cholesterol increases, and the blood thickens during the colder months which may contribute to these deaths. Questions remain about the extent to which colder temperatures in the winter cause higher mortality.
- Deaths from hypothermia are only a fraction of winter mortality; in fact, many deaths from hypothermia occur at other times of the year.
- There is no robust justification for including cold and hot temperature analyses in the same model. The lag between exposure and mortality significantly differs between cold and hot temperatures. Questions remain about the extent to which Gasparrini and colleagues adequately controlled for the different lag structures.
- U.S. households have a significant penetration of air conditioning that would tend to depress heat-related deaths. This would mean that Gasparrini's results could underestimate the mortality associated with a heat event and an electrical outage. Some of the anecdotal

evidence indicates that some heat-related deaths are due to outside exposure. But the actual understanding of location of exposure is not yet quantified in many locations. In Phoenix, most deaths are in the unhoused. Some of the deaths occurred in houses with air conditioning but they were not turned on. This variable has not been quantified.

Appendix H – Occupant Mortality Estimates

The tables below summarize the excess deaths estimated for new and existing single-family (SF) and multifamily (MF) buildings determined from the building simulation model results and the Gasparrini damage curves. The results indicate mortality rates associated with the three building conditions for the six locations studied. For existing building, the data are represented by the 5%, median, and 95% building condition datapoints, which are based on SET degree hours. The data highlighted in red are the excess death values associated with each extreme event. The reductions in excess deaths are highlighted in green. The event value multiplied by the joint probability yields the estimated annualized value. These values support making impact comparisons and are used in the efficiency improvement benefit–cost ratio (BCR) calculation.

Table H-1. New Single-Family Building Estimates of Excess Deaths Attributed to Extreme Events

		Estimated Event Mortality			Event Mortality Reduction*				Annual Mortality Reduction*†	
		Deaths per Event			Lives Saved per Event		Improvement		Lives Saved per Year	
Location (Climate Zone)	Event	Historic Code IECC 2006	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	80.1	78.6	76.3	1.46	**3.75**	1.8%	4.7%	0.05	**0.12**
	Short Cold	29.3	28.9	28.2	0.45	1.19	1.5%	4.0%	0.01	0.04
	Long Heat	11.8	5.0	4.0	6.80	7.87	58%	**67%**	5.13	**5.94**
	Short Heat	8.9	4.8	3.2	4.16	5.75	47%	64%	3.14	4.33
Atlanta, GA (3A)	Long Cold	21.2	21.1	21.0	0.08	0.15	0.4%	0.7%	0.00	0.01
	Short Cold	4.9	4.7	4.6	0.22	0.32	4.5%	6.6%	0.01	0.01
	Long Heat	5.0	3.6	3.1	1.41	1.86	28%	37%	0.14	0.18
	Short Heat	1.2	1.0	1.0	0.16	0.20	13%	17%	0.02	0.02
Los Angeles, CA (3B)	Long Cold	72.8	73.2	73.3	-0.42	**-0.51**	-0.6%	**-0.7%**	-0.06	**-0.08**
	Short Cold	5.6	5.0	4.9	0.66	0.72	12%	13%	0.10	0.11
	Long Heat	138.2	129.6	133.4	8.62	4.79	6.2%	3.5%	2.95	1.64
	Short Heat	58.4	46.7	42.3	11.7	**16.1**	20%	28%	3.99	5.51
Portland, OR (4C)	Long Cold	15.7	15.6	15.5	0.10	0.19	0.6%	1.2%	0.01	0.01
	Short Cold	2.3	2.1	1.9	0.21	0.46	8.9%	**20%**	0.02	0.03
	Long Heat	28.9	28.9	28.6	0.01	0.28	0.0%	1.0%	0.00	0.03
	Short Heat	1.4	1.4	1.3	0.03	0.15	2.5%	11%	0.00	0.02
Detroit, MI (5A)	Long Cold	32.8	32.3	31.4	0.47	1.37	1.4%	4.2%	0.04	0.10
	Short Cold	10.6	10.4	10.0	0.20	0.62	1.8%	5.8%	0.01	0.05
	Long Heat	43.0	44.1	44.3	-1.13	**-1.31**	-2.6%	-3.0%	-0.19	**-0.22**
	Short Heat	15.2	15.7	15.6	-0.49	-0.41	**-3.2%**	-2.7%	-0.08	-0.07
Minneapolis/ St. Paul, MN (6A)	Long Cold	34.1	33.5	32.3	0.63	1.78	1.8%	5.2%	0.02	0.04
	Short Cold	9.4	9.3	9.1	0.07	0.24	0.8%	2.6%	0.00	0.01
	Long Heat	41.1	40.7	39.3	0.37	1.75	0.9%	4.3%	0.06	0.26
	Short Heat	13.7	13.9	13.6	-0.20	0.07	-1.5%	0.5%	-0.03	0.01

* Changes relative to Historic Code (IECC 2006)

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Table H-2. Existing Single-Family Building Estimates of Excess Deaths Attributed to Extreme Events

		Estimated Event Mortality									Event Mortality Reduction*												Annual Mortality Reduction*†					
		Deaths per Event									Lives Saved per Event						Improvement						Lives Saved per Year					
		5th Percentile			Median			95th Percentile			Current Code IECC 2021			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS		
Location (Climate Zone)	Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Houston, TX (2A)	Long Cold	82.1	70.2	55.3	62.5	42.5	19.3	40.6	23.9	11.9	11.9	20.0	16.7	26.8	**43.2**	28.7	14%	32%	41%	33%	69%	71%	0.39	0.66	0.55	0.88	1.43	0.95
	Short Cold	28.6	17.9	9.9	19.4	10.2	5.1	11.4	5.5	2.5	10.7	9.2	5.9	18.6	14.3	9.0	37%	47%	52%	65%	74%	**78%**	0.35	0.30	0.19	0.61	0.47	0.30
	Long Heat	80.6	71.6	55.1	52.4	10.3	2.2	2.1	1.8	0.6	9.0	42.1	0.3	25.5	50.2	1.5	11%	80%	14%	32%	**96%**	72%	6.77	31.7	0.22	19.2	37.8	1.12
	Short Heat	12.7	14.4	7.0	9.2	1.2	0.8	0.2	0.5	0.1	-1.7	7.9	-0.2	5.6	8.4	0.2	-14%	86%	-109%	44%	92%	77%	-1.30	5.96	-0.19	4.24	6.32	0.13
Atlanta, GA (3A)	Long Cold	20.5	17.5	13.3	16.7	13.1	8.0	11.2	7.6	4.7	2.9	3.6	3.6	7.2	8.7	6.5	14%	21%	33%	35%	52%	58%	0.11	0.14	0.14	0.27	0.33	0.25
	Short Cold	4.7	3.2	2.1	3.6	2.4	1.5	2.2	1.4	1.1	1.5	1.3	0.8	2.6	2.2	1.0	31%	35%	36%	56%	59%	49%	0.06	0.05	0.03	0.10	0.08	0.04
	Long Heat	8.4	7.7	7.3	6.3	5.4	0.4	2.5	1.8	1.9	0.70	0.89	0.64	1.08	5.87	0.55	8%	14%	26%	13%	93%	22%	0.07	0.09	0.06	0.11	0.58	0.05
	Short Heat	2.1	1.4	0.5	1.0	0.4	0.3	0.6	0.6	0.6	0.65	0.53	-0.05	1.52	0.63	-0.10	32%	55%	-10%	74%	66%	-17%	0.06	0.05	-0.01	0.15	0.06	-0.01
Los Angeles, CA (3B)	Long Cold	40.6	30.6	18.5	21.2	16.0	15.8	15.8	16.9	15.3	10.0	5.2	**-1.2**	22.1	5.4	0.5	25%	25%	**-7%**	54%	25%	3%	1.49	0.77	**-0.17**	**3.30**	0.80	0.08
	Short Cold	5.6	4.4	4.4	4.7	4.7	5.0	4.8	3.2	3.2	1.2	0.0	1.7	1.2	-0.2	1.6	22%	1%	34%	21%	-5%	34%	0.18	0.01	0.25	0.18	-0.04	0.24
	Long Heat	392	370	306	241	114	38.0	18.1	7.0	10.0	22.1	127	11.1	85.7	**203**	8.1	6%	53%	61%	22%	84%	45%	7.56	43.4	3.79	29.3	**69.4**	2.76
	Short Heat	110	117	44.8	71.3	17.3	14.0	11.8	1.6	2.9	**-7.2**	54.0	10.2	64.7	57.3	9.0	-7%	76%	87%	59%	80%	76%	**-2.48**	18.5	3.50	22.1	19.6	3.07
Portland, OR (4C)	Long Cold	16.2	13.2	10.0	14.7	11.5	6.1	11.7	7.0	3.1	2.9	3.2	4.6	6.2	8.6	8.6	18%	22%	40%	38%	58%	74%	0.22	0.24	0.35	0.46	0.64	0.64
	Short Cold	3.6	2.5	1.8	3.0	1.7	1.0	2.0	0.9	0.7	1.11	1.25	1.12	1.84	1.95	1.30	31%	42%	56%	51%	65%	65%	0.08	0.09	0.08	0.14	0.15	0.10
	Long Heat	36.5	39.5	38.8	34.4	37.0	9.9	24.0	1.8	1.9	-3.0	-2.6	22.1	-2.3	24.5	22.1	-8%	-8%	92%	-6%	71%	92%	-0.29	-0.26	2.19	-0.23	2.43	2.18
	Short Heat	4.7	5.7	4.2	1.9	2.1	0.8	0.5	0.2	0.2	-0.97	-0.27	0.29	0.59	1.08	0.33	-21%	-15%	58%	12%	58%	68%	-0.10	-0.03	0.03	0.06	0.11	0.03
Detroit, MI (5A)	Long Cold	39.0	35.8	28.7	35.5	30.4	24.7	28.4	23.5	18.4	3.2	5.1	5.0	10.3	10.8	10.0	8%	14%	17%	26%	30%	35%	0.24	0.38	0.37	0.78	0.81	0.75
	Short Cold	11.2	9.6	6.1	10.3	7.7	5.3	7.7	6.1	4.1	1.60	2.52	1.55	5.12	4.97	3.51	14%	25%	20%	46%	48%	46%	0.12	0.19	0.12	0.38	0.37	0.26
	Long Heat	110	106	103	75.1	68.2	49.1	6.3	1.3	1.7	3.6	6.9	5.0	6.1	26.0	4.6	3%	9%	79%	6%	35%	73%	0.60	1.14	0.82	1.01	4.29	0.75
	Short Heat	31.0	31.8	31.8	19.7	17.5	3.2	0.4	0.6	1.0	-0.74	2.23	-0.27	-0.74	16.6	-0.64	-2%	11%	-73%	-2%	84%	**-175%**	-0.12	0.37	-0.04	-0.12	2.73	-0.11
Minneapolis/ St. Paul, MN (6A)	Long Cold	44.2	37.8	30.2	39.4	32.1	25.4	31.8	24.5	19.4	6.4	7.3	7.2	14.0	14.0	12.4	14%	19%	23%	32%	36%	39%	0.16	0.18	0.18	0.35	0.35	0.31
	Short Cold	9.8	6.6	5.1	8.2	5.3	3.7	6.0	4.5	2.1	3.1	2.8	1.5	4.7	4.5	3.8	32%	35%	25%	48%	55%	64%	0.08	0.07	0.04	0.12	0.11	0.10
	Long Heat	72.8	71.7	64.9	54.2	49.8	39.5	3.2	0.7	0.6	1.0	4.4	2.4	7.9	14.7	2.6	1%	8%	77%	11%	27%	82%	0.16	0.66	0.37	1.19	2.21	0.39
	Short Heat	24.3	24.8	24.8	15.7	8.9	3.7	1.1	0.6	0.6	-0.5	6.8	0.5	-0.5	11.9	0.5	-2%	43%	45%	-2%	76%	46%	-0.08	1.01	0.08	-0.08	1.79	0.08

* Changes relative to Existing Stock

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Table H-3. New Multifamily Building Estimates of Excess Deaths Attributed to Extreme Events

Location (Climate Zone)	Event	Estimated Event Mortality						Event Mortality Reduction*								Annual Mortality Reduction*†			
		Deaths per Event						Lives Saved per Event				Improvement				Lives Saved per Year			
		Middle Floor Zones			Top Floor Zones			Middle Floors		Top Floors		Middle Floors		Top Floors		Middle Floors		Top Floors	
		Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	27.1	16.7	9.7	73.1	61.5	43.4	10.39	17.39	11.55	**29.69**	38.4%	64.2%	15.8%	40.6%	0.34	0.57	0.38	0.98
	Short Cold	6.9	3.0	1.4	22.7	17.1	9.3	3.88	5.46	5.59	13.42	56.3%	79.2%	24.6%	59.1%	0.13	0.18	0.18	0.44
	Long Heat	16.6	10.9	8.4	56.9	48.8	46.8	5.75	8.18	8.13	10.16	34.6%	49.2%	14.3%	17.8%	4.34	6.17	6.13	7.66
	Short Heat	0.4	0.5	0.6	12.0	5.9	3.6	-0.06	-0.18	6.07	8.32	-14.9%	**-42.8%**	50.8%	**69.6%**	-0.05	-0.13	4.58	6.27
Atlanta, GA (3A)	Long Cold	9.1	8.5	5.6	20.0	18.9	15.2	0.60	3.50	1.12	4.85	6.6%	38.3%	5.6%	24.2%	0.02	0.13	0.04	0.18
	Short Cold	1.4	1.3	0.9	3.9	3.4	2.3	0.18	0.58	0.50	1.51	12.5%	40.3%	13.0%	39.2%	0.01	0.02	0.02	0.06
	Long Heat	3.5	2.9	2.5	6.8	5.7	5.2	0.61	0.95	1.11	1.61	17.5%	27.2%	16.4%	23.7%	0.06	0.09	0.11	0.16
	Short Heat	0.3	0.2	0.2	1.6	1.2	1.0	0.06	0.10	0.37	0.53	19.5%	32.2%	24.1%	34.3%	0.01	0.01	0.04	0.05
Los Angeles, CA (3B)	Long Cold	13.6	14.5	12.1	36.6	34.9	24.4	**-0.97**	1.42	1.75	12.22	**-7.2%**	10.5%	4.8%	33.4%	**-0.15**	0.21	0.26	**1.82**
	Short Cold	1.8	1.6	1.6	4.8	4.9	4.4	0.25	0.16	-0.11	0.34	13.7%	9.2%	-2.4%	7.2%	0.04	0.02	-0.02	0.05
	Long Heat	159.3	158.2	159.4	280.1	241.9	246.8	1.11	-0.10	**38.18**	33.30	0.7%	-0.1%	13.6%	11.9%	0.38	-0.04	**13.06**	11.39
	Short Heat	31.0	34.2	32.7	76.2	66.0	61.0	**-3.18**	-1.66	10.23	15.26	-10.3%	-5.4%	13.4%	20.0%	**-1.09**	-0.57	3.50	5.22
Portland, OR (4C)	Long Cold	8.4	6.8	3.6	15.5	14.4	12.2	1.53	4.77	1.13	3.28	18.4%	57.1%	7.3%	21.2%	0.12	0.36	0.08	0.25
	Short Cold	0.7	0.5	0.2	2.4	1.8	1.1	0.18	0.47	0.57	1.34	27.6%	70.3%	23.8%	55.7%	0.01	0.04	0.04	0.10
	Long Heat	27.8	28.0	27.5	35.7	35.9	35.8	-0.20	0.25	-0.15	-0.11	-0.7%	0.9%	-0.4%	-0.3%	-0.02	0.03	-0.02	-0.01
	Short Heat	2.6	3.0	3.1	4.9	5.1	5.0	-0.38	-0.51	-0.19	-0.17	-14.9%	-19.9%	-3.9%	-3.4%	-0.04	-0.05	-0.02	-0.02
Detroit, MI (5A)	Long Cold	20.5	18.1	11.2	36.0	32.9	27.3	2.43	9.29	3.10	8.70	11.8%	45.3%	8.6%	24.2%	0.18	0.70	0.23	0.65
	Short Cold	5.3	4.5	3.0	10.5	9.1	6.9	0.82	2.39	1.34	3.58	15.4%	44.7%	12.8%	34.1%	0.06	0.18	0.10	0.27
	Long Heat	39.8	42.0	41.7	77.5	78.4	79.2	-2.15	-1.91	-0.87	-1.70	-5.4%	-4.8%	-1.1%	-2.2%	-0.36	-0.32	-0.14	-0.28
	Short Heat	5.6	5.5	5.1	22.0	20.4	18.7	0.10	0.56	1.59	3.36	1.8%	9.9%	7.2%	15.3%	0.02	0.09	0.26	0.56
Minneapolis/ St. Paul, MN (6A)	Long Cold	22.0	18.6	10.5	42.0	37.8	30.4	3.39	11.43	4.18	11.58	15.4%	52.0%	10.0%	27.6%	0.08	0.29	0.10	0.29
	Short Cold	3.2	2.3	0.5	8.2	6.8	4.7	0.98	2.73	1.36	3.44	30.3%	**84.5%**	16.7%	42.2%	0.02	0.07	0.03	0.09
	Long Heat	34.5	34.6	33.7	59.5	58.0	56.5	-0.12	0.73	1.44	2.94	-0.4%	2.1%	2.4%	4.9%	-0.02	0.11	0.22	0.44
	Short Heat	5.6	5.7	5.4	16.5	15.4	14.4	-0.05	0.24	1.05	2.05	-0.9%	4.3%	6.4%	12.5%	-0.01	0.04	0.16	0.31

* Changes relative to Historic Code (90.1 2004)

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Table H-4. Existing Multifamily Building Estimates of Excess Deaths Attributed to Extreme Events (Middle Floor Zones)

Middle Floor Zones		Estimated Event Mortality									Event Mortality Reduction*												Annual Mortality Reduction*†					
		Deaths per Event									Lives Saved per Event						Improvement						Lives Saved per Year					
		5th Percentile			Median			95th Percentile			Current Code 90.1 2019			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS			Current Code 90.1 2019			Beyond Code PHIUS		
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Houston, TX (2A)	Long Cold	24.4	15.0	10.2	19.3	14.1	9.5	14.8	13.4	9.1	9.37	5.16	1.42	**14.25**	9.76	5.69	38%	27%	10%	58%	51%	38%	0.31	0.17	0.05	0.47	0.32	0.19
	Short Cold	5.7	3.0	1.5	4.5	2.2	1.3	3.0	1.8	1.2	2.71	2.27	1.17	4.22	3.16	1.81	47%	51%	39%	74%	71%	61%	0.09	0.07	0.04	0.14	0.10	0.06
	Long Heat	21.6	9.9	8.3	31.7	10.3	8.7	39.0	10.8	9.2	11.72	21.35	28.23	13.34	22.97	29.82	54%	67%	72%	62%	73%	**77%**	8.83	16.10	21.28	10.06	17.32	**22.48**
	Short Heat	0.4	0.5	0.6	0.3	0.5	0.5	0.4	0.4	0.5	-0.13	-0.21	-0.10	-0.22	**-0.28**	-0.13	-34%	-80%	-27%	-58%	**-109%**	-38%	-0.09	-0.16	-0.07	-0.16	**-0.21**	-0.10
Atlanta, GA (3A)	Long Cold	9.1	7.5	6.2	7.8	7.3	5.9	6.5	7.0	5.6	1.66	0.47	-0.55	2.96	1.88	0.84	18%	6%	-9%	32%	24%	13%	0.06	0.02	-0.02	0.11	0.07	0.03
	Short Cold	1.6	1.2	1.0	1.3	1.1	0.9	1.2	1.1	0.9	0.35	0.20	0.08	0.57	0.44	0.29	23%	15%	7%	36%	32%	25%	0.01	0.01	0.00	0.02	0.02	0.01
	Long Heat	3.7	2.8	2.5	4.4	2.8	2.6	5.1	2.9	2.6	0.94	1.58	2.18	1.19	1.83	2.42	25%	36%	43%	32%	42%	48%	0.09	0.16	0.22	0.12	0.18	0.24
	Short Heat	0.4	0.2	0.2	0.5	0.2	0.2	0.6	0.3	0.2	0.15	0.22	0.30	0.17	0.25	0.33	41%	48%	53%	49%	54%	58%	0.01	0.02	0.03	0.02	0.02	0.03
Los Angeles, CA (3B)	Long Cold	15.0	12.9	12.3	10.9	12.3	13.1	7.2	13.2	12.5	2.09	-1.35	**-5.97**	2.68	-2.12	-5.34	14%	-12%	**-83%**	18%	-19%	-74%	0.31	-0.20	**-0.89**	0.40	-0.32	-0.80
	Short Cold	1.8	1.2	1.2	2.4	1.4	1.5	4.0	1.7	1.8	0.55	1.00	2.26	0.54	0.94	2.18	31%	41%	57%	30%	39%	55%	0.08	0.15	0.34	0.08	0.14	0.33
	Long Heat	155.0	141.8	140.6	179.1	145.8	144.5	200.0	149.4	148.2	13.12	33.4	50.6	14.37	34.6	**51.8**	8%	19%	25%	9%	19%	26%	4.49	11.41	17.32	4.91	11.84	17.71
	Short Heat	32.4	25.2	24.3	38.7	26.6	25.8	44.3	28.1	27.3	7.26	12.03	16.23	8.12	12.87	17.06	22%	31%	37%	25%	33%	39%	2.48	4.11	5.55	2.78	4.40	5.84
Portland, OR (4C)	Long Cold	8.3	5.5	4.5	7.5	5.4	4.1	6.3	5.1	3.6	2.81	2.13	1.13	3.84	3.39	2.62	34%	28%	18%	46%	45%	42%	0.21	0.16	0.08	0.29	0.25	0.20
	Short Cold	1.1	0.5	0.3	0.9	0.4	0.2	0.7	0.3	0.2	0.63	0.50	0.37	0.82	0.71	0.44	57%	55%	54%	74%	**78%**	65%	0.05	0.04	0.03	0.06	0.05	0.03
	Long Heat	29.3	27.1	26.4	30.6	27.4	26.8	31.5	27.7	27.1	2.19	3.26	3.80	2.85	3.85	4.34	7%	11%	12%	10%	13%	14%	0.22	0.32	0.38	0.28	0.38	0.43
	Short Heat	2.5	2.6	2.6	2.7	2.7	2.7	2.9	2.8	2.8	-0.07	0.04	0.17	-0.13	-0.02	0.11	-3%	2%	6%	-5%	-1%	4%	-0.01	0.00	0.02	-0.01	-0.00	0.01
Detroit, MI (5A)	Long Cold	23.2	16.8	13.6	21.7	16.5	13.3	19.6	16.3	12.4	6.46	5.13	3.24	9.63	8.36	7.11	28%	24%	17%	41%	39%	36%	0.48	0.38	0.24	**0.72**	0.63	0.53
	Short Cold	5.5	3.8	3.2	5.0	3.7	3.1	4.4	3.7	3.0	1.64	1.25	0.78	2.24	1.85	1.41	30%	25%	18%	41%	37%	32%	0.12	0.09	0.06	0.17	0.14	0.11
	Long Heat	44.1	39.0	38.2	48.0	40.2	39.5	51.4	41.3	40.7	5.03	7.81	10.09	5.82	8.48	10.66	11%	16%	20%	13%	18%	21%	0.83	1.29	1.66	0.96	1.40	1.76
	Short Heat	6.4	5.1	4.7	7.5	5.5	5.1	8.5	5.9	5.5	1.31	2.02	2.63	1.66	2.36	2.98	21%	27%	31%	26%	31%	35%	0.22	0.33	0.43	0.27	0.39	0.49
Minneapolis/ St. Paul, MN (6A)	Long Cold	24.2	16.8	12.5	22.5	16.6	12.1	20.0	16.3	11.8	7.39	5.93	3.74	11.69	10.34	8.28	31%	26%	19%	48%	46%	41%	0.18	0.15	0.09	0.29	0.26	0.21
	Short Cold	3.6	2.2	1.4	3.2	2.0	1.0	2.7	1.9	0.6	1.38	1.12	0.74	2.14	2.19	2.03	39%	35%	28%	60%	69%	76%	0.03	0.03	0.02	0.05	0.05	0.05
	Long Heat	37.0	33.1	32.1	40.2	33.4	32.5	42.9	33.8	32.9	3.98	6.79	9.16	4.94	7.71	10.03	11%	17%	21%	13%	19%	23%	0.60	1.02	1.37	0.74	1.16	1.50
	Short Heat	6.1	5.3	5.1	6.7	5.6	5.4	7.3	5.9	5.7	0.81	1.15	1.46	1.03	1.36	1.66	13%	17%	20%	17%	20%	23%	0.12	0.17	0.22	0.15	0.20	0.25

* Changes relative to Historic Code (90.1 2004)

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Table H-5. Existing Multifamily Building Estimates of Excess Deaths Attributed to Extreme Events (Top Floor Zones)

Top Floor Zones		Estimated Event Mortality									Event Mortality Reduction*												Annual Mortality Reduction*†					
		Deaths per Event									Lives Saved per Event						Improvement						Lives Saved per Year					
		5th Percentile			Median			95th Percentile			Current Code 90.1 2019			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS			Current Code 90.1 2019			Beyond Code PHIUS		
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Houston, TX (2A)	Long Cold	88.8	57.6	45.5	82.9	57.0	44.3	74.8	55.5	41.9	31.25	25.96	19.29	**43.33**	38.59	32.88	35%	31%	26%	49%	47%	44%	1.03	0.86	0.64	1.43	1.27	1.09
	Short Cold	29.3	14.8	10.8	26.9	14.2	9.7	23.1	13.3	8.3	14.55	12.62	9.78	18.50	17.18	14.76	50%	47%	42%	63%	64%	64%	0.48	0.42	0.32	0.61	0.57	0.49
	Long Heat	66.4	53.9	49.3	75.2	54.1	49.5	79.0	54.5	50.0	12.52	21.03	24.54	17.19	25.64	29.00	19%	28%	31%	26%	34%	37%	9.44	15.85	18.50	12.96	19.33	21.87
	Short Heat	20.1	7.7	4.3	23.9	8.0	4.6	23.9	8.3	4.8	12.33	15.88	15.59	15.73	19.29	19.05	61%	67%	65%	78%	**81%**	80%	9.30	11.97	11.76	11.86	14.55	14.36
Atlanta, GA (3A)	Long Cold	23.0	17.5	15.2	21.9	17.4	15.1	20.3	17.0	14.4	5.47	4.42	3.36	7.75	6.74	5.90	24%	20%	17%	34%	31%	29%	0.21	0.17	0.13	0.29	0.26	0.22
	Short Cold	5.5	3.0	2.4	5.1	3.0	2.3	4.6	2.9	2.2	2.43	2.12	1.68	3.08	2.79	2.37	44%	41%	37%	56%	55%	52%	0.09	0.08	**0.06**	0.12	0.11	0.09
	Long Heat	7.4	6.1	5.4	8.1	6.1	5.4	8.5	6.1	5.5	1.38	2.05	2.38	2.07	2.73	3.05	18%	25%	28%	28%	34%	36%	0.14	0.20	0.24	0.21	0.27	0.30
	Short Heat	1.9	1.3	1.1	2.2	1.3	1.1	2.5	1.3	1.1	0.69	0.94	1.15	0.88	1.14	1.33	35%	42%	47%	45%	51%	54%	0.07	0.09	0.11	0.09	0.11	0.13
Los Angeles, CA (3B)	Long Cold	61.3	29.9	24.4	50.0	29.3	24.0	36.7	28.2	23.0	31.42	20.68	8.43	36.92	25.97	13.72	51%	41%	23%	60%	52%	37%	4.68	3.08	1.26	**5.50**	3.87	2.04
	Short Cold	7.9	5.0	4.9	6.8	4.9	4.4	5.6	4.7	4.0	2.97	1.92	**0.88**	3.07	2.42	1.56	37%	28%	**16%**	39%	36%	28%	0.44	0.29	0.13	0.46	0.36	0.23
	Long Heat	287.2	255.6	244.1	347.2	257.2	245.6	390.4	260.3	248.7	31.67	90.0	130.1	43.12	101.5	**141.7**	11%	26%	33%	15%	29%	36%	10.83	30.79	44.51	14.75	34.73	**48.45**
	Short Heat	97.3	64.9	57.1	117.8	65.7	57.9	128.0	66.4	58.7	32.32	52.15	61.62	40.20	59.90	69.25	33%	44%	48%	41%	51%	54%	11.05	17.84	21.07	13.75	20.49	23.68
Portland, OR (4C)	Long Cold	17.1	13.7	12.4	16.8	13.6	12.3	16.2	13.3	11.8	3.42	3.18	2.94	4.67	4.47	4.42	20%	19%	18%	27%	27%	27%	0.26	0.24	0.22	0.35	0.34	0.33
	Short Cold	4.1	1.7	1.2	3.8	1.7	1.2	3.4	1.6	1.1	2.32	2.14	1.75	2.84	2.67	2.32	57%	56%	52%	**70%**	70%	69%	0.17	0.16	0.13	0.21	0.20	0.17
	Long Heat	36.2	35.7	35.3	38.2	35.8	35.4	39.1	35.9	35.6	**0.48**	2.38	3.13	0.87	2.75	3.49	**1%**	6%	8%	2%	7%	9%	**0.05**	0.24	0.31	0.09	0.27	0.35
	Short Heat	5.4	4.8	4.6	7.2	4.8	4.7	8.9	4.9	4.7	0.61	2.33	4.00	0.80	2.52	4.19	11%	32%	45%	15%	35%	47%	0.06	0.23	0.40	0.08	0.25	0.42
Detroit, MI (5A)	Long Cold	41.2	32.5	27.9	40.4	32.3	27.7	39.0	32.0	27.1	8.75	8.10	7.02	13.30	12.73	11.90	21%	20%	18%	32%	31%	31%	0.66	0.61	0.53	1.00	0.95	0.89
	Short Cold	12.3	8.3	7.0	12.0	8.3	6.9	11.3	7.9	6.4	3.96	3.68	3.32	5.31	5.07	4.83	32%	31%	29%	43%	42%	43%	0.30	0.28	0.25	0.40	0.38	0.36
	Long Heat	86.1	78.1	76.9	97.7	78.5	77.5	105.8	79.3	78.3	8.03	19.23	26.46	9.21	20.28	27.43	9%	20%	25%	11%	21%	26%	1.33	3.17	4.37	1.52	3.35	4.53
	Short Heat	26.6	20.1	18.3	29.8	20.3	18.6	31.8	20.6	18.9	6.52	9.53	11.19	8.30	11.27	12.91	25%	32%	35%	31%	38%	41%	1.08	1.57	1.85	1.37	1.86	2.13
Minneapolis/ St. Paul, MN (6A)	Long Cold	47.9	36.9	31.1	46.9	36.8	30.9	45.1	36.3	30.1	10.99	10.09	8.77	16.77	15.97	15.00	23%	22%	19%	35%	34%	33%	0.27	0.25	0.22	0.42	0.40	0.38
	Short Cold	10.6	6.4	4.9	10.1	6.3	4.8	9.3	6.1	4.5	4.28	3.86	3.18	5.72	5.35	4.75	40%	38%	34%	54%	53%	51%	0.11	0.10	0.08	0.14	0.13	0.12
	Long Heat	67.0	57.6	55.8	75.6	57.7	56.0	80.5	57.8	56.1	9.37	17.92	22.69	11.14	19.65	24.40	14%	24%	28%	17%	26%	30%	1.41	2.69	3.40	1.67	2.95	3.66
	Short Heat	21.5	15.2	14.1	24.4	15.4	14.3	24.8	15.6	14.6	6.27	9.01	9.14	7.44	10.13	10.22	29%	37%	37%	35%	41%	41%	0.94	1.35	1.37	1.12	1.52	1.53

* Changes relative to Historic Code (90.1 2004)
† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Table H-6. Existing Multifamily Estimates of Excess Deaths Attributed to Extreme Events (Combined Floor Zones)

Combined Floor Zones		Estimated Event Mortality									Event Mortality Reduction*												Annual Mortality Reduction*†					
		Deaths per Event									Lives Saved per Event						Improvement						Lives Saved per Year					
		5th Percentile			Median			95th Percentile			Current Code 90.1 2019			Beyond Code PHIUS			Current Code IECC 2021			Beyond Code PHIUS			Current Code 90.1 2019			Beyond Code PHIUS		
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%	5%	Med	95%
Houston, TX (2A)	Long Cold	113.3	72.6	55.7	102.2	71.1	53.8	89.6	68.9	51.0	40.62	31.11	20.71	**57.58**	48.36	38.57	36%	30%	23%	51%	47%	43%	1.34	1.03	0.68	1.90	1.60	1.27
	Short Cold	35.1	17.8	12.3	31.3	16.4	11.0	26.1	15.1	9.5	17.26	14.90	10.95	22.72	20.34	16.57	49%	48%	42%	65%	65%	64%	0.57	0.49	0.36	0.75	0.67	0.55
	Long Heat	88.1	63.8	57.5	106.8	64.5	58.2	118.0	65.2	59.1	24.24	42.37	52.77	30.53	48.61	58.82	28%	40%	45%	35%	45%	50%	18.28	31.95	39.79	23.02	36.65	44.35
	Short Heat	20.4	8.2	4.9	24.1	8.5	5.1	24.2	8.7	5.3	12.20	15.67	15.50	15.52	19.01	18.92	60%	65%	64%	76%	**79%**	78%	9.20	11.82	11.68	11.70	14.33	14.26
Atlanta, GA (3A)	Long Cold	32.1	25.0	21.4	29.6	24.7	21.0	26.8	24.0	20.1	7.13	4.89	2.81	10.71	8.62	6.74	22%	17%	10%	33%	29%	25%	0.27	0.19	0.11	0.41	0.33	0.26
	Short Cold	7.0	4.3	3.4	6.5	4.1	3.2	5.7	4.0	3.1	2.78	2.32	**1.76**	3.65	3.23	2.65	40%	36%	31%	52%	50%	46%	0.11	0.09	**0.07**	0.14	0.12	0.10
	Long Heat	11.1	8.8	7.9	12.5	8.9	8.0	13.6	9.0	8.1	2.31	3.63	4.55	3.26	4.56	5.47	21%	29%	34%	29%	36%	40%	0.23	0.36	0.45	0.32	0.45	0.54
	Short Heat	2.3	1.5	1.2	2.7	1.5	1.3	3.0	1.6	1.4	0.83	1.16	1.45	1.05	1.38	1.66	36%	43%	48%	46%	52%	55%	0.08	0.12	0.14	0.10	0.14	0.16
Los Angeles, CA (3B)	Long Cold	76.3	42.8	36.7	60.9	41.6	37.0	43.9	41.4	35.5	33.51	19.33	2.46	39.59	23.85	8.37	44%	32%	**6%**	52%	39%	19%	4.99	2.88	0.37	**5.90**	3.55	1.25
	Short Cold	9.7	6.2	6.1	9.3	6.3	5.9	9.6	6.4	5.8	3.52	2.92	3.14	3.61	3.37	3.74	36%	31%	33%	37%	36%	39%	0.52	0.43	0.47	0.54	0.50	0.56
	Long Heat	442.2	397.4	384.7	526.3	402.9	390.1	590.4	409.6	397.0	44.78	123.4	180.8	57.49	136.2	**193.5**	10%	23%	31%	13%	26%	33%	15.32	42.20	61.83	19.66	46.57	**66.16**
	Short Heat	129.7	90.1	81.4	156.5	92.3	83.7	172.3	94.5	86.0	39.58	64.18	77.85	48.32	72.76	86.31	31%	41%	45%	37%	47%	50%	13.54	21.95	26.62	16.53	24.89	29.52
Portland, OR (4C)	Long Cold	25.4	19.2	16.9	24.3	19.0	16.4	22.5	18.4	15.4	6.22	5.32	4.07	8.51	7.86	7.04	24%	22%	18%	33%	32%	31%	0.47	0.40	0.31	0.64	0.59	0.53
	Short Cold	5.2	2.2	1.5	4.7	2.1	1.4	4.1	1.9	1.3	2.96	2.64	2.12	3.66	3.38	2.77	57%	56%	52%	71%	**71%**	68%	0.22	0.20	0.16	0.27	0.25	0.21
	Long Heat	65.5	62.8	61.7	68.8	63.2	62.2	70.6	63.6	62.7	2.67	5.64	6.93	3.72	6.61	7.83	**4%**	8%	10%	6%	10%	11%	0.26	0.56	0.69	0.37	0.65	0.77
	Short Heat	7.9	7.3	7.2	9.9	7.5	7.4	11.8	7.7	7.5	**0.54**	2.37	4.17	0.67	2.50	4.30	7%	24%	35%	8%	25%	36%	**0.05**	0.23	0.41	0.07	0.25	0.43
Detroit, MI (5A)	Long Cold	64.4	49.2	41.5	62.1	48.9	41.0	58.6	48.3	39.6	15.21	13.23	10.26	22.94	21.09	19.02	24%	21%	18%	36%	34%	32%	1.14	0.99	0.77	1.72	1.58	1.43
	Short Cold	17.8	12.2	10.2	16.9	12.0	10.0	15.7	11.6	9.5	5.60	4.93	4.10	7.55	6.92	6.24	31%	29%	26%	42%	41%	40%	0.42	0.37	0.31	0.57	0.52	0.47
	Long Heat	130.2	117.1	115.1	145.7	118.7	117.0	157.1	120.6	119.1	13.06	27.03	36.54	15.03	28.76	38.08	10%	19%	23%	12%	20%	24%	2.15	4.46	6.03	2.48	4.75	6.28
	Short Heat	33.0	25.2	23.0	37.3	25.8	23.7	40.3	26.5	24.4	7.83	11.56	13.83	9.96	13.62	15.89	24%	31%	34%	30%	36%	39%	1.29	1.91	2.28	1.64	2.25	2.62
Minneapolis/ St. Paul, MN (6A)	Long Cold	72.1	53.7	43.6	69.4	53.3	43.1	65.1	52.6	41.8	18.38	16.02	12.50	28.46	26.31	23.28	26%	23%	19%	39%	38%	36%	0.46	0.40	0.31	0.71	0.66	0.58
	Short Cold	14.2	8.5	6.3	13.3	8.3	5.8	12.0	8.0	5.2	5.66	4.98	3.93	7.85	7.55	6.78	40%	37%	33%	55%	57%	57%	0.14	0.12	0.10	0.20	0.19	0.17
	Long Heat	104.0	90.7	87.9	115.8	91.1	88.5	123.4	91.6	89.0	13.36	24.71	31.85	16.08	27.36	34.43	13%	21%	26%	15%	24%	28%	2.00	3.71	4.78	2.41	4.10	5.16
	Short Heat	27.6	20.5	19.1	31.2	21.0	19.7	32.1	21.5	20.2	7.08	10.16	10.60	8.47	11.49	11.88	26%	33%	33%	31%	37%	37%	1.06	1.52	1.59	1.27	1.72	1.78

* Changes relative to Historic Code (90.1 2004)

† Event Mortality Reduction multiplied by the appropriate joint probability factor (see Table 9)

Appendix I – Summary Tables

Table I-1. Impact of Improved Efficiency on Resilience in New Single-Family Buildings

Location (Climate Zone)	Event	SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
		Historic Code IECC 2006	Current Code IECC 2021	Beyond Code PHIUS	Historic Code IECC 2006	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	371	363	347	6.29	6.33	6.38	1%	1%	1.46	3.75	2%	5%
	Short Cold	228	230	227	1.88	1.88	1.88	-	-	0.45	1.19	2%	4%
	Long Heat	451	290	197	4.42	5.75	7	23%	18%	6.80	7.87	58%	67%
	Short Heat	228	182	155	1.79	2	2	10%	-	4.16	5.75	47%	64%
Atlanta, GA (3A)	Long Cold	1,572	1,536	1,509	0.88	0.88	0.88	-	-	0.08	0.15	0%	1%
	Short Cold	270	232	213	0.92	1.04	2	12%	48%	0.22	0.32	4%	7%
	Long Heat	328	132	50	3.63	7	7	48%	-	1.41	1.86	28%	37%
	Short Heat	92	46	25	2	2	2	-	-	0.16	0.20	13%	17%
Los Angeles, CA (3B)	Long Cold	90	70	54	7	7	7	-	-	-0.42	-0.51	-1%	-1%
	Short Cold	-	-	-	2	2	2	-	-	0.66	0.72	12%	13%
	Long Heat	34	1.7	-	7	7	7	-	-	8.62	4.79	6%	3%
	Short Heat	20	2.2	-	2	2	2	-	-	11.67	16.10	20%	28%
Portland, OR (4C)	Long Cold	1,366	1,328	1,289	1.04	1.08	1.13	4%	4%	0.10	0.19	1%	1%
	Short Cold	1.3	0.4	-	2	2	2	-	-	0.21	0.46	9%	20%
	Long Heat	195	149	101	7	7	7	-	-	0.01	0.28	0%	1%
	Short Heat	-	-	-	2	2	2	-	-	0.03	0.15	2%	11%
Detroit, MI (5A)	Long Cold	1,544	1,430	1,212	1.25	1.42	1.71	12%	17%	0.47	1.37	1%	4%
	Short Cold	706	650	538	0.79	0.83	0.88	5%	5%	0.20	0.62	2%	6%
	Long Heat	90	69	44	7	7	7	-	-	-1.13	-1.31	-3%	-3%
	Short Heat	55	44	34	2	2	2	-	-	-0.49	-0.41	-3%	-3%
Minneapolis/ St. Paul, MN (6A)	Long Cold	2,049	1,895	1,594	0.58	0.71	0.83	18%	15%	0.63	1.78	2%	5%
	Short Cold	487	467	418	0.88	0.96	1.08	9%	12%	0.07	0.24	1%	3%
	Long Heat	206	180	136	7	7	7	-	-	0.37	1.75	1%	4%
	Short Heat	90	84	71	2	2	2	-	-	-0.20	0.07	-1%	1%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (IECC 2006)

Table I-2. Impact of Improved Efficiency on Resilience in the 5th Percentile Building of Existing Single-Family Building Sample

5th Percentile		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	1,571	1,139	634	1.79	3.00	4.33	40%	31%	11.88	26.79	14%	33%
	Short Cold	632	302	52	0.96	1.63	2	41%	19%	10.70	18.63	37%	65%
	Long Heat	1,188	896	651	1.96	3.00	4.54	35%	34%	8.98	25.46	11%	32%
	Short Heat	323	144	47	1.33	2	2	33%	-	-1.72	5.63	-14%	44%
Atlanta, GA (3A)	Long Cold	3,468	2,754	1,720	1.21	1.75	2.79	31%	37%	2.94	7.23	14%	35%
	Short Cold	714	309	61	0.88	1.58	2	45%	21%	1.47	2.62	31%	56%
	Long Heat	981	696	308	1.71	2.75	4.88	38%	44%	0.70	1.08	8%	13%
	Short Heat	206	36	1	2	2	2	-	-	0.65	1.52	32%	74%
Los Angeles, CA (3B)	Long Cold	360	20	-	4.25	7	7	39%	-	10.01	22.12	25%	54%
	Short Cold	-	-	-	2	2	2	-	-	1.22	1.20	22%	21%
	Long Heat	423	349	95	4.58	5.63	7	19%	20%	22.09	85.67	6%	22%
	Short Heat	127	31	-	2	2	2	-	-	-7.24	64.67	-7%	59%
Portland, OR (4C)	Long Cold	3,687	2,492	1,234	0.92	1.96	2.83	53%	31%	2.93	6.20	18%	38%
	Short Cold	598	222	35	0.92	1.92	2	52%	4%	1.11	1.84	31%	51%
	Long Heat	857	1,014	569	3.54	3.13	4.54	-13%	31%	-2.98	-2.29	-8%	-6%
	Short Heat	11	-	-	2	2	2	-	-	-0.97	0.59	-21%	12%
Detroit, MI (5A)	Long Cold	5,227	4,479	2,589	0.63	1.21	1.38	48%	12%	3.23	10.34	8%	26%
	Short Cold	1,671	1,142	358	0.63	0.83	1.58	25%	47%	1.60	5.12	14%	46%
	Long Heat	687	686	670	2.50	3.21	3.33	22%	4%	3.65	6.10	3%	6%
	Short Heat	168	127	53	2	2	2	-	-	-0.74	-0.74	-2%	-2%
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,746	5,094	3,228	0.42	0.88	1.17	52%	25%	6.36	14.00	14%	32%
	Short Cold	1,151	503	203	0.58	1.25	2	53%	38%	3.14	4.67	32%	48%
	Long Heat	714	681	609	3.67	4.46	4.96	18%	10%	1.05	7.90	1%	11%
	Short Heat	247	255	209	1.79	1.71	2	-5%	15%	-0.51	-0.51	-2%	-2%

* Cooling hours > 86°F, Heating hours < 54°F
† Changes relative to Existing Stock

Table I-3. Impact of Improved Efficiency on Resilience in the Median Building of Existing Single-Family Building Sample

Medians		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	749	222	-	3.79	6.92	7	45%	1%	20.00	43.21	32%	69%
	Short Cold	295	32	-	1.50	2	2	25%	-	9.21	14.34	47%	74%
	Long Heat	600	141	-	4.00	7	7	43%	-	42.09	50.19	80%	96%
	Short Heat	120	7	-	2	2	2	-	-	7.91	8.38	86%	92%
Atlanta, GA (3A)	Long Cold	2,558	1,610	200	1.38	2.25	7	39%	68%	3.60	8.74	21%	52%
	Short Cold	410	94	-	1.29	2	2	35%	-	1.27	2.15	35%	59%
	Long Heat	438	59	-	2.92	7	7	58%	-	0.89	5.87	14%	93%
	Short Heat	36	-	-	2	2	2	-	-	0.53	0.63	55%	66%
Los Angeles, CA (3B)	Long Cold	87	-	-	7	7	7	-	0%	5.19	5.35	25%	25%
	Short Cold	-	-	-	2	2	2	-	0%	0.05	-0.24	1%	-5%
	Long Heat	100	-	-	7	7	7	-	-	126.88	202.82	53%	84%
	Short Heat	25	-	-	2	2	2	-	-	53.98	57.29	76%	80%
Portland, OR (4C)	Long Cold	2,963	1,849	237	1.08	2.42	6.75	55%	64%	3.18	8.58	22%	58%
	Short Cold	366	89	-	1.46	5.46	2	73%	-173%	1.25	1.95	42%	65%
	Long Heat	371	319	-	4.71	7	7	33%	-	-2.61	24.55	-8%	71%
	Short Heat	-	-	-	2	2	2	-	-	-0.27	1.08	-15%	58%
Detroit, MI (5A)	Long Cold	4,248	3,020	1,778	0.92	1.67	2.38	45%	30%	5.11	10.81	14%	30%
	Short Cold	1,291	670	211	0.75	1.17	2	36%	42%	2.52	4.97	25%	48%
	Long Heat	223	53	0.3	6.83	7	7	2%	-	6.90	26.00	9%	35%
	Short Heat	30	1	-	2	2	2	-	-	2.23	16.55	11%	84%
Minneapolis/ St. Paul, MN (6A)	Long Cold	5,397	3,699	2,190	0.58	1.17	1.83	50%	36%	7.33	14.02	19%	36%
	Short Cold	802	293	61	0.92	1.71	2	46%	15%	2.83	4.47	35%	55%
	Long Heat	215	66	5	7	7	7	-	-	4.39	14.71	8%	27%
	Short Heat	40	0.2	-	2	2	2	-	-	6.75	11.91	43%	76%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Existing Stock

Table I-4. Impact of Improved Efficiency on Resilience in the 95th Percentile Building of Existing Single-Family Building Sample

95th Percentile		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	136	0.3	-	7	7	7	-	-	16.75	28.72	41%	71%
	Short Cold	28	-	-	2	2	2	-	-	5.89	8.95	52%	78%
	Long Heat	56	-	-	7	7	7	-	-	0.30	1.49	14%	72%
	Short Heat	0.03	-	-	2	2	2	-	-	-0.25	0.17	-109%	77%
Atlanta, GA (3A)	Long Cold	1,047	112	-	2.75	7	7	61%	-	3.64	6.53	33%	58%
	Short Cold	56	-	-	2	2	2	-	-	0.79	1.05	36%	49%
	Long Heat	1.4	-	-	7	7	7	-	-	0.64	0.55	26%	22%
	Short Heat	-	-	-	2	2	2	-	-	-0.05	-0.10	-10%	-17%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	-1.16	0.54	-7%	3%
	Short Cold	-	-	-	2	2	2	-	-	1.66	1.64	34%	34%
	Long Heat	-	-	-	7	7	7	-	-	11.07	8.07	61%	45%
	Short Heat	-	-	-	2	2	2	-	-	10.24	8.97	87%	76%
Portland, OR (4C)	Long Cold	1,692	379	-	1.92	5.71	7	66%	18%	4.64	8.58	40%	74%
	Short Cold	77	-	-	2	2	2	-	-	1.12	1.30	56%	65%
	Long Heat	3	-	-	7	7	7	-	-	22.12	22.06	92%	92%
	Short Heat	-	-	-	2	2	2	-	-	0.29	0.33	58%	68%
Detroit, MI (5A)	Long Cold	2,547	1,484	637	1.71	2.50	4.42	32%	43%	4.96	10.05	17%	35%
	Short Cold	637	300	30	1.17	1.63	2	28%	19%	1.55	3.51	20%	46%
	Long Heat	-	-	-	7	7	7	-	-	4.98	4.56	79%	73%
	Short Heat	-	-	-	2	2	2	-	-	-0.27	-0.64	-73%	-175%
Minneapolis/ St. Paul, MN (6A)	Long Cold	3,575	1,967	912	0.96	2.00	3.67	52%	45%	7.22	12.39	23%	39%
	Short Cold	384	110	-	1.38	2	2	31%	-	1.51	3.82	25%	64%
	Long Heat	-	-	-	7	7	7	-	-	2.44	2.62	77%	82%
	Short Heat	-	-	-	2	2	2	-	-	0.51	0.51	45%	46%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Existing Stock

Table I-5. Impact of Improved Efficiency on Resilience in the Middle Floor Zones of New Multifamily Buildings

Middle Floor Zones		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	-	-	-	7	7	7	-	-	10.39	17.39	38%	64%
	Short Cold	-	-	-	2	2	2	-	-	3.88	5.46	56%	79%
	Long Heat	197	133	110	7	7	7	-	-	5.75	8.18	35%	49%
	Short Heat	-	-	-	2	2	2	-	-	-0.06	-0.18	-15%	-43%
Atlanta, GA (3A)	Long Cold	98	57	-	7	7	7	-	-	0.60	3.50	7%	38%
	Short Cold	-	-	-	2	2	2	-	-	0.18	0.58	13%	40%
	Long Heat	-	-	-	7	7	7	-	-	0.61	0.95	18%	27%
	Short Heat	-	-	-	2	2	2	-	-	0.06	0.10	19%	32%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	-0.97	1.42	-7%	10%
	Short Cold	-	-	-	2	2	2	-	-	0.25	0.16	14%	9%
	Long Heat	-	-	-	7	7	7	-	-	1.11	-0.10	1%	0%
	Short Heat	-	-	-	2	2	2	-	-	-3.18	-1.66	-10%	-5%
Portland, OR (4C)	Long Cold	255	95	-	5.71	7	7	18%	-	1.53	4.77	18%	57%
	Short Cold	-	-	-	2	2	2	-	-	0.18	0.47	28%	70%
	Long Heat	-	-	-	7	7	7	-	-	-0.20	0.25	-1%	1%
	Short Heat	-	-	-	2	2	2	-	-	-0.38	-0.51	-15%	-20%
Detroit, MI (5A)	Long Cold	573	288	-	4.38	5.50	7	20%	21%	2.43	9.29	12%	45%
	Short Cold	45	1	-	2	2	2	-	-	0.82	2.39	15%	45%
	Long Heat	-	-	-	7	7	7	-	-	-2.15	-1.91	-5%	-5%
	Short Heat	-	-	-	2	2	2	-	-	0.10	0.56	2%	10%
Minneapolis/ St. Paul, MN (6A)	Long Cold	802	412	0	4.08	5.13	7	20%	27%	3.39	11.43	15%	52%
	Short Cold	-	-	-	2	2	2	-	-	0.98	2.73	30%	84%
	Long Heat	21	19	16	7	7	7	-	-	-0.12	0.73	0%	2%
	Short Heat	-	-	-	2	2	2	-	-	-0.05	0.24	-1%	4%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-6. Impact of Improved Efficiency on Resilience in the Top Floor Zones of New Multifamily Buildings

Top Floor Zones		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	483	273	84	5.00	5.75	7	13%	18%	11.55	29.69	16%	41%
	Short Cold	207	80	-	2	2	2	-	-	5.59	13.42	25%	59%
	Long Heat	613	509	500	3.00	3.75	3.92	20%	4%	8.13	10.16	14%	18%
	Short Heat	206	126	83	2	2	2	-	-	6.07	8.32	51%	70%
Atlanta, GA (3A)	Long Cold	2,164	1,964	1,203	0.75	1.04	2.04	28%	49%	1.12	4.85	6%	24%
	Short Cold	209	126	0	2	2	2	-	-	0.50	1.51	13%	39%
	Long Heat	355	169	98	1.88	7	7	73%	-	1.11	1.61	16%	24%
	Short Heat	79	30	16	2	2	2	-	-	0.37	0.53	24%	34%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	1.75	12.22	5%	33%
	Short Cold	-	-	-	2	2	2	-	-	-0.11	0.34	-2%	7%
	Long Heat	61	9	3	7	7	7	-	-	38.18	33.30	14%	12%
	Short Heat	11	1	-	2	2	2	-	-	10.23	15.26	13%	20%
Portland, OR (4C)	Long Cold	2,282	1,850	1,177	0.79	1.25	2.25	37%	44%	1.13	3.28	7%	21%
	Short Cold	53	4	-	2	2	2	-	-	0.57	1.34	24%	56%
	Long Heat	276	212	154	3.83	7	7	45%	-	-0.15	-0.11	0%	0%
	Short Heat	-	-	-	2	2	2	-	-	-0.19	-0.17	-4%	-3%
Detroit, MI (5A)	Long Cold	3,297	2,599	1,524	0.88	1.42	2.63	38%	46%	3.10	8.70	9%	24%
	Short Cold	982	673	290	-	0.21	0.79	100%	74%	1.34	3.58	13%	34%
	Long Heat	126	105	99	7	7	7	-	-	-0.87	-1.70	-1%	-2%
	Short Heat	54	36	26	2	2	2	-	-	1.59	3.36	7%	15%
Minneapolis/ St. Paul, MN (6A)	Long Cold	4,719	3,731	2,178	0.04	0.46	1.54	91%	70%	4.18	11.58	10%	28%
	Short Cold	485	274	33	0.29	0.79	2	63%	60%	1.36	3.44	17%	42%
	Long Heat	290	255	232	5.63	5.79	5.92	3%	2%	1.44	2.94	2%	5%
	Short Heat	89	66	45	2	2	2	-	-	1.05	2.05	6%	12%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-7. Impact of Improved Efficiency on Resilience in New Multifamily Buildings (Combined Middle and Top Floor Zones)

Combined Floor Zones		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	483	273	84	5.00	5.75	7	13%	18%	21.94	47.08	22%	47%
	Short Cold	207	80	-	2	2	2	-	-	9.48	18.88	32%	64%
	Long Heat	810	642	609	3.00	3.75	3.92	20%	4%	13.88	18.34	19%	25%
	Short Heat	206	126	83	2	2	2	-	-	6.01	8.14	49%	66%
Atlanta, GA (3A)	Long Cold	2,262	2,020	1,203	0.75	1.04	2.04	28%	49%	1.72	8.34	6%	29%
	Short Cold	209	126	0	2	2	2	-	-	0.68	2.09	13%	40%
	Long Heat	355	169	98	1.88	7	7	73%	-	1.72	2.55	17%	25%
	Short Heat	79	30	16	2	2	2	-	-	0.43	0.63	23%	34%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	0.77	13.64	2%	27%
	Short Cold	-	-	-	2	2	2	-	-	0.13	0.51	2%	8%
	Long Heat	61	9	3	7	7	7	-	-	39.29	33.19	9%	8%
	Short Heat	11	1	-	2	2	2	-	-	7.05	13.60	7%	13%
Portland, OR (4C)	Long Cold	2,537	1,945	1,177	0.79	1.25	2.25	37%	44%	2.67	8.05	11%	34%
	Short Cold	53	4	-	2	2	2	-	-	0.76	1.81	25%	59%
	Long Heat	276	212	154	3.83	7	7	45%	-	-0.36	0.15	-1%	0%
	Short Heat	-	-	-	2	2	2	-	-	-0.57	-0.68	-8%	-9%
Detroit, MI (5A)	Long Cold	3,870	2,887	1,524	0.88	1.42	2.63	38%	46%	5.53	17.99	10%	32%
	Short Cold	1,027	674	290	-	0.21	0.79	100%	74%	2.17	5.96	14%	38%
	Long Heat	126	105	99	7	7	7	-	-	-3.02	-3.61	-3%	-3%
	Short Heat	54	36	26	2	2	2	-	-	1.69	3.92	6%	14%
Minneapolis/ St. Paul, MN (6A)	Long Cold	5,521	4,142	2,178	0.04	0.46	1.54	91%	70%	7.58	23.01	12%	36%
	Short Cold	485	274	33	0.29	0.79	2	63%	60%	2.34	6.16	21%	54%
	Long Heat	311	274	248	5.63	5.79	5.92	3%	2%	1.32	3.67	1%	4%
	Short Heat	89	66	45	2	2	2	-	-	1.00	2.30	5%	10%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-8. Impact of Improved Efficiency on Resilience in the 5th Percentile of the Middle Floor Zones in Existing Multifamily Buildings

Middle Floor Zones 5th Percentile		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	-	-	-	7	7	7	-	-	9.37	14.25	38%	58%
	Short Cold	-	-	-	2	2	2	-	-	2.71	4.22	47%	74%
	Long Heat	254	127	108	6.58	7	7	6%	-	11.72	13.34	54%	62%
	Short Heat	-	-	-	2	2	2	-	-	-0.13	-0.22	-34%	-58%
Atlanta, GA (3A)	Long Cold	132	5	-	7	7	7	-	-	1.66	2.96	18%	32%
	Short Cold	-	-	-	2	2	2	-	-	0.35	0.57	23%	36%
	Long Heat	0.4	-	-	7	7	7	-	-	0.94	1.19	25%	32%
	Short Heat	-	-	-	2	2	2	-	-	0.15	0.17	41%	49%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	2.09	2.68	14%	18%
	Short Cold	-	-	-	2	2	2	-	-	0.55	0.54	31%	30%
	Long Heat	-	-	-	7	7	7	-	-	13.12	14.37	8%	9%
	Short Heat	-	-	-	2	2	2	-	-	7.26	8.12	22%	25%
Portland, OR (4C)	Long Cold	293	3.4	-	6.46	7	7	8%	-	2.81	3.84	34%	46%
	Short Cold	-	-	-	2	2	2	-	-	0.63	0.82	57%	74%
	Long Heat	-	-	-	7	7	7	-	-	2.19	2.85	7%	10%
	Short Heat	-	-	-	2	2	2	-	-	-0.07	-0.13	-3%	-5%
Detroit, MI (5A)	Long Cold	917	154	-	4.38	7	7	38%	-	6.46	9.63	28%	41%
	Short Cold	67	-	-	2	2	2	-	-	1.64	2.24	30%	41%
	Long Heat	-	-	-	7	7	7	-	-	5.03	5.82	11%	13%
	Short Heat	-	-	-	2	2	2	-	-	1.31	1.66	21%	26%
Minneapolis/ St. Paul, MN (6A)	Long Cold	1,126	247	10	4.13	6.75	7	39%	4%	7.39	11.69	31%	48%
	Short Cold	-	-	-	2	2	2	-	-	1.38	2.14	39%	60%
	Long Heat	35	18	14	7	7	7	-	-	3.98	4.94	11%	13%
	Short Heat	-	-	-	2	2	2	-	-	0.81	1.03	13%	17%

* Cooling hours > 86°F, Heating hours < 54°F
† Changes relative to Historic Code (90.1 2004)

Table I-9. Impact of Improved Efficiency on Resilience in the Median of the Middle Floor Zones in Existing Multifamily Buildings

Middle Floor Zones Median		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
		Historic Code	Current Code	Beyond Code	Historic Code	Current Code	Beyond Code	Current Code	Beyond Code	Current Code	Beyond Code	Current Code	Beyond Code
Location (Climate Zone)	**Event**	90.1 2004	90.1 2019	PHIUS	90.1 2004	90.1 2019	PHIUS	90.1 2019	PHIUS	90.1 2019	PHIUS	90.1 2019	PHIUS
Houston, TX (2A)	Long Cold	-	-	-	7	7	7	-	-	5.16	9.76	27%	51%
	Short Cold	-	-	-	2	2	2	-	-	2.27	3.16	51%	71%
	Long Heat	347	132	113	5.96	7	7	15%	-	21.35	22.97	67%	73%
	Short Heat	1.3	-	-	2	2	2	-	-	-0.21	-0.28	-80%	-109%
Atlanta, GA (3A)	Long Cold	23	3	-	7	7	7	-	-	0.47	1.88	6%	24%
	Short Cold	-	-	-	2	2	2	-	-	0.20	0.44	15%	32%
	Long Heat	15	-	-	7	7	7	-	-	1.58	1.83	36%	42%
	Short Heat	-	-	-	2	2	2	-	-	0.22	0.25	48%	54%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	-1.35	-2.12	-12%	-19%
	Short Cold	-	-	-	2	2	2	-	-	1.00	0.94	41%	39%
	Long Heat	-	-	-	7	7	7	-	-	33.35	34.62	19%	19%
	Short Heat	-	-	-	2	2	2	-	-	12.03	12.87	31%	33%
Portland, OR (4C)	Long Cold	186	1.6	-	7	7	7	-	-	2.13	3.39	28%	45%
	Short Cold	-	-	-	2	2	2	-	-	0.50	0.71	55%	78%
	Long Heat	2.1	-	-	7	7	7	-	-	3.26	3.85	11%	13%
	Short Heat	-	-	-	2	2	2	-	-	0.04	-0.02	2%	-1%
Detroit, MI (5A)	Long Cold	705	142	-	4.96	7	7	29%	-	5.13	8.36	24%	39%
	Short Cold	21	-	-	2	2	2	-	-	1.25	1.85	25%	37%
	Long Heat	-	-	-	7	7	7	-	-	7.81	8.48	16%	18%
	Short Heat	-	-	-	2	2	2	-	-	2.02	2.36	27%	31%
Minneapolis/ St. Paul, MN (6A)	Long Cold	885	236	6	4.75	6.83	7	30%	2%	5.93	10.34	26%	46%
	Short Cold	-	-	-	2	2	2	-	-	1.12	2.19	35%	69%
	Long Heat	54	18	15	7	7	7	-	-	6.79	7.71	17%	19%
	Short Heat	-	-	-	2	2	2	-	-	1.15	1.36	17%	20%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-10. Impact of Improved Efficiency on Resilience in the 95th Percentile of the Middle Floor Zones in Existing Multifamily Buildings

Middle Floor Zones 95th Percentile		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	**Event**	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS
Houston, TX (2A)	Long Cold	-	-	-	7	7	7	-	-	1.42	5.69	10%	38%
	Short Cold	-	-	-	2	2	2	-	-	1.17	1.81	39%	61%
	Long Heat	430	139	119	5.46	7	7	22%	-	28.23	29.82	72%	77%
	Short Heat	9	-	-	2	2	2	-	-	-0.10	-0.13	-27%	-38%
Atlanta, GA (3A)	Long Cold	0.02	0.97	-	7	7	7	-	-	-0.55	0.84	-9%	13%
	Short Cold	-	-	-	2	2	2	-	-	0.08	0.29	7%	25%
	Long Heat	49	-	-	7	7	7	-	-	2.18	2.42	43%	48%
	Short Heat	-	-	-	2	2	2	-	-	0.30	0.33	53%	58%
Los Angeles, CA (3B)	Long Cold	-	-	-	7	7	7	-	-	-5.97	-5.34	-83%	-74%
	Short Cold	-	-	-	2	2	2	-	-	2.26	2.18	57%	55%
	Long Heat	-	-	-	7	7	7	-	-	50.64	51.78	25%	26%
	Short Heat	-	-	-	2	2	2	-	-	16.23	17.06	37%	39%
Portland, OR (4C)	Long Cold	68	0.2	-	7	7	7	-	-	1.13	2.62	18%	42%
	Short Cold	-	-	-	2	2	2	-	-	0.37	0.44	54%	65%
	Long Heat	10	-	-	7	7	7	-	-	3.80	4.34	12%	14%
	Short Heat	-	-	-	2	2	2	-	-	0.17	0.11	6%	4%
Detroit, MI (5A)	Long Cold	445	131	-	5.79	7	7	17%	-	3.24	7.11	17%	36%
	Short Cold	2	-	-	2	2	2	-	-	0.78	1.41	18%	32%
	Long Heat	-	-	-	7	7	7	-	-	10.09	10.66	20%	21%
	Short Heat	-	-	-	2	2	2	-	-	2.63	2.98	31%	35%
Minneapolis/ St. Paul, MN (6A)	Long Cold	577	222	3	5.50	6.92	7	20%	1%	3.74	8.28	19%	41%
	Short Cold	-	-	-	2	2	2	-	-	0.74	2.03	28%	76%
	Long Heat	72	18	15	7	7	7	-	-	9.16	10.03	21%	23%
	Short Heat	-	-	-	2	2	2	-	-	1.46	1.66	20%	23%

* Cooling hours > 86°F, Heating hours < 54°F
† Changes relative to Historic Code (90.1 2004)

Table I-11. Impact of Improved Efficiency on Resilience in the 5th Percentile of the Top Floor Zones in Existing Multifamily Buildings

Top Floor Zones 5th Percentile		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	**Event**	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS
Houston, TX (2A)	Long Cold	972	204	88	2.96	7	7	58%	-	31.25	43.33	35%	49%
	Short Cold	387	32	-	1.17	2	2	42%	-	14.55	18.50	50%	63%
	Long Heat	893	598	533	2.63	4.38	4.71	40%	7%	12.52	17.19	19%	26%
	Short Heat	346	151	97	1.42	2	2	29%	-	12.33	15.73	61%	78%
Atlanta, GA (3A)	Long Cold	2,843	1,701	1,216	1.00	2.21	2.96	55%	25%	5.47	7.75	24%	34%
	Short Cold	575	76	1	0.92	2	2	54%	-	2.43	3.08	44%	56%
	Long Heat	654	216	116	1.79	7	7	74%	-	1.38	2.07	18%	28%
	Short Heat	176	39	19	2	2	2	-	-	0.69	0.88	35%	45%
Los Angeles, CA (3B)	Long Cold	253	-	-	6.08	7	7	13%	-	31.42	36.92	51%	60%
	Short Cold	-	-	-	2	2	2	-	-	2.97	3.07	37%	39%
	Long Heat	241	20	5	6.46	7	7	8%	-	31.67	43.12	11%	15%
	Short Heat	76	2.2	-	2	2	2	-	-	32.32	40.20	33%	41%
Portland, OR (4C)	Long Cold	3,118	1,642	1,237	1.00	2.54	3.13	61%	19%	3.42	4.67	20%	27%
	Short Cold	461	1.1	-	1.13	2	2	44%	-	2.32	2.84	57%	70%
	Long Heat	539	211	149	3.58	7	7	49%	-	0.48	0.87	1%	2%
	Short Heat	23	-	-	2	2	2	-	-	0.61	0.80	11%	15%
Detroit, MI (5A)	Long Cold	4,612	2,492	1,623	0.88	2.38	3.46	63%	31%	8.75	13.30	21%	32%
	Short Cold	1,627	531	304	0.54	1.33	1.71	59%	22%	3.96	5.31	32%	43%
	Long Heat	371	107	85	3.58	7	7	49%	-	8.03	9.21	9%	11%
	Short Heat	147	34	24	2	2	2	-	-	6.52	8.30	25%	31%
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,247	3,552	2,328	0.29	1.54	2.38	81%	35%	10.99	16.77	23%	35%
	Short Cold	1,011	216	51	0.58	1.92	2	70%	4%	4.28	5.72	40%	54%
	Long Heat	552	256	225	4.58	6.75	6.88	32%	2%	9.37	11.14	14%	17%
	Short Heat	199	65	42	2	2	2	-	-	6.27	7.44	29%	35%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-12. Impact of Improved Efficiency on Resilience in the Median of the Top Floor Zones in Existing Multifamily Buildings

Top Floor Zones Median		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	**Event**	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS
Houston, TX (2A)	Long Cold	829	200	85	3.21	7	7	54%	-	25.96	38.59	31%	47%
	Short Cold	316	24	-	1.29	2	2	35%	-	12.62	17.18	47%	64%
	Long Heat	1,123	601	535	1.88	4.38	4.71	57%	7%	21.03	25.64	28%	34%
	Short Heat	416	155	102	1.21	2	2	40%	-	15.88	19.29	67%	81%
Atlanta, GA (3A)	Long Cold	2,609	1,688	1,197	1.13	2.25	3.04	50%	26%	4.42	6.74	20%	31%
	Short Cold	498	71	0	1.04	2	2	48%	v	2.12	2.79	41%	55%
	Long Heat	855	217	117	1.58	6.79	7	77%	3%	2.05	2.73	25%	34%
	Short Heat	245	40	20	1.71	2	2	15%	-	0.94	1.14	42%	51%
Los Angeles, CA (3B)	Long Cold	169	-	-	7	7	7	-	-	20.68	25.97	41%	52%
	Short Cold	-	-	-	2	2	2	-	-	1.92	2.42	28%	36%
	Long Heat	402	21	5	4.50	7	7	36%	-	90.03	101.54	26%	29%
	Short Heat	134	2	-	2	2	2	-	-	52.15	59.90	44%	51%
Portland, OR (4C)	Long Cold	2,940	1,627	1,219	1.13	2.54	3.17	56%	20%	3.18	4.47	19%	27%
	Short Cold	385	0.6	-	1.29	2	2	35%	-	2.14	2.67	56%	70%
	Long Heat	708	212	150	2.79	7	7	60%	-	2.38	2.75	6%	7%
	Short Heat	56	-	-	2	2	2	-	-	2.33	2.52	32%	35%
Detroit, MI (5A)	Long Cold	4,397	2,476	1,602	0.96	2.42	3.50	60%	31%	8.10	12.73	20%	31%
	Short Cold	1,490	521	292	0.63	1.33	1.75	53%	24%	3.68	5.07	31%	42%
	Long Heat	560	108	88	2.46	7	7	65%	-	19.23	20.28	20%	21%
	Short Heat	210	35	25	2	2	2	-	-	9.53	11.27	32%	38%
Minneapolis/ St. Paul, MN (6A)	Long Cold	5,984	3,533	2,298	0.38	1.54	2.42	76%	36%	10.09	15.97	22%	34%
	Short Cold	905	210	43	0.75	2	2	63%	-	3.86	5.35	38%	53%
	Long Heat	750	257	226	3.46	6.75	6.88	49%	2%	17.92	19.65	24%	26%
	Short Heat	263	66	44	1.63	2	2	19%	-	9.01	10.13	37%	41%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-13. Impact of Improved Efficiency on Resilience in the 95th Percentile of the Top Floor Zones in Existing Multifamily Buildings

Top Floor Zones 95th Percentile		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
		Historic Code	Current Code	Beyond Code	Historic Code	Current Code	Beyond Code	Current Code	Beyond Code	Current Code	Beyond Code	Current Code	Beyond Code
Location (Climate Zone)	**Event**	90.1 2004	90.1 2019	PHIUS	90.1 2004	90.1 2019	PHIUS	90.1 2019	PHIUS	90.1 2019	PHIUS	90.1 2019	PHIUS
Houston, TX (2A)	Long Cold	619	179	64	4.17	7	7	40%	-	19.29	32.88	26%	44%
	Short Cold	226	13	-	1.92	2	2	4%	-	9.78	14.76	42%	64%
	Long Heat	1,309	611	545	1.58	4.29	4.67	63%	8%	24.54	29.00	31%	37%
	Short Heat	463	159	106	1.00	2	2	50%	-	15.59	19.05	65%	80%
Atlanta, GA (3A)	Long Cold	2,287	1,597	1,057	1.29	2.33	3.25	45%	28%	3.36	5.90	17%	29%
	Short Cold	377	54	-	1.29	2	2	35%	-	1.68	2.37	37%	52%
	Long Heat	989	220	119	1.50	6.75	7	78%	4%	2.38	3.05	28%	36%
	Short Heat	292	42	21	1.54	2	2	23%	-	1.15	1.33	47%	54%
Los Angeles, CA (3B)	Long Cold	57	-	-	7	7	7	-	-	8.43	13.72	23%	37%
	Short Cold	-	-	-	2	2	2	-	-	0.88	1.56	16%	28%
	Long Heat	532	23	6	3.50	7	7	50%	-	130.15	141.67	33%	36%
	Short Heat	180	2	-	2	2	2	-	-	61.62	69.25	48%	54%
Portland, OR (4C)	Long Cold	2,627	1,521	1,076	1.33	2.75	3.46	52%	20%	2.94	4.42	18%	27%
	Short Cold	253	0.02	-	1.79	2	2	10%	-	1.75	2.32	52%	69%
	Long Heat	840	213	150	2.58	7	7	63%	-	3.13	3.49	8%	9%
	Short Heat	88	-	-	2	2	2	-	-	4.00	4.19	45%	47%
Detroit, MI (5A)	Long Cold	4,004	2,400	1,489	1.17	2.46	3.63	53%	32%	7.02	11.90	18%	31%
	Short Cold	1,245	465	229	0.79	1.42	1.92	44%	26%	3.32	4.83	29%	43%
	Long Heat	696	113	94	1.79	7	7	74%	-	26.46	27.43	25%	26%
	Short Heat	254	36	26	1.67	2	2	17%	-	11.19	12.91	35%	41%
Minneapolis/ St. Paul, MN (6A)	Long Cold	5,515	3,425	2,131	0.58	1.63	2.54	64%	36%	8.77	15.00	19%	33%
	Short Cold	722	187	21	0.92	2	2	54%	-	3.18	4.75	34%	51%
	Long Heat	893	261	230	2.54	6.71	6.88	62%	2%	22.69	24.40	28%	30%
	Short Heat	308	67	46	1.50	2	2	25%	-	9.14	10.22	37%	41%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-14. Impact of Improved Efficiency on Resilience in the 5th Percentile of Existing Multifamily Buildings (Combined Middle and Top Floor Zones)

Combined Floor Zones 5th Percentile		**SET Degree Hours***			**Habitability**					**Mortality†**			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	**Event**	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Historic Code** 90.1 2004	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS	**Current Code** 90.1 2019	**Beyond Code** PHIUS
Houston, TX (2A)	Long Cold	972	204	88	2.96	7	7	58%	-	40.62	57.58	36%	51%
	Short Cold	387	32	-	1.17	2	2	42%	-	17.26	22.72	49%	65%
	Long Heat	1,147	725	640	2.63	2.63	2.63	-	-	24.24	30.53	28%	35%
	Short Heat	346	151	97	1.42	2	2	29%	-	12.20	15.52	60%	76%
Atlanta, GA (3A)	Long Cold	2,975	1,706	1,216	1.00	1.00	1.00	-	-	7.13	10.71	22%	33%
	Short Cold	575	76	1	0.92	2	2	54%	-	2.78	3.65	40%	52%
	Long Heat	655	216	116	1.79	7	7	74%	-	2.31	3.26	21%	29%
	Short Heat	176	39	19	2	2	2	-	-	0.83	1.05	36%	46%
Los Angeles, CA (3B)	Long Cold	253	-	-	6.08	7	7	13%	-	33.51	39.59	44%	52%
	Short Cold	-	-	-	2	2	2	-	-	3.52	3.61	36%	37%
	Long Heat	241	20	5	6.46	7	7	8%	-	44.78	57.49	10%	13%
	Short Heat	76	2	-	2	2	2	-	-	39.58	48.32	31%	37%
Portland, OR (4C)	Long Cold	3,411	1,645	1,237	1.00	1.00	1.00	-	-	6.22	8.51	24%	33%
	Short Cold	461	1.1	-	1.13	2	2	44%	-	2.96	3.66	57%	71%
	Long Heat	539	211	149	3.58	7	7	49%	-	2.67	3.72	4%	6%
	Short Heat	23	-	-	2	2	2	-	-	0.54	0.67	7%	8%
Detroit, MI (5A)	Long Cold	5,529	2,646	1,623	0.88	0.88	0.88	-	-	15.21	22.94	24%	36%
	Short Cold	1,694	531	304	0.54	0.54	0.54	-	-	5.60	7.55	31%	42%
	Long Heat	371	107	85	3.58	7	7	49%	-	13.06	15.03	10%	12%
	Short Heat	147	34	24	2	2	2	-	-	7.83	9.96	24%	30%
Minneapolis/ St. Paul, MN (6A)	Long Cold	7,373	3,799	2,338	0.29	0.29	0.29	-	-	18.38	28.46	26%	39%
	Short Cold	1,011	216	51	0.58	0.58	2	-	71%	5.66	7.85	40%	55%
	Long Heat	587	273	239	4.58	4.58	4.58	-	-	13.36	16.08	13%	15%
	Short Heat	199	65	42	2	2	2	-	-	7.08	8.47	26%	31%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Table I-15. Impact of Improved Efficiency on Resilience in the Median of Existing Multifamily Buildings (Combined Middle and Top Floor Zones)

Combined Floor Zones Median		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	829	200	85	3.21	7	7	54%	-	31.11	48.36	30%	47%
	Short Cold	316	24	-	1.29	2	2	35%	-	14.90	20.34	48%	65%
	Long Heat	1,470	733	648	1.88	1.88	1.88	-	-	42.37	48.61	40%	45%
	Short Heat	417	155	102	1.21	2	2	40%	-	15.67	19.01	65%	79%
Atlanta, GA (3A)	Long Cold	2,632	1,690	1,197	1.13	1.13	1.13	-	-	4.89	8.62	17%	29%
	Short Cold	498	71	0	1.04	2	2	48%	-	2.32	3.23	36%	50%
	Long Heat	870	217	117	1.58	1.58	7	-	77%	3.63	4.56	29%	36%
	Short Heat	245	40	20	1.71	2	2	15%	-	1.16	1.38	43%	52%
Los Angeles, CA (3B)	Long Cold	169	-	-	7	7	7	-	-	19.33	23.85	32%	39%
	Short Cold	-	-	-	2	2	2	-	-	2.92	3.37	31%	36%
	Long Heat	402	21	5	4.50	7	7	36%	-	123.38	136.16	23%	26%
	Short Heat	134	2	-	2	2	2	-	-	64.18	72.76	41%	47%
Portland, OR (4C)	Long Cold	3,126	1,629	1,219	1.13	1.13	1.13	-	-	5.32	7.86	22%	32%
	Short Cold	385	0.6	-	1.29	2	2	35%	-	2.64	3.38	56%	71%
	Long Heat	710	212	150	2.79	7	7	60%	-	5.64	6.61	8%	10%
	Short Heat	56	-	-	2	2	2	-	-	2.37	2.50	24%	25%
Detroit, MI (5A)	Long Cold	5,102	2,618	1,602	0.96	0.96	0.96	-	-	13.23	21.09	21%	34%
	Short Cold	1,511	521	292	0.63	0.63	0.63	-	-	4.93	6.92	29%	41%
	Long Heat	560	108	88	2.46	7	7	65%	-	27.03	28.76	19%	20%
	Short Heat	210	35	25	2	2	2	-	-	11.56	13.62	31%	36%
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,869	3,768	2,304	0.38	0.38	0.38	-	-	16.02	26.31	23%	38%
	Short Cold	905	210	43	0.75	2	2	63%	-	4.98	7.55	37%	57%
	Long Heat	804	275	240	3.46	3.46	3.46	-	-	24.71	27.36	21%	24%
	Short Heat	263	66	44	1.63	2	2	19%	-	10.16	11.49	33%	37%

* Cooling hours > 86°F, Heating hours < 54°F
† Changes relative to Historic Code (90.1 2004)

Table I-16. Impact of Improved Efficiency on Resilience in the 95^{th} Percentile of Existing Multifamily Buildings (Combined Middle and Top Floor Zones)

Combined Floor Zones 95^{th} Percentile		SET Degree Hours*			Habitability					Mortality†			
					Days of Safety			Improvement†		Lives Saved (per Event)		Improvement	
Location (Climate Zone)	Event	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Historic Code 90.1 2004	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS	Current Code 90.1 2019	Beyond Code PHIUS
Houston, TX (2A)	Long Cold	619	179	64	4.17	7	7	40%	-	20.71	38.57	23%	43%
	Short Cold	226	13	-	1.92	2	2	4%	-	10.95	16.57	42%	64%
	Long Heat	1,740	749	664	1.58	1.58	1.58	-	-	52.77	58.82	45%	50%
	Short Heat	472	159	106	1.00	2	2	50%	-	15.50	18.92	64%	78%
Atlanta, GA (3A)	Long Cold	2,287	1,598	1,057	1.29	1.29	1.29	-	-	2.81	6.74	10%	25%
	Short Cold	377	54	-	1.29	2	2	35%	-	1.76	2.65	31%	46%
	Long Heat	1,038	220	119	1.50	1.50	7	-	79%	4.55	5.47	34%	40%
	Short Heat	292	42	21	1.54	2	2	23%	-	1.45	1.66	48%	55%
Los Angeles, CA (3B)	Long Cold	57	-	-	7	7	7	-	-	2.46	8.37	6%	19%
	Short Cold	-	-	-	2	2	2	-	-	3.14	3.74	33%	39%
	Long Heat	532	23	6	3.50	7	7	50%	-	180.79	193.45	31%	33%
	Short Heat	180	2	-	2	2	2	-	-	77.85	86.31	45%	50%
Portland, OR (4C)	Long Cold	2,695	1,521	1,076	1.33	1.33	1.33	-	-	4.07	7.04	18%	31%
	Short Cold	253	0.02	-	1.79	2	2	10%	-	2.12	2.77	52%	68%
	Long Heat	850	213	150	2.58	7	7	63%	-	6.93	7.83	10%	11%
	Short Heat	88	-	-	2	2	2	-	-	4.17	4.30	35%	36%
Detroit, MI (5A)	Long Cold	4,450	2,530	1,489	1.17	1.17	1.17	-	-	10.26	19.02	18%	32%
	Short Cold	1,247	465	229	0.79	0.79	0.79	-	-	4.10	6.24	26%	40%
	Long Heat	696	113	94	1.79	7	7	74%	-	36.54	38.08	23%	24%
	Short Heat	254	36	26	1.67	2	2	17%	-	13.83	15.89	34%	39%
Minneapolis/ St. Paul, MN (6A)	Long Cold	6,092	3,647	2,134	0.58	0.58	0.58	-	-	12.50	23.28	19%	36%
	Short Cold	722	187	21	0.92	2	2	54%	-	3.93	6.78	33%	57%
	Long Heat	966	279	245	2.54	2.54	2.54	-	-	31.85	34.43	26%	28%
	Short Heat	308	67	46	1.50	2	2	25%	-	10.60	11.88	33%	37%

* Cooling hours > 86°F, Heating hours < 54°F

† Changes relative to Historic Code (90.1 2004)

Appendix J – Summary of Methods with Assumptions and Caveats

Throughout the report procedures, assumptions and limitations are described for each component comprising the applied methodology. The assumptions and caveats listed below represent an effort to annotate key application strengths, potential areas for improvement, and the overall influence of each component.

J.1 Hazard Risk Identification and Coincident Probability Assessment

Extreme temperature hazards are identified from historical extreme temperature event data. Comparing their characteristics informs the selection of a representative event, which is used in the simulation analysis to assess occupant exposure. The probability of occurrence of these events coinciding with a power outage is assessed to annualize the efficiency benefits determined for a single representative event. The joint probability values are used in the benefit-cost ratio (BCR) net present value calculation to annualize loss values, such as for occupant and property damages, attributed to the representative extreme temperature event. Influential factors potentially impacting results include:

- Extreme temperature events used in the analysis are based on historical data and do not account for future effects of climate change.
- Due to the absence of standardized procedures, professional judgement was used to select the representative extreme heat and cool events for each location.
- Joint probability of extreme temperature power outage occurrence is determined from DOE's Office of Cybersecurity, Energy Security and Emergency Response Electrical Emergency Incident and Disturbance data, collected on Form OE-417, which was identified as the best currently available data source. The approach followed results in a distribution of outage probability and duration associated with the occurrence of extreme hot and cold temperatures. Due to lack of geographic granularity provided in the outage records, the probability values may be biased upward due to the assumption that all outages reported for the state affected the entire state. For the purposes of this research, this approach was viewed as acceptable, though future work should both refine the power outage data assessment and perform a more detailed analysis of the temperature and power outage distribution.

J.2 Occupant Exposure and Passive Survivability

Building simulation modeling of the base case, current code, and beyond-code efficiency cases are performed to evaluate the impact of increased passive efficiency on thermal comfort during extreme temperature events. The thermal comfort conditions are reflected in passive survivability (PS) metrics to quantify and compare differences. Influential factors potentially impacting results are highlighted here:

- The analysis assumes simplified and consistent operation of windows by occupants across the population of buildings. The models did not include overcooling to charge thermal mass.
- Occupant operation of interior or exterior window shades is not considered. Residential model energy code does not include requirements for window SHGC in colder climates, including those for Portland, Detroit, and Minneapolis/St. Paul. This may contribute to poorer

thermal comfort conditions and higher standard effective temperature (SET) degree hour values occurring during extreme heat events for these locations than would normally be experienced based on actual occupant behavior.

- Since the modeling of building performance excluded occupant operation of shading devices, the window SHGC is a strong influencing factor of comfort conditions during extreme heat and cold. Low values favor extreme heat and high values favor extreme cold. This highlights the importance of good passive solar design that includes proper side overhangs, which support shading during warm months and solar gains during cold months. Future work could include the impact of exterior or interior shading devices.
- The SET degree hour habitability assessment for each event is based on a specified thermal comfort temperature range with values outside the range aggregated over a 7-day period, which is consistent with currently applied methods, such as the procedures underlying the USGBC LEED 2022 resilience pilot credit. The 7-day convention accommodates comparing values across locations and between events. However, actual extreme temperature event duration can be longer and varies by location and event type.

J.3 Occupant Damage and Loss

The Gasparrini et al. (2015) epidemiology-based relative rate of mortality fragility curves are used to estimate the impact of passive efficiency on indoor space conditions and excess mortality during extreme temperature events. The Gasparrini damage data relate average daily outdoor temperature and death rates specific to 135 U.S. cities/counties. To apply the damage curves in the study, several simplifying assumptions were made:

- To detect the impact of improved passive efficiency on excess deaths using the Gasparrini fragility curves, average daily indoor temperatures determined from the simulation analysis is used instead of outdoor temperatures. Since the result of interest is a differential, between the base case and the improved efficiency case, any introduced bias may be minimized.
- The Gasparrini fragility curves extend to the minimum and maximum temperatures indicated for each location. For Portland during extreme heat, the average daily indoor temperature exceeded the maximum outdoor temperature of the curve. In this case, the excess death rate was assumed to equal that relative rate associated with the maximum temperature. This is a conservative approach that prevents extrapolation beyond published data but may underestimate the reduction in excess death attributed to passive efficiency improvements.
- A 7-day period of extreme temperature coincident with a power outage is the basis for the excess death estimates and associated monetized losses determined in the study. However, for the 2021 Houston winter storm case study, the excess death estimate is based on the actual extreme temperature event duration of 12 days. The case study results are 80% of the published excess death value. The results indicate that using a 7-day period with the Gasparrini model for our application to assess occupant damage may markedly underestimate excess deaths and the investment benefit of efficiency.

J.4 Property Damage and Loss

No attempt was made to model the impact of extreme temperatures on property damage or determine the probability risk; instead, values published in the FEMA National Risk Index (NRI) dataset were used. These data are the annualized monetary losses recorded for property damage attributed to extreme heat and cold temperature events. The key data limitation includes:

- The NRI property damage data appear to be deficient and underestimate damages when compared to published damage values for recent U.S. extreme temperature events. For example, the Texas Department of Insurance reports the paid claims for residential and commercial property damage for the 2021 winter storm total $5.7 billion (TDI 2021). Assuming a coincident probability of 3.3% of extreme cold coinciding with a power outage, the annualized loss value for Texas is $188 million. The value for Harris County (including Houston and the surrounding area) is estimated at $62 million, based on its population relative to the state (33%), The FEMA NRI data reports no annualized property loss value for extreme cold for Harris County. Yet based on the published data for the Texas winter storm, the economic loss associated with property damage is about 75% of the loss associated with the reported excess deaths (Aldhous and Hirji 2022, TDI 2021).
- The method applied in the study to estimate the impact of increased efficiency on property damage should be reexamined. Instead of using excess mortality reduction to prorate property damage, SET degree hours or days of habitability could be used.

J.5 Benefit-Cost Analysis

The BCR, which follows a net present value costing approach, compares the annualized monetary benefits to the first costs of the passive improvement. The benefits are determined for building energy performance from simulation modeling, estimates of excess death from the Gasparrini models, and estimates of property damage from published historical data. Influential factors potentially impacting the robustness of the calculated BCR values are outlined here:

- The methods applied in the study may underestimate population damage, property damage, and their associated losses. As a result, the benefit of efficiency investment to mitigate damage from extreme temperature events may also be underestimated.
- Efficiency measure costs are based on the sum of individual measure costs. For existing buildings, the cost is not considered incremental to a planned or needed retrofit or innovative construction methods that may result in lower first costs. This results in BCR values being underestimated for existing buildings.

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov