

Trials and Tribulations of Valuing Building Energy Resilience

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ABSTRACT

Extreme temperature events are an increasingly prevalent threat to our energy infrastructure and the built environment at large. When power disruptions coincide with extreme heat or cold, the risk of unsafe exposure is sharply magnified. Recent events, such as 2021 Winter Storm Uri, reveal a new paradigm in disasters, defined by the convergence of multiple, cascading natural and technological or operational hazards. Such events reinforce the need for energy resilient buildings to help mitigate adverse impacts facing communities.

As a means of reducing energy demand and maintaining safe thermal conditions, building efficiency measures are a requisite to energy resilient design. Yet in order to actualize the resilience co-benefits in practice, a standardized and replicable framework is necessary to assess building performance under extreme heat and cold scenarios. Recognizing this need, DOE's Building Technologies Office (BTO) funded an 18-month project to quantify the value of energy resilience against joint extreme temperature-power outage events.

This paper captures the culmination of the project's multi-year effort, presenting its key findings, challenges, and recommendations. We first introduce the methodology developed to measure energy resilience based on probabilistic scenarios simulated through building energy models for both new and existing buildings types (single-family homes, mid-rise apartments, and assisted living facilities). We go through the full valuation framework, drawing on illustrative examples from the study that reflect key trends and resilient design considerations. We conclude by discussing key lessons learned and implications to model building code development, building technology research, and hazard risk assessment at large.

The Promise of Resilience

Vast portions of the northern hemisphere will have experienced a heat wave before the 2022 summer solstice. Across the US, over one third of the population was under a heat advisory halfway through June, with cities across the southwest to east coast, setting new record highs (Cappucci and Samenow 2022). Amid the pervasive heat, grid operators are warning of major energy shortfalls to meet peak summer conditions across the western, central, and midwestern portions of the grid (NERC 2022). The Electric Reliability Council of Texas (ERCOT) was forced to operate under emergency conditions as a prolonged heat wave settled over the region throughout July. These concerns are only further amplified by the ongoing volatility across the energy sector due to the Russia-Ukraine conflict that has driven the cost of energy globally.

As with many disaster events, such times evoke calls for greater resilience. Yet resilience becomes an increasingly difficult concept to actualize as we contend against new and existing hazards. Resilience is synonymous with both energy security, climate adaption, and efficiency. Resilience has become our reactionary response to energy disruptions, detached from the day-to-day benefits solutions might offer. As the scale of resilience broadens, so do the challenges of operationalizing a coordinated strategy across multiple entities.

Some of the earliest solutions to energy resilience are rooted in local, efficiency-based action (Molina, Kiker, and Nowak 2016). In the 1970s energy efficiency was the United States' national push to bolster energy security and independence (Lovins 2005). Calls for resilience must account for the social and economic inequalities that render communities more vulnerable to extreme weather events. Addressing energy resilience at the building level offers perhaps the most robust pathway to provide longer-term, tangible benefits for communities. In turn, buildings that are both the resilient and efficient, enhance the resilience of the broader energy system and community at large.

New reality of extreme temperature and power disruptions.

The rising cost of disaster events expose deeper vulnerabilities between buildings, community services, and the electric grid. In February 2021, Winter Storm Uri set off a series of power system disruptions to the grid and natural gas supply, leaving buildings—many of which ill-equipped without heat, power and sufficient insulation—to frigid conditions. The drop in indoor temperatures led to consequential occupant health outcomes and significant property damage, primarily driven by frozen pipes. Recent analysis links nearly 200 deaths and \$18 billion in property damage to the winter storm blackout in Texas and surrounding states, making it the costliest winter disaster event in U.S. history (Despart, Serrano, and Lamb 2021; Jacobs and Figuracion 2021). That summer, the Pacific Northwest experienced an unprecedented heat wave responsible for over 600 excess deaths across the US and Canada (Popovich and Choi-Schagrin 2021).

Of particular relevance to building energy systems, U.S. exposure to extreme heat is anticipated to increase in coming years. Average temperatures are not just on the rise, but temperature extremes as experts project excess heat days to increase in both intensity and duration (Dahl 2019). As the leading cause of death from weather-related events, extreme heat leaves populations, notably vulnerable and elderly groups, subjected to adverse health impacts.

Modeling these impacts in three U.S. cities, new research estimates that compound heat wave and grid failure events would expose over two-thirds of urban residents to dangerous heat stresses (Stone 2021). The resilience of a building is intrinsically tied to the availability of continuous power; disruptions to the electric grid compromise the critical services buildings provide, reshaping how the thermal performance of a building during extreme temperatures. As building technologies become increasingly dependent on grid connectivity, it is critical to address the potential consequences when energy supplies are disrupted (Specian et al. 2020).

Recentering resilience around buildings.

The increase in compound disaster events (e.g., when two hazards occur at the same time) introduces greater complexity into building design and community resilience. Energy resilience strategies will vary by climate region, building type, occupant needs, and local infrastructure systems. In some cases, energy efficiency and resilience may produce conflicting outcomes. For example, windows with high solar heat gain coefficients (SHGC) reduce winter heating loads, but exacerbate indoor temperatures during the summer months. More research is needed to better characterize and evaluate these type of interactions between different building technologies.

Strengthening the resilience of buildings equips communities, states, and the nation at large against the complex risks and uncertainties extreme events impose. Yet, a lack of concise definitions, methods to measure progress, and actionable guidance has made the concept of resilience difficult to operationalize (Davison et al. 2016). Embedding energy efficiency within

resilience, this report defines building energy resilience as: the ability to operate building energy services, such as heating, cooling, ventilation, critical plug loads, and shelter, during and in response to a major disruption (DOE Building Technologies Office 2020).

This study focuses specifically on the capacity of buildings to provide safe environments during extreme events where power supply may be disrupted. This concept is often referred to as passive survivability, defined as the ability to maintain safe indoor conditions in the event of extended power outage or loss of power supply (Wilson 2005). When extreme temperature events coincide with power loss, the risk to building occupants sharply increases. In practice, buildings designed with passive survivability in mind are able to maintain safe thermal temperatures in the event of a power disruption. As a measure of a building's thermal performance, passive survivability offers an integrated metric reflective of both energy efficiency and resilience. Strategies such as insulation, efficient windows, envelope air tightness and passive ventilation can prolong safe indoor temperatures during a power outage. Efficient buildings, particularly when combined with a backup power or energy storage system, are better equipped to function and maintain operability under such conditions.

Project Background and Motivation

The scope of this research project builds on earlier Building Technologies Office (BTO) activities on the topic of resilience. In 2019, BTO held a two-day workshop, which brought together a diverse group of industry experts and stakeholders to discuss the application of energy efficiency technologies in the design of resilient buildings (Ott, Morgan, and Antes 2019). Results of the workshop further highlighted how a standardized methodology to value resilience was pivotal for garnering support across the broader building sector.

Based on the collective recommendations and identified research gaps, BTO funded a multi-year research project to develop a quantitative methodology for valuing building energy resilience against extreme temperature events. This paper offers a comprehensive review of the effort, focusing on its contributions towards advancing the application of energy resilient buildings. We first provide a generalized overview of the methodology, drawing on several illustrative examples from the study's analysis. We present preliminary results, focusing on findings that demonstrate notable trends and key observations.

Valuation Framework

The proposed framework establishes a new approach to evaluate the impacts of extreme temperature events that occur during power disruptions on buildings and its occupants. The methodology builds on the traditional elements of hazard risk assessment to account for building-level temperature performance impacts. Conventional approaches generally yield an assessment describing the relationship between a building's performance and a hazard risk (i.e., seismic activity, hurricane winds, flooding). The relationship is primarily a function of hazard intensity, shaped by several other factors, most notably the baseline conditions, or susceptibility of a building to a given perturbation.

When treating extreme temperature as a primary hazard, additional considerations are needed to assess impacts within indoor environments. Extreme temperature events are a function of both temperature intensity and duration, adding a spatial dimension to the relationship. Additional steps are also required to measure the thermal performance within the building enclosure. This consideration is a unique aspect of this study that enables a more granular

understanding of the interaction between extreme temperatures, buildings, and impacts to building occupants. Together, this study builds the methodological groundwork to elevate the study of extreme temperature and building performance as part of hazard mitigation.

This section details our valuation framework, highlighting key aspects of the methodology that advance the overall study of building energy resilience. We present the framework alongside illustrated examples from our study's analysis.

Methodology Overview

The methodology is comprised of four primary stages of analysis: hazard risk assessment, exposure analysis, vulnerability assessment, and value-at-risk quantification. The overall process is applied iteratively where outputs from a previous stage serve as inputs for the next as presented in Figure 1 below.

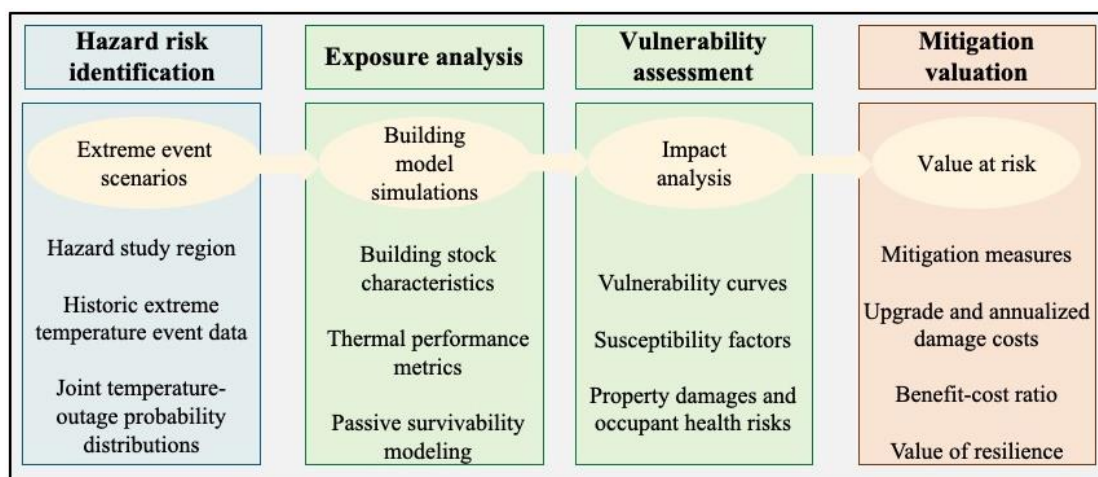


Figure 1: Resilience valuation methodology framework.

- Hazard risk identification:** the first phase of the methodology identifies extreme temperature-outage events. Historic weather and outage data is cross-referenced to derive joint probability distributions for a given geographic region. This process is then repeated for both extreme heat and cold events. From the historic data, representative events are then selected to be used as an input to the next phase of the methodology.
- Exposure analysis:** identified temperature scenarios serve as inputs to simulate the indoor thermal conditions of the study area's building stock or a set of building prototypes. Simulations are run via building energy modeling software (for this study EnergyPlus) with several inputs manipulated to replicate an outage event and track indoor temperature performance over the course of the simulated event. Model parameters are generated using building characteristic data that reflect the study area. Initial simulations generate the initial baseline results, while additional runs are later conducted to reflect building upgrade packages.
- Vulnerability assessment:** thermal resilience data from the exposure analysis provides input for estimating the associated impacts to property, building occupants, and other identified assets. Vulnerability assesses the potential damage severity that would likely occur given exposure risk and underlying susceptibility of the given asset or population. Vulnerability is both of function of the initial building conditions, sociodemographic

characteristics of the population, and the thermal performance of the building. These inputs are then used to estimate the specific outcomes (property damage, morbidity, mortality, etc.) that occur during an event.

- **Mitigation valuation:** estimated damage impacts are assigned dollar values and applied over the event probabilities derived from the first phase to determine the baseline value-at-risk estimate. The exposure and vulnerability analysis are repeated to assess selected mitigation measures, or building upgrades that enhance thermal building resilience. Associated upfront costs are annualized for each upgrade scenario and combined with the initial baseline results to produce a final benefit cost ratio.

Project Scope Considerations

As part of the larger project, six U.S. locations representing three distinct hazard and climate regions were analyzed using the developed methodology. The study was conducted to better understand the merit of the assessment framework as well as gain deeper insight on the resilience value of certain building measures. For example, the modeling team adjusted the length of the outage event to determine when indoor thermal conditions reached equilibrium with outsider temperatures. These considerations are elaborated further throughout the remainder of the paper. Table 1 below lists some of the key components of the study scope included in the analysis.

Table 1: Key components of study analysis

Scope Component	Description
Study regions	Six U.S. cities [Houston, Atlanta, Los Angeles, Portland, Detroit, and Minneapolis/St. Paul] from 6 climate zones [2A, 3A, 3B, 4C, 5A), and 6A], in three hazard regions [Gulf south, Great Lakes, & Pacific]
Hazard scenarios	1 long duration and 1 short duration scenario [Extreme heat and cold]
Building types	Single-family building [existing and new] Midrise multi-family [existing and new] Assisted living facility [counterfactual analysis]
Efficiency/ resilience measures	Baseline [existing or historic code] Efficiency packages [current code and beyond code measures]
Resilience impacts	Impact on occupant mortality, property damage, annual energy use, and annual carbon emissions

Each phase of the valuation framework offers new context to the field of building resilience analysis. Drawing on examples from the study's applied analysis, we present key trends and findings generated from each stage of the analysis. Rather than focusing on a single city or building type, we present a compilation of examples that demonstrate a given concept.

Hazard Risk Identification

There are two goals of the extreme temperature-outage hazard risk identification process to: (1) develop weather data files characterizing extreme temperature scenarios to be used in building simulation modeling and (2) define the joint probability distribution of extreme temperature events coinciding with a power outage. The prevailing challenge lied in combing

historic power outage and extreme temperature data to form one cohesive joint probability distribution.

Selection of extreme temperature events.

To first identify extreme temperature events, historic hourly weather data was collected for a given hazard region. The study applies a method defined by Ouzeau et al. (2016) and later adopted by the International Energy Agency Annex 80 Resilient Cooling of Buildings project.¹ The method involves converting hourly weather data into daily mean temperature data, which is then used to detect heat waves using thresholds that correspond with extreme event percentiles. The approach characterizes heat waves based on: (1) duration, (2) maximal mean temperature, and (3) cumulative intensity. Figure 2 below presents the characterization of identified heat waves for Minneapolis, Minnesota between 2001 and 2020. The same process is repeated for cold events.

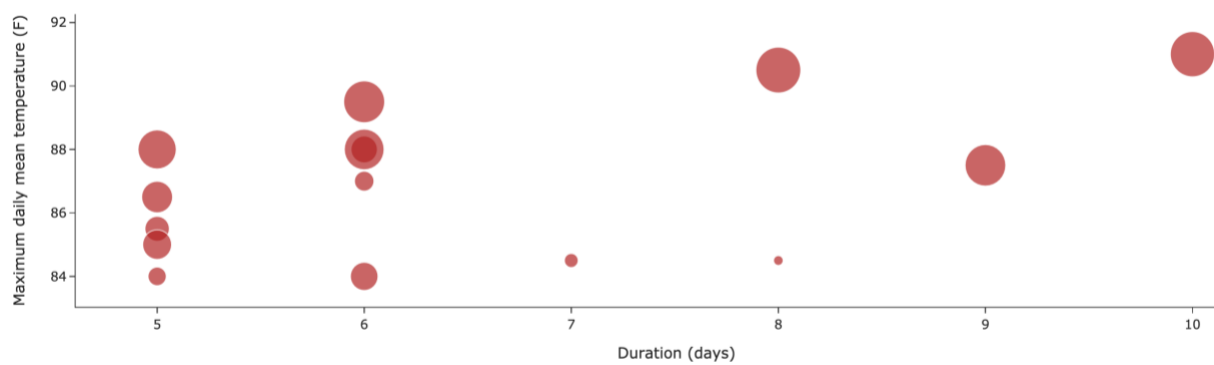


Figure 2. Heat waves detected during 2001-2020 for Minneapolis, MN. The size of each bubble reflects the cumulative intensity of the heat wave event.

Joint extreme temperature-outage event probability distributions.

To establish the coincident risk, the historical extreme temperature events identified from the NASA data are cross-referenced against local power outage data, made available via the DOE's Office of Cybersecurity, Energy Security and Emergency Response (CESER) Electric Emergency Incident and Disturbance Report (DOE 2018). Given the limited outage data available, we consider all joint events that occur over the summer and winter months, respectively. For the purposes of this research, this approach was viewed as acceptable, although future work would benefit from higher resolution power outage data, including outage geographic distribution and local duration. The coincident probability distributions for each temperature event type are combined following the general equation where:

$$\text{Joint Probability} = \frac{\# \text{ of Power outages that occur during extreme temperature event}}{\text{No. of Extreme Temperature Events}} \quad (\text{Eq. 1})$$

The estimates determined for Texas are shown in Table 2. The approach results in a distribution of outage probability and duration associated with extreme hot and cold temperatures. Given our assumptions, these numbers will be biased upward, and future work should seek to correct this.

¹ For more information, see www.annex80.iea-ebc.org/.

Table 2. Estimate of the probability of extreme temperature event coinciding with a power outage in Texas.

	Probability of a Cold Snap Power Outage > 24 hours	Approximate Equivalent Rate	Probability of a Heat Wave Power Outage > 24 hours	Approximate Equivalent Rate
Texas	5.8%	1 every 20 years	7.9%	1 every 12 years

Exposure Analysis

Capturing exposure impacts through thermal resilience metrics.

As listed in Table 1, both new and existing buildings were simulated as part of the larger study. The research team conducted simulations using the following tools: NREL’s ResStock model (Wilson et al. 2017), LBNL’s nursing home model (Sun, Specian, and Hong 2020), and PNNL’s code prototype building models. In order to properly assess and compare the numerous simulations, we rely on a set of standardized, temperature-based metrics to track indoor temperatures over the course of the simulation. Despite reference to a variety of different metrics throughout relevant literature, there is no agreed upon standard or threshold to distinguish between safe and unsafe conditions (Homaie, Shabnam, and Hamdy 2021). The development of such thresholds require multi-disciplinary input from public health and medical experts.² A summary of the metrics and associated thresholds are found in Table 3 below.

Table 3: Summary of thermal resilience metrics adapted for study

Thermal resilience metric	Description	Threshold
Heat Index (HI)	Combines air temperature and relative humidity to measure the human-perceived equivalent temperature.	Safe ($\leq 80^{\circ}\text{F}$); Caution ($80 - 90^{\circ}\text{F}$); Extreme caution ($90 - 105^{\circ}\text{F}$); Danger ($105 - 130^{\circ}\text{F}$); Extreme danger ($\text{HI} > 130^{\circ}\text{F}$)
Standard Effective Temperature (SET)	Thermal metric adopted by ASHRAE that considers secondary comfort factors	Below 54°F and above 86°F considered ‘unlivable conditions’
SET degree-hours	Estimates both the magnitude (degrees) and duration (time) above SET threshold	216 SET-hours considered threshold for 7-day outage as used by USGBC
Hours of Safety	Number of hours building can maintain safe temperatures during extreme temperature event, most useful for cold events	Mild cold stress ($60\text{-}50^{\circ}\text{F}$); Moderate cold stress ($50\text{-}40^{\circ}\text{F}$); Severe cold stress ($<40^{\circ}\text{F}$)

Source: NOAA/ NWS 2017; ASHRAE 2020; USGBC 2015; RMI 2020.

Visualizing thermal performance.

The project team elected to prioritize Standard Effective Temperature (SET) and SET degree-hours for final analysis. When consolidated within a single figure, one can easily chart both the cumulative and temporal dimensions of the building simulations. Figure 3 presents a sample exposure analysis output of single-family residential homes in Atlanta. SET values are graphed for three building scenarios. The graphs reflect the aggregated results from a sampled set of single-family residential homes representing the city’s building stock. Results are bounded by the 5th percentile (worst) to 95th percentile (best) range of temperature conditions. The second and third graphs reflect the two upgrade packages to existing building stock. The purple graph reflects bringing all homes up to the latest energy code (IECC 2021). The green graph represents

² This was mentioned as a key research gap by several members of the project’s Technical Advisory Group (TAG).

upgrading all homes to the 2021 PHIUS Standard.³ The dotted line in each graph tracks the cumulative SET degree-hours over the simulated scenario, providing a useful means of comparison between packages.

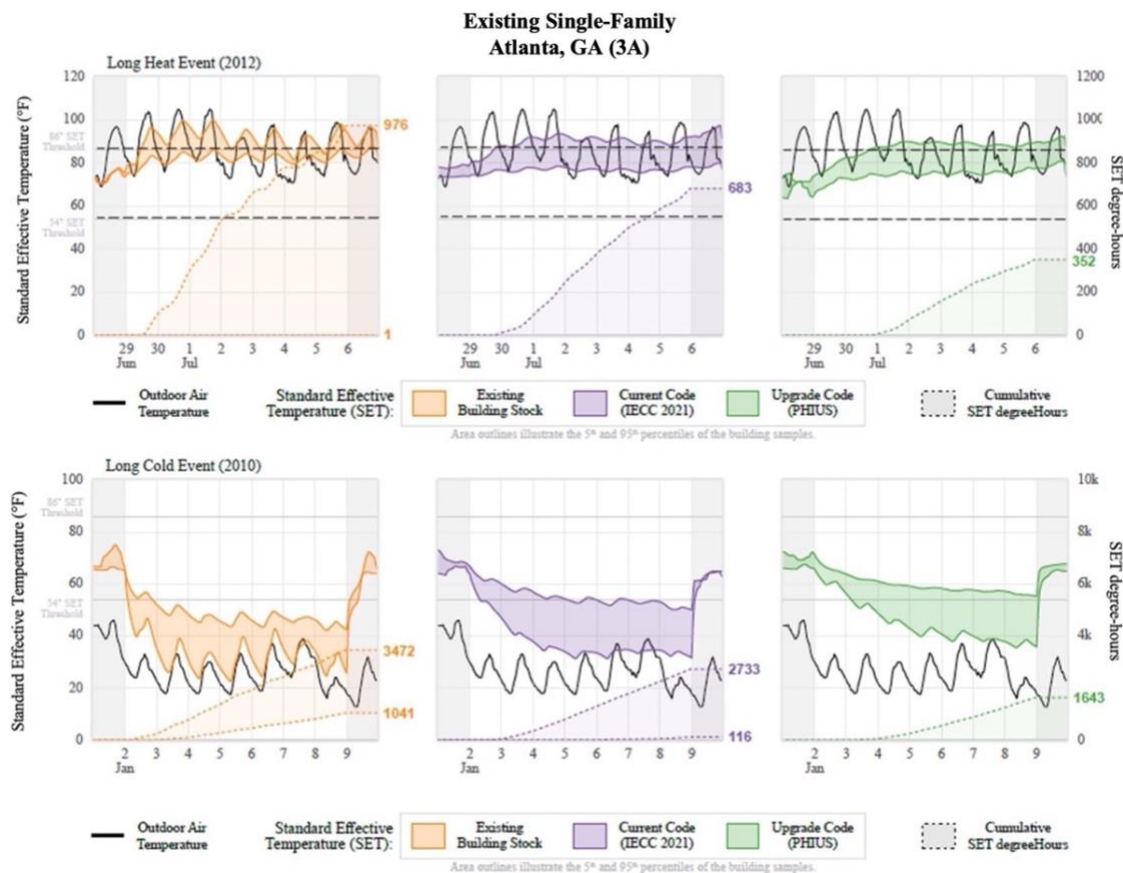


Figure 3. Exposure analysis results for Atlanta single-family existing homes long heat wave event and cold event. baseline (orange), upgrade to current energy code edition (purple), and PHIUS package. In the top portion of each graph, the shaded portion represents the range in temperatures between the 5th and 95th percentile.

Across all climates, we generally observe distinct interactions for hot and cold events respectively. During heat events, indoor temperatures fluctuate with outside diurnal changes. Buildings that mitigate solar heat gain during the day and expunge heat in the evening see lower temperatures, whereas the worst-performing sample of buildings may see temperatures surpass outdoor conditions, gaining heat as the outage event progresses. During cold events, building act as thermal storage system, slowly losing internal heat over time. We also see wide variation in thermal performance across the building stock. It is important to note that these results are a sample taken across the simulated building stock and may not sufficiently capture the performance of the lowest-performing portion of buildings.

Figure 4 provides an example analysis for an existing multi-family building prototype. For existing multi-family, we rely on PNNL’s building energy model prototypes. Similar to the trends described above, newer buildings, or code editions, outperform their historic versions.

³ The performance criteria calculator specifies project specific requirements that meet PHIUS 2021 certification.

Temperature data from both the top floor and middle floor of the building were tracked, revealing a stark contrast in results. Building on previous studies, these results reinforce the elevated risk of exposure on the top floors of buildings.



Figure 4. Exposure analysis results for Minneapolis existing multi-family existing prototype during a long heat and cold event. The feasibility study reflects a similar upgrade package to that of PHIUS.

Vulnerability Assessment

Results from the exposure analysis serve as inputs to the vulnerability assessment to estimate the degree of loss incurred for a given asset (e.g., property damage, business interruption losses, etc.) or population (e.g., hospitalizations, mortality). Damage risk is the product of the results from each of the first three phases of the framework, as represented by equation 2 below:

$$\text{Damage Risk} = \text{Frequency} * \text{Exposure} * \text{Vulnerability} \quad (\text{Eq. 2.})$$

Frequency is the probability of each extreme temperature events coinciding with power outages in a given year, taken from the hazard risk identification phase. *Exposure* is the number of people or buildings exposed to unsafe indoor conditions for each probability hazard event. *Vulnerability* is the relationship between indoor conditions during extreme events and consequences like discomfort, injuries, or mortality.

Estimating Mortality Impacts.

Developing population-level mortality estimates proved to be an arduous task. While numerous studies have successfully produced models that generate mortality estimates based on the severity of a heat wave event, there are currently no studies that produce these estimates based on indoor temperature data. Part of this challenge lies in the fact we lack the necessary public health data to capture whether a fatality occurred inside a building or not. Results are further skewed by the fact that the data does not distinguish whether or not an extreme temperature event coincided with a power outage, or whether a building had air conditioning at the time of an incident. With these caveats in mind, the research team elected to proceed with estimating health impacts as a more experimental exercise.

The impact of severe temperature on human health is dependent on several factors including age, gender, socioeconomic status, and climate adaptation; thus, damage curves for assessing death rates by temperature need to be specific to a given location. The Gasparrini et al. (2015) study provides mortality data associated with extreme temperature events that are suitable for this application. The Gasparrini model assesses the relative rate of mortality based on average daily outdoor temperature conditions. In this application, changes in mortality were evaluated based on average daily indoor temperature. To assess the validity of the method, a case study of the 2021 Winter Storm was modeled for Houston (Harris County), Texas.

Houston 2021 Winter Storm Estimated Mortality Validation.

In February 2021, Winter Storm Uri caused nearly 10 million people to lose power. Texas was hit the hardest with three-quarters of Texan experiencing rolling blackouts. Freezing temperatures caused natural gas generators who weren’t winterized appropriately to fail requests for generation. In Texas, the storm left 4.5 million homes without power. The storm’s property damage reached \$295 billion. More than two of three people interviewed lost power between February 14-20 for an average of 42 hours. The official number of cold-related deaths in Texas was 246 (Hellerstedt 2021). However, using an excess death approach, an independently reviewed analysis by BuzzFeed News suggests that 702 people were killed by the storm that week (Aldhous and Hirji 2022). An estimate of 247 deaths can be attributed to the Houston area by prorating the 755 state average value based on population.

We use ResStock to run building stock simulations for Houston and apply the temperature exposure results to Gasparrini et al. (2015) mortality curves. Results from the exposure analysis and estimated excess deaths are summarized in Table 4 below. The 206 deaths estimated for Houston existing building conditions is conservatively comparable. The analysis indicates that approximately 74 deaths, or 37% of the mortality, could be avoided by deploying the advanced passive efficiency measures.

Table 4: Summary of thermal resilience metrics adapted for study

Houston, TX (2A)	Event	Existing Stock			Passive Measure Upgrade			Deaths Avoided		
		5%	Median	95%	5%	Median	95%	5%	Median	95%
	2021 Winter Storm	246	202	166	198	128	80	48	74	85

Mitigation Valuation

The final phase of the framework packages the estimated losses up to yield an annual value representing the total value at risk for the baseline scenario. The value at risk is determined by associating a monetary value to the resulting damage and exposure impacts. The monetary value associated with damages incurred are annualized by taking into account the probability of occurrence. Quantifying these valuation components underlie the determination of the mitigation benefit cost ratio (BCR) value. The process is repeated for the mitigation packages assessed, along with their respective upgrade costs. From those values, a benefit cost ratio is determined where a value greater than 1 indicates that the reduction in estimated losses outweighs the cost of the retrofit. Final BCR results will be published within the final DOE report.

Additional Trends to Highlight

Beyond the few examples presented in this study, the project ran numerous simulations and trial runs that helped shape our overall approach. Summarized below are additional trends identified over the course of the analysis that present noteworthy results.

Buildings can exacerbate extreme heat exposure.

It is broadly recognized that certain building design characteristics, particularly with solar heat gain, can result in internal temperature increases that exceed outdoor conditions. This reality is particularly consequential in humid climates. In such instances, older homes may in fact outperform the PHIUS package upgrade. Figure 5 presents such a case for existing single-family homes in Detroit. The PHIUS upgrade package results in higher SET degree-hours than the existing building stock. The PHIUS package results in a much wider variability in thermal performance as well, which speaks to the complexities of modeling existing buildings. While the existing building stock experiences greater diurnal temperature swings, it is able to cool off in the evening hours.

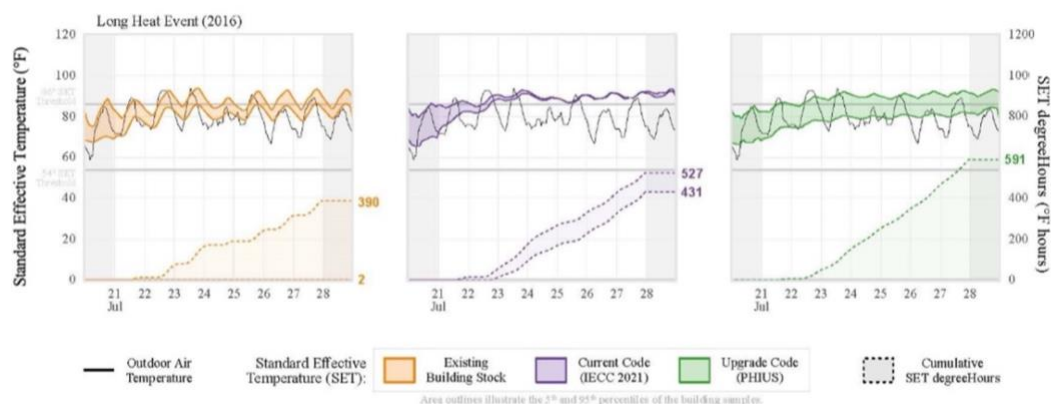


Figure 5. Exposure analysis results for Detroit existing single-family homes. Results demonstrate a case where energy efficiency improvements conflict with resilience

This trend is further exemplified within the analysis of an Assisted Living Facility in Houston, Texas. The figure on the left presents the initial baseline results of a simulated outage-heat wave event. The graph on the right summarizes the percent reduction in SET degree-hours for 7 passive efficiency measures. Environmental air tightening in fact increase exposure to

unsafe temperatures. The graph resoundingly shows that simple measures, such as natural ventilation, are capable of providing meaningful reduction in heat exposure.

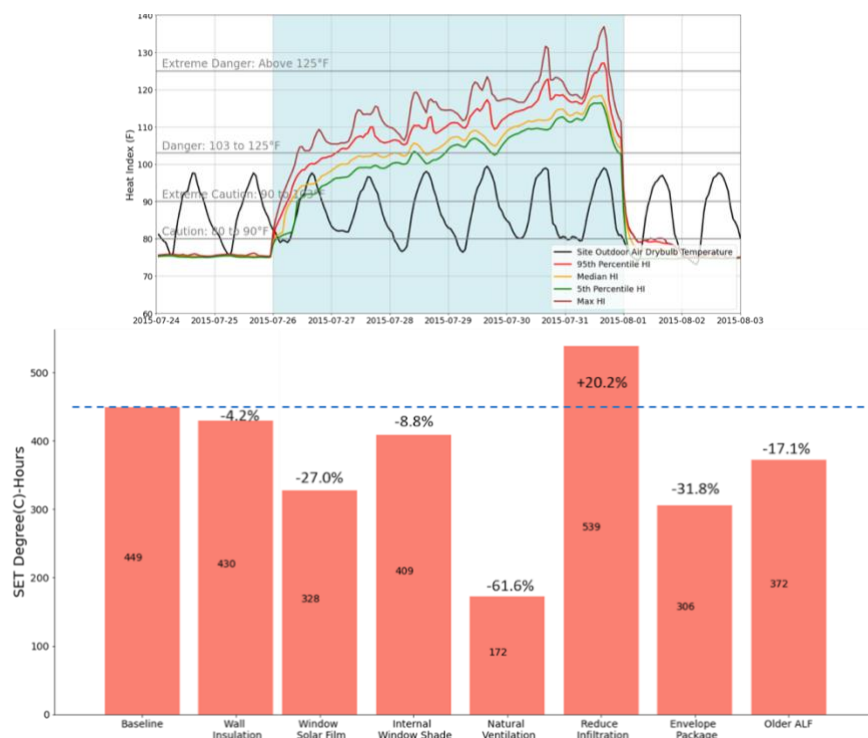


Figure 6. Top: Exposure analysis results for modeled assisted living facility in Houston, Texas. Figure on the right presents baseline thermal performance as Heat Index. Below: reduction in SET degree-hours from different passive efficiency upgrades.

Buildings designed to meet energy code support thermal resilience.

For both new single-family and multi-family building types, both historic and above-code prototypes mitigated exposure. Outside of extreme cold events in Detroit and Minneapolis, newly constructed homes provided safe indoor environments. It is important to note that these results simply reflect simulated prototypes and do not account for building construction quality nor other design considerations that might impact performance in practice.

For new single-family homes, we generally observe less variation between model code editions with limited exposure to unsafe thermal conditions. For extreme heat events, the 2006 IECC prototype led exceeded the 216 SET degree-hour threshold in both Houston and Atlanta, likely due to the more extreme heat wave. In these two instances, both the current code (2021) and upgraded code prototypes outperformed the historic code building model. Nearly all cities experienced unsafe temperatures during the simulated long cold event, although there was much less variation between code editions. This can likely be explained by the different temperature dynamics cold events present, driven by the larger temperature differential between outdoor temperatures and the cut-off temperature.

For the mid-rise, multi-family building analysis, we witness similar trends across extreme temperature scenario and hazard region. The most concerning trend, however, is produced between building floor levels, where top floors see much greater exposure to both extreme heat and cold. This is likely due to the increased heat loss (during cold events) and heat gain (during extreme heat events) that the top floor experiences. Figure 7 depicts this phenomenon.

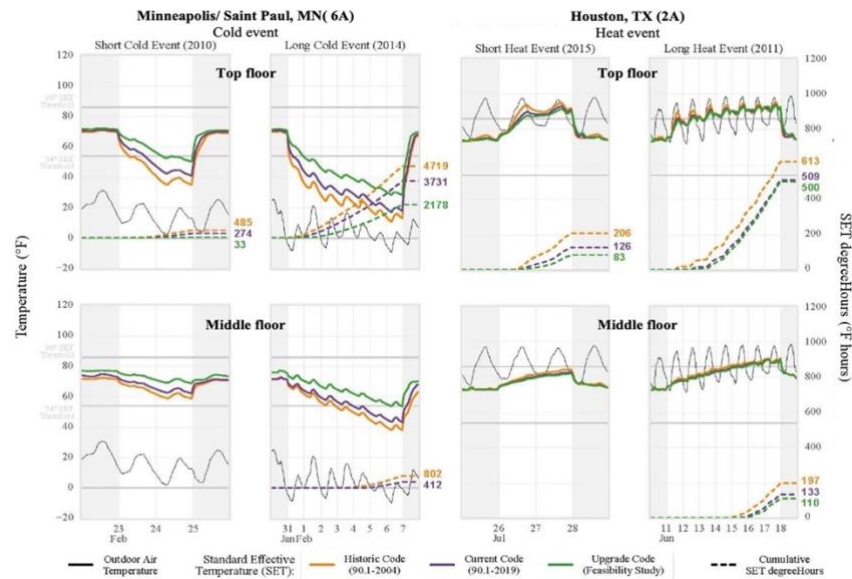


Figure 7. Exposure analysis results for modeled new multi-family building prototypes showing where exposure varies widely between middle and top floor levels. Graphs on the left represent two cold events in Minneapolis. Graphs on the right represent two heat events in Houston.

Lessons Learned

As a newer research area, this project faced inherent challenges that necessitate further investigation. We anticipate that future research activities can build off of this work to expand the valuation of building energy resilience under temperature extremes. Reflecting on the project's main challenges, we address some of the prevailing lessons learned below:

- *Multidisciplinary collaboration:* Developing a robust methodology to assess building thermal resilience draws on expertise from public health, risk analysis, economics, and climate modeling domains. Our framework demonstrates how building energy modeling applies to hazard risk assessment, a discipline outside of traditional building analysis. Multidisciplinary collaboration is key to integrating data, methodologies, and assessment methods across multiple disciplines. For our project, earlier collaboration with public health experts could have improved our method used to estimate excess deaths. Future work should recognize the importance of having a diverse project team to cover all aspects of hazard risk assessment.
- *Variability of building stock-level results:* The existing building exposure analyses yielded a wide variation in results, likely due to the composition of a city's building stock. In some cases, the median and 5th and 95th percentile outputs would produce conflicting results for the upgrade package simulations. Further research is needed to understand these interactions, notably for the worst-performing portion of building stock.
- *Estimating mortality risk:* Our study's findings further highlight the role buildings can play to mitigate occupant exposure to extreme temperature events. Applying the Gasparrini 2015 method to estimate mortality outcomes, however, yields rough estimates, as it only accounts for temperature changes at the city-level. Further research is needed to

establish appropriate methods that account for temperature at performance at the building-level. Such efforts require more extensive collaboration between public health experts, building modelers, and other federal agencies, such as the CDC and NIH.

- *Property damage data gaps:* The property damage caused by 2021 Winter Storm Uri was driven by frozen pipes rupturing. While simple interventions, such as pipe insulation, can mitigate frozen pipe damage, further research is required to attribute the impacts to building design interventions. The same could be said for heat waves and moisture damage, depending on the extent of the power outage.

This research establishes a new approach to assess the impacts of coincident extreme temperature-outage events on buildings. The overlap between extreme temperatures and power disruptions fundamentally alters the risk to building occupants and communities at large. The design of resilient buildings reflects not just its structural integrity against natural hazards, but its resilience against temperature extremes. Building energy design, particularly with respect to building energy codes, is developed based on average temperature conditions; yet other building code requirements are explicitly set based on extreme conditions. To confront and adapt to the emerging realities of climate change and extreme temperature risk, new building design practices and standards are necessary. Our valuation framework offers a means to evaluate building energy resilience as part of broader hazard risk mitigation efforts.

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