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Quantifying the Value of Energy Efficiency for Energy Resilience using Building Simulation Analysis

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Abstract

Considering the impact of energy efficiency on energy resilience is a relatively new application area for building simulation analysis. Such an analysis can assess the impact of increased efficiency on occupant exposure to extreme heat and cold. This research study performs an exposure assessment for 6 climate zone locations within 3 U.S. geographic regions. The study scope includes hazard risk identification, vulnerability assessment, and mitigation valuation. The research expands traditional building simulation scope and advances methods to quantify efficiency resilience benefits. This paper summarizes the research, describes analysis methods, presents resilience metric values, and discusses follow-on collaboration opportunities to continue advancement.

Introduction

Over the past two decades, the United States has experienced 265 weather and climate disasters that exceed $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, 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. Such climate change-related events are also motivating efforts to reduce greenhouse gas emissions attributed to the buildings sector. 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 operational energy use.

While some studies have quantified the resilience benefit of higher standards for the building structure (FEMA 2021 MMC 2018), the co-benefits of building energy codes on resilience have yet to be quantified. To address this, the research includes: 1) developing a standardized methodology for quantifying the value of resilience, 2) analyzing the impacts of efficiency measures during extreme temperature events, 3) determining the benefit-cost-ratio of current and beyond-code measures, and 4) demonstrating the added value of resilience proffered by efficiency investment.

This paper delves into the energy resilience analysis workflow and metrics. It shares examples of promising applications for the metrics that capture resilience benefits to support efficiency investment decision-making and quantify the value of current and stretch energy code adoption. To promote method application and continued development, the analysis workflow, methods, and metrics are being documented and shared on GitHub, an open source collaboration platform.

Approach and Scope

The study examines the ability of existing and new residential buildings to withstand extreme temperatures and exposure impacts on occupants and property. The scope includes developing and applying a methodology to quantify the resilience benefits of building energy efficiency, particularly as it relates to energy code adoption. The intention is to more fully value efficiency by capturing traditional benefits, such as reduced annual operating energy costs and the societal value of associated greenhouse gas emissions, as well as resilience impacts indicated by various metrics. The resilience metrics can inform extreme temperature hazard mitigation action by indicating the effect of efficiency on:

- Shelter-in-place capability
- Excess mortality and property damage
- Investment benefits and costs

The assessment focuses on extreme heat and cold events coincident with a power outage. It is conducted for representative U.S. geographic regions, climate zone locations, building types, building conditions, and improved efficiency cases. Figure 1 presents the geographic areas and locations characterized in the study. Figure 2 outlines the building types and base case and improved conditions analyzed. The analysis scope includes new and existing single-family (SF) homes and multifamily (MF) apartment buildings located in six U.S. cities that span three diverse geographic regions.

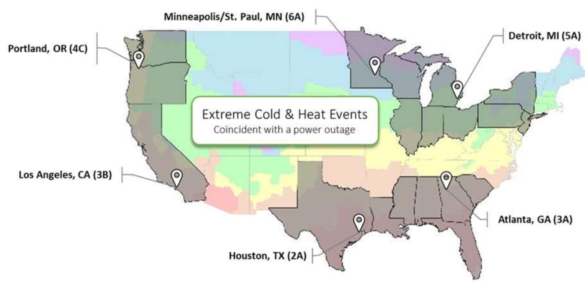

Figure 1 Geographic regions and locations

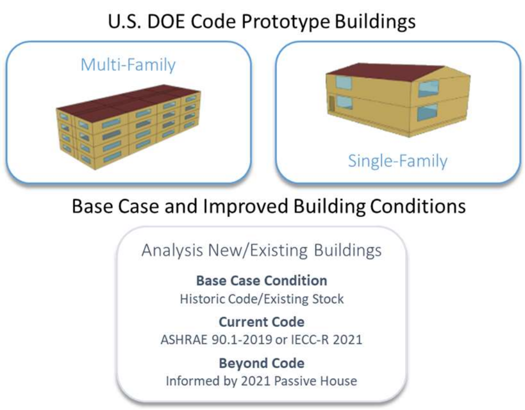

Figure 2 Building type and condition

The building efficiency improvements are tied to requirements specified in current model energy code (MEC)[1] and stretch code. For residential buildings, current MEC is the 2021 IECC. For commercial buildings current MEC is ASHRAE Standard 90.1-2022. The stretch code package is informed by envelope and infiltration requirements included in the 2021 Passive House Institute U.S. (PHIUS) Standard (PHIUS 2021). For existing buildings, the base case condition is characterized by published county-level housing survey and utility data. For new buildings, the base case condition is represented by historic model energy code, which is the 2006 IECC for SF buildings and the ASHRAE Standard 90.1-2004 for MF buildings. The impact of resilience mitigation is assessed by comparing the building performance, occupant exposure, and property exposure occurring for the base case condition with that determined for the improved conditions.

Workflow

The resilience aspects of the analysis require expanding the workflow of conventional building performance simulation analysis. The study includes four analysis categories as depicted in Table 1. A short description of each workflow component is provided below. More details of the methods are outlined in Table 1 and described in section *Performance Analysis and Simulation*. Full details are available in the research study final report (Franconi et al. 2023).[2]

Hazard Risk Identification – This activity quantifies the hazard probability and thresholds. It includes identifying representative extreme heat and cold events and creating representative extreme event simulation weather data files. It also involves evaluating the risk of extreme heat and cold events coinciding with a power outage for each location studied.

Exposure Analysis – This assessment uses building simulation analysis to evaluate the impact of improved building efficiency or resistance on occupant exposure during extreme heat and cold during no power conditions.

Vulnerability Assessment – This step translates the effect of exposure to extreme heat and cold by the occupants and assets (e.g., property) to damages incurred. For occupants, the study examined the impact of exposure on excess mortality. For property, published data was used to estimate the impact on damages incurred.

Mitigation Valuation – The valuation considers annualized risk, event exposure metrics, and value at risk to quantify the effect of increased efficiency on resilience impact and monetization. The resilience impact is considered as part of the overall impact of efficiency that includes annual energy use, operational energy greenhouse gas emissions, and the associated costs.

Metrics

The valuation methodology developed and applied in the study includes procedures for completing a passive survivability assessment. The building simulation analysis provides performance results that indicate occupant exposure. Occupant exposure, quantified and expressed as thermal resilience metrics, can be compared individually or in combination with other metrics to support mitigation planning and the prioritization of efforts. Table 2 lists the key metrics applied in the study

[1] MEC are available for adoption by states and local jurisdictions. The 2021 IECC (ICC 2021) is recognized by U.S. DOE as the current MEC for residential buildings. ASHRAE Standard 90.1-2022 is recognized as the current MEC for commercial buildings.
[2] Available at https://www.energycodes.gov/sites/default/files/2023-07/Efficiency_for_Building_Resilience_PNNL-32727_Rev1.pdf

Table 1 Analysis Components and Workflow

	1. Hazard Risk Identification	2. Exposure Analysis	3. Vulnerability Assessment	4. Mitigation Valuation
Objectives	Identify historical extreme temperature events	Identify indoor comfort conditions during no-power, extreme events	Evaluate the sensitivity of location populations to extreme temperatures	Perform an energy efficiency investment net present value analysis that includes resilience benefits
	Create extreme event weather data files			
	Determine power outage-extreme event annual probability	Calculate thermal resilience metrics	Determine the impact of efficiency improvements on excess mortality	
Methods	Ouzeau et al. heat wave analysis	Energy Plus building simulation modeling	Gasparrini et al. temporal variations in mortality	Weimar et al. valuing resilience methodology
	Customized scripts	Customized scripts	Customized scripts	Customized scripts
Inputs	NASA, NOAA historical weather data Baseline, current code, and stretch code building models	Baseline, current code, and stretch code building models	Average daily zone temperatures	Efficiency improvement first costs
			Temporal, excess mortality fragility curves	Joint probability for no-power, extreme event
	DOE Form OE-417 utility power outage data	Extreme event weather data files	Population data	Monetized energy use, carbon emissions, excess mortality, property damage
Outputs	Extreme event weather data files	Thermal resilience metrics	Occupant damage metrics	Economic metrics
	Joint probability of no-power, extreme event occurrence	Average daily zone temperature		

Table 2 Key Metrics Used in Study

Category	Name	Description
Thermal Resilience Metrics	Standard Effective Temperature (SET)	Indoor conditions measurement that considers dry-bulb temperature, relative humidity, and other comfort factors.
	SET Degree Hours	Cumulative hourly SET degrees that fall outside of a specified range (e.g., 54°F to 86° F).
	Days of Safety	The time elapsed during which the SET degree hours do not exceed a value of 216.
Occupant damage metrics	Excess deaths	Deaths attributed to occupant exposure due to an extreme temperature event.
Economic Metrics	Investment cost	First costs for the measure package.
	Cost savings	Evaluated based on a typical weather year.
	Emission savings	Societal value of reduced greenhouse gas emissions.
	Excess mortality	Losses associated with excess deaths based on $10 million per lost life.
	Property damage	Based on FEMA national risk index data.
	Benefit cost ratio (BCR)	Annualized energy cost savings, emissions savings, and extreme event monetization.

characterizing thermal resilience, occupant exposure, and economic valuation.

The building simulation analysis provides the performance data to quantify metrics listed in the table. For example, standard effective temperature (SET) is a thermal comfort metric that combines the effect of indoor dry-bulb temperature, relative humidity, mean surface radiant temperature, and air velocity, while also considering the anticipated activity rate and clothing level of occupants. SET degree hours is a cumulative measurement of SET degrees that fall outside a specified temperature threshold. Days of safety indicate the elapsed time in which habitable conditions are maintained. Ideally habitability thresholds and impacts on health and mortality consider the vulnerability of different population groups that may vary due to age, income, and related factors such as access to healthcare and local social services. Traditional economic metrics included in the analysis are mitigation measure capital cost, energy cost savings, and energy emissions reduction. In the study, reductions in excess deaths and property damages are determined for representative heat and cold events for each of the six analysis locations. To consider these effects as part of traditional net present value benefits and costs, event impacts need to be annualized by multiplying by the annual risk probability.

Resilience Analysis and Building Simulation

This section explains the four areas of analysis comprising the energy efficiency for energy resilience assessment workflow outlined in Table 1. Its purpose is to raise awareness of new analyses needing to be layered on to a traditional building simulation analysis to consider resilience benefits. For a more expansive treatment, refer to the project final report.

Hazard Risk Identification

The hazard risk is identified for each of the six locations studied. There are two main outcomes for the evaluation: (1) the determination of the annual probability of extreme heat or cold events coinciding with a power outage, and (2) the characterization of representative extreme temperature events to be used in building simulation modeling. Each applied approach aims to utilize the best currently available data sources and/or published methods.

Representative extreme heat and cold events

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), 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. In addition, the NASA and NOAA data were examined to identify extreme temperature events. Events that appeared in the NASA dataset were favored but were seconded by NOAA data. Identified events that occurred since 2011 were prioritized since they are most current and readily available in the EnergyPlus weather file format. To assess the data for reasonableness, they were compared to other data source values accessed from the NOAA Climate Resilience Toolkit (USGCRP 2018).

The Ouzeau et al. (2016) method, adopted for the use in the International Energy Agency's Energy in Buildings and Communities Annex 80 Resilient Cooling project, was applied in the study to identify extreme heat and cold events.[3] The method involves converting hourly weather data into daily mean temperature data. The top 0.5%, 2.5%, and 5.0% temperatures are used 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. In this study, the same approach was adopted to determine corresponding temperatures for characterizing extreme cold events.

Annual probability of extreme temperature events coinciding with a power outage

To establish the coincident risk, the historical extreme heat and cold temperature events identified from the NASA data must be cross-referenced against local power outage data. However, a uniform, nation-wide, customer-weighted database of power outages does not currently exist to produce an annual power outage or coincident extreme heat/cold event probability at the county level, referred to here as the 'coincident 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. To make the data usable, several assumptions were made, namely that an outage recorded in OE-417 affected the entire state. This assumption affects the accuracy of the coincident probability estimate. Specifically, the value determined for larger states may be overstated.

Exposure Analysis

This assessment uses building simulation analysis to evaluate the impact of improved efficiency on occupant exposure during extreme heat and cold during no power conditions. Exposure is quantified in terms of passive survivability metrics. In this study, the performance analysis is completed using the EnergyPlus building simulation engine. Building performance is assessed for the baseline and improved efficiency conditions using the representative extreme heat and cold event weather data, as well as typical meteorological year (TMY)

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

weather data. Performance is modeled without power during the extreme events and with power for the TMY analysis. The level of exposure of building occupants to extreme temperatures is expressed in terms of SET or heat index (HI), which are output values available directly from EnergyPlus. The SET values, coupled with threshold ranges defined by industry, are used to quantify exposure in terms of SET degree hours and days of safety. The TMY analysis is used to determine the energy use and cost savings associated with the two packages of efficiency measures, which represent current code and PHIUS 2021 envelope and infiltration requirements.

Existing single family buildings are modeled using ResStock. ResStock couples statistically representative residential household and efficiency characterizations with the OpenStudio building modeling interface (Langevin 2019). Approximately 3000 single family buildings were selected from the population of buildings studied to represent the existing buildings in each of the six locations analyzed.

The new single family and new and existing multifamily building performance are modeled using the DOE code prototype building models maintained by PNNL. The prototypes represent code-compliant buildings as characterized by model code that is published every three years. The prototypes currently include 32 residential and 16 commercial building models, each with performance characteristics defined for 16 cities representing U.S. climate zones. The basis for the new single family baseline building condition is IECC 2006, as representative of adopted residential energy code. The basis for the new multifamily building condition is the midrise apartment model meeting the requirements of ASHRAE 90.1 Standard 2004, as representative of the adopted commercial energy code. The existing multifamily building is developed from the midrise apartment prototype building depicting ASHRAE Standard 90.1-2004 requirements. However, characteristics of the 2004 model are modified to indicate existing building performance characteristics captured by the U.S. Energy Information Administration [EIA] Residential Energy Consumption Survey (RECS) 2015 RECs data.

Vulnerability Assessment

Vulnerability is the outcome that results from exposure. When stated as a function of temperature, the expression is described as a damage or fragility curve. 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 a large, dispersed population, such as the population of the United States. Damage curves that provide death rates by temperature are needed for each city/county of interest. Additional health impacts, which do not result in death, 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 to support quantifying these damages and they were not accounted for in the analysis.

In this study, the impact of occupant exposure to extreme heat and cold was evaluated using fragility curves published by Gasparrini et al. (2015). This relative-risk calculation uses death records to establish the average daily mortality in a city. 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. The data are developed for 384 global locations, including 132 U.S. cities. The curves are based on average daily outdoor temperatures. A relative-risk value of 1 indicates that the associated temperature resulted in no increase in the rate of 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 published data.

Figure 3 presents the fragility curves for Houston and Minneapolis-St. Paul. The vertical dashed lines indicate the temperature of the 2.5th percentile and the 97.5th percentile. The vertical dotted line indicates the temperature at which the relative rate of death is one, which implies no excess deaths attributed to temperature occur.

The curves demonstrate the trends described by Guo. The steepness of the mortality curve during extreme heat is much steeper for the colder climate compared to the hot climate. The differences in the curve shapes also convey the importance of considering location-specific influencing factors when evaluating the impact of extreme heat and cold on building occupants. To apply curves in the study to estimate the impact that changes in indoor building conditions may have on excess mortality, average daily indoor temperatures are used instead of outdoor temperatures. The authors believe that any bias that may be introduced from this application is reduced or eliminated since the change in mortality rates are used in the loss valuation and not absolute numbers.

Mitigation Valuation

Extreme heat and cold hazard mitigation valuation includes establishing the value at risk, by monetizing damages resulting in loss and considering annualized impact. Losses associated with extreme heat and cold

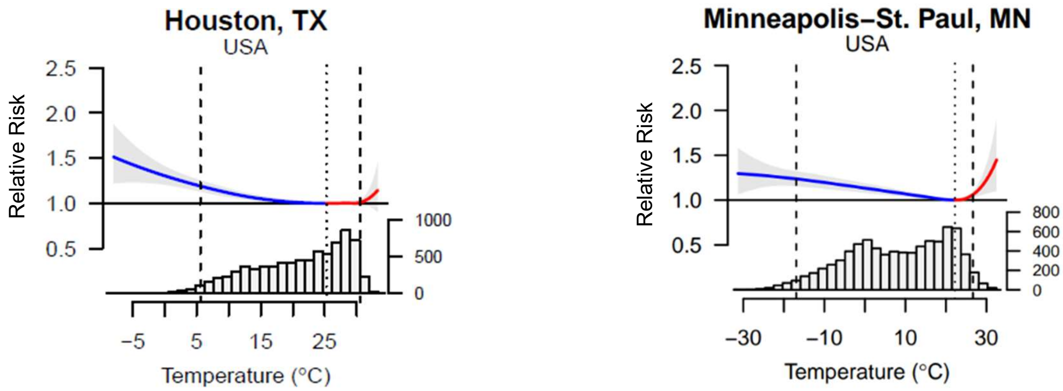

Figure 3 Example Gasparrini damage functions characterizing excess mortality for Houston and Minneapolis (Source: Gasparrini et al. 2015)

considered as part of the analysis include excess mortality and property damage. Excess mortality is determined using the Gasparrini fragility curves. Its monetization is based on the value of a statistical life (VSL), estimated at $10 million per life. The value is in the range of different estimates, with a low VSL of $7.6 million (FEMA 2020b) to a high VSL of $13.3 million (Viscuzzi 2020). The annualized excess mortality monetary loss for extreme heat is the product of the event excess mortality, the VSL value, and the coincident probability risk. Excess mortality monetary loss is calculated in the same manner for extreme cold.

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. Considering these challenges, property damage risk estimates used in the study stem from data published by FEMA as part of the National Risk Index (NRI) database (FEMA 2021a). The NRI uses data published in Arizona State University's SHELDUS (Spatial Hazard Events and Losses Database of the United States). The property damage reported data are annualized values based on historical costs incurred. The data appear to underrepresent property damages losses. The values are low and indicate that property damages are about 1% of the damages estimated for mortality. However, when compared to published data for recent extreme temperature events, building damage is much more 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).[4] The excess mortality estimated for Texas for the 2021 winter storm is 755 (Aldous and Hirji 2022). Based on a VSL Of $10 million, the value results in a monetized loss of $7.6 billion. These values indicate that for this event property losses are about 75% of population losses. It is worth noting that the annualized property damage costs published in NRI for Harris County, Texas, which includes Houston and 33% of the Texas population, is $0/year for cold events and $1,760/year for heat events. Since the valuation is drastically underestimated following the adopted approach, the annualized valuation of property losses is a non-consequential component of this study. Follow-on analysis is needed to improve the assessment.

The valuation accounting includes traditional economic costs and benefits typically considered when analyzing the cost effectiveness of energy efficiency investments. These include annual energy use, annual energy costs, the societal value of greenhouse gas emissions, and the efficiency measure costs. Energy costs are based on U.S. average costs published by the Energy Information Agency and adopted for use in model energy code development (EIA 2020a and 2020b). 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

[4] 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.

Table 3 SET degree hours for existing single-family buildings with median performance

Median Building		7-Day SET Degree Hours		
Location (Climate Zone)	Extreme Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Cold	749	222	0
	Heat	600	141	0
Atlanta, GA (3A)	Cold	2,558	1,610	200
	Heat	438	59	0
Los Angeles, CA (3B)	Cold	87	0	0
	Heat	100	0	0
Portland, OR (4C)	Cold	2,963	1,849	237
	Heat	371	319	0
Detroit, MI (5A)	Cold	4,248	3,020	1,778
	Heat	223	53	0
Minneapolis/ St. Paul, MN (6A)	Cold	5,397	3,699	2,190
	Heat	215	66	5

Greenhouse Gases.[5] First Costs follow procedures applied to evaluate the impact of newly released MEC code requirements, as documented by Hart and Liu. (2015). 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 assumed to be incremental.

Example Results and Applications

The methods and workflow outlined in Table 1 is applied to single family and multifamily 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) occupant impact, and (3) economic impact. Example results in these three areas of analysis are presented below. Two applications for using the metrics, (1) to support investment decision making and (2) to highlight resilience associated with energy code adoption, are also provided.

Passive Survivability Metrics

The USGBC LEED Passive Survivability Pilot Credit 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. This study used building performance simulation to determine SET and cumulative SET degree hours over a 7-day power outage period during representative extreme heat and cold events for the base case and two efficiency conditions considered. The values determined for existing single-family buildings are provided in Table 3.

Of the population of buildings analyzed, the values are based on the median building performance. Values in red text indicate that the 216 habitability threshold is not achieved. The data trends indicate that increasing efficiency decreases SET degree hours, improves habitability, and the ability to shelter in place during extreme heat and cold.

Occupant Impact Metrics

The average daily indoor temperature determined from the building simulation analysis was used to evaluate the relative impact on excess mortality during extreme heat and cold. The indoor temperature data was applied to the Gasparrini fragility curves published for each of the six locations studied. The excess mortality results are listed in Table **4**.

Table 4 Excess mortality for existing single-family buildings with median performance

Median Building		7-Day Excess Mortality		
Location (Climate Zone)	Extreme Event	Existing Stock	Current Code IECC 2021	Beyond Code PHIUS
Houston, TX (2A)	Cold	62.5	42.5	19.3
	Heat	52.4	10.3	2.2
Atlanta, GA (3A)	Cold	16.7	13.1	8.0
	Heat	6.3	5.4	0.4
Los Angeles, CA (3B)	Cold	21.2	16.0	15.8
	Heat	241	114	38.0
Portland, OR (4C)	Cold	14.7	11.5	6.1
	Heat	34.4	37.0	9.9
Detroit, MI (5A)	Cold	35.5	30.4	24.7
	Heat	75.1	68.2	49.1
Minneapolis/ St. Paul, MN (6A)	Cold	39.4	32.1	25.4
	Heat	54.2	49.8	39.5

The data characterize the impact of efficiency on occupant damage for the median existing single-family building in the population of buildings analyzed. While the table presents total excess death values, the change in excess deaths is of key importance to the study. The

[5]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

value is used in the BCR calculations and as a metric to inform decision making. The table data trends indicate that in most all cases increased efficiency reduces excess mortality during extreme heat and cold. The table data also reveal the effect of the fragility curve steepness on mortality rate during extreme cold and heat. In the mild and cooler locations, excess deaths attributed to extreme heat are higher than that attributed to extreme cold. However, for the warmest locations, including Atlanta and Houston, the extreme cold deaths are higher than the extreme heat deaths. In addition, a comparison of the Table **3** and Table **4** data reveal that there is not a direct relationship between SET degree hours and excess deaths. SET degree hours are much higher for extreme cold yet than extreme heat yet excess deaths during extreme heat are higher than extreme cold for 4 of the 6 locations analyzed.

Table 5 Economic metrics for existing single-family buildings with median performance

Existing Single-Family						
BCR	**Houston**	**Atlanta**	**Los Angeles**	**Portland**	**Detroit**	**Minn./ St Paul**
Current Code						
Mortality Reduction	0.09	0.00	0.06	0.00	0.01	0.01
Property Damage Reduction	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
Carbon Cost Savings	0.06	0.09	0.03	0.08	0.13	0.15
Benefits	0.40	0.40	0.21	0.38	0.49	0.59
First Costs	0.63	0.69	0.69	0.68	0.67	0.70
BCR	**0.63**	**0.59**	**0.30**	**0.56**	**0.73**	**0.84**
Beyond Code						
Mortality Reduction	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
Energy Cost Savings	0.33	0.40	0.13	0.32	0.50	0.51
Carbon Cost Savings	0.08	0.12	0.03	0.07	0.19	0.18
Benefits	0.53	0.54	0.26	0.44	0.73	0.72
First Costs	0.77	0.83	0.86	1.60	1.63	1.67
BCR	**0.68**	**0.65**	**0.31**	**0.28**	**0.45**	**0.43**

Table 6 Economic metrics for new single-family buildings

New Single-Family						
BCR	**Houston**	**Atlanta**	**Los Angeles**	**Portland**	**Detroit**	**Minn./ St Paul**
Current Code						
Mortality Reduction	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
Energy Cost Savings	0.16	0.19	0.16	0.12	0.13	0.13
Carbon Cost Savings	0.04	0.06	0.03	0.03	0.04	0.04
Benefits	0.22	0.25	0.19	0.14	0.17	0.17
First Costs	0.03	0.07	0.07	0.07	0.07	0.06
BCR	**6.27**	**3.76**	**2.92**	**2.12**	**2.53**	**2.88**
Beyond Code						
Mortality Reduction	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
Energy Cost Savings	0.28	0.30	0.19	0.18	0.29	0.33
Carbon Cost Savings	0.07	0.09	0.04	0.05	0.10	0.11
Benefits	0.37	0.39	0.24	0.23	0.39	0.44
First Costs	0.13	0.19	0.19	0.22	0.24	0.25
BCR	**2.96**	**2.05**	**1.25**	**1.07**	**1.61**	**1.79**

Economic Metrics

The study evaluated economic metrics associated with the costs and benefits of increased efficiency associated with energy and resilience. The costs include the first cost of the efficiency improvements. The benefits include energy use cost reduction, carbon emissions reduction, excess mortality reduction, and property damage reduction. The ratio of the annualized benefits to costs equals the benefit-cost ratio (BCR). A BCR value greater than 1 signifies that the efficiency investment benefits are greater than the costs. The economic metric values for new and existing buildings are listed in Table 6 and Table 5, respectively. Due to data limitations, reductions in property damage costs could not be effectively estimated and is indicated as zero in the tables. Therefore, the BCR values may be underestimated.

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. The 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. For existing buildings, 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 were determined to have a higher risk of extreme temperatures coinciding with a power outage.

Decision Matrix Application

The calculation of BCR values is informative for resilience investment considerations. However, since the quantification of efficiency impacts on resiliency are still in its nascency, customizable methods that consider stakeholder concerns and objectives may provide strong application value. Such an approach is a decision matrix The approach applies weighting factors to normalized values of resilience metrics. Scores are developed for each investment option. The option with the highest score reflects the solution that best meets the stakeholders needs. An example of a decision matrix applied to Houston resilience metrics is provided in Table 7. Six metrics are considered. For each, the data for the two cases are normalized relative to the better value, which is underscored in the table. Weighting factors totaling 100% are assigned to metrics. The total scores for the two cases indicate that beyond code, PHIUS 2021-informed efficiency package, is the preferred investment option given the weights applied.

Code Impact Assessment Application

The U.S. DOE and PNNL evaluate and publish impacts associated with energy codes at the national and state level. This includes issuing determinations of the energy efficiency improvement of the most recent versions of commercial and residential building codes and standards. The assessments indicate the significant

Table 7 Example decision matrix to inform resilience planning and investment decision making

	Metric Values		Assigned Weights	Normalized Values	
	Current Code	Beyond Code		Current Code	Beyond Code
BCR	0.63	<u>0.68</u>	30%	0.92	1.00
First Costs ($/ft^2/year)	<u>0.63</u>	0.77	15%	1.00	0.82
Energy Savings (kWh/ft^2/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 Reduction	985	<u>1348</u>	30%	0.73	1.00
			Weighted Total	**0.86**	**0.94**

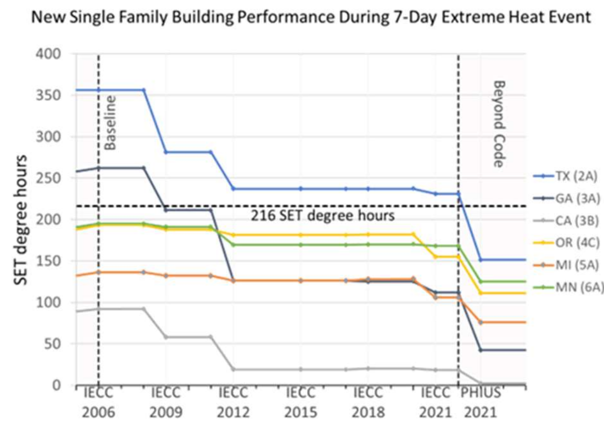

Figure 4 Demonstrating the added value of current and stretch energy code adoption with resilience metrics

energy savings opportunities associated with current code adoption by states and local jurisdictions. The metrics quantified as part of this study can be used in a similar fashion to indicate the added resilience benefits also provided by current and stretch energy code adoption. Error! Reference source not found. Figure 4 demonstrates the concept. The chart presents the SET degree hours determined over a 7-day period during a representative extreme heat event for a prototypical single family building in the six study locations. Seven different levels of building efficiency requirements are depicted. They include IECC residential requirements for six code cycles, from 2006 through 2021) and the PHIUS 2021 requirements (for envelope efficiency and infiltration). The data reveal that improved resilience does track with energy code advancement, particularly when requirements address passive efficiency as indicated by the PHIUS 2021 improvements. For 5 of the 6 locations, new single family buildings meet the 216 SET degree hour habitability threshold with the IECC 2009 or later requirements. Houston, the hottest of the climates studied, exceeds the threshold during an extreme heat event with current published code but meets it with PHIUS 2021 requirements.

Future Work

The study authors evaluated the robustness of each analysis component to inform future development. An overview of the assessment is provided below.

Hazard Identification

Overall, the application of the Ouzeau method to identify extreme heat and cold events for the study's purposes is considered to have a high robustness. The procedures are directly applicable. Some considerations for follow-on method refinement include the following:

- Use future projected weather data to capture the impacts of climate change.
- Develop a standardized methodology for identifying representative extreme heat and cold events for a given location.
- Publish a standardized set of representative extreme heat and cold weather data files to be used in resilience analysis studies.
- Publish a standardized set of weather data files representing future typical meteorological year conditions to use in annual building energy use, energy costs, and emissions analyses.

The use of data reported on Form OE-417 to estimate the coincident risk of extreme heat or cold events coinciding with a power outage is considered to have medium-low robustness. The database does not indicate power outage and its duration specific to a county. To apply the data, we assumed that any outage reported affected the entire state. As noted, this assumption may result in higher estimates of coincident risk in larger states compared to smaller states. Also, our initial analysis of future weather data indicate that extreme events will occur more frequently than the historical data indicate (e.g., 2 to 3 times per year compared to 1 time every 2 to 5 years), which may increase the coincident probability risk. Follow-on efforts to improve this analysis component should consider the following:

- Improve the geographic resolution in the reporting of power outages; include extreme heat and extreme cold as subcategories of severe weather.
- Consider the increase in frequency of extreme heat and cold events due to the impacts of climate change.
- Consider other metrics as indicators of hazard risk for extreme heat and cold coinciding with a power outage, such as grid capacity constraints, grid age, and winterization of energy supply systems.

Exposure Analysis

The occupant exposure to extreme heat and cold is quantified in terms of passive survivability metrics. These metrics, like SET degree hours or heat index, are considered to have high robustness. They are calculated based on established thresholds and are useful for making efficiency impact comparisons. The SET degree hour metric, for example, provides good resolution for demonstrating improvements in habitability achieved through the adoption of current MEC or stretch energy code. Future work to advance methods might include the following:

- Obtain broad industry acceptance of the uninhabitability temperature ranges and cumulative threshold limits applied to SET degree hours or other metrics used to indicate passive survivability. The thresholds and duration may differ for different population groups.

Vulnerability Assessment

The Gasparrini method is applied in the study to estimate excess mortality resulting from extreme heat and cold events. It is a robust epidemiological method but has some flaws for efficiency resilience applications since 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. 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.

These shortcomings aside, Gasparrini is likely the most useful method for making comparisons of the impact of mitigation strategies in a city. In its application, however, the appropriate number of days to be used in the analysis of the extreme heat or cold event is not clear. In calculating each location BCR values in the study, a period of 7 days was used. This is longer than the anticipated coincident power outage but shorter than the duration of the extreme event. A case study analysis of the 2021 Texas Winter Storm event used the event duration, which was 12 days per the Ouzeau method. Based on this period, the estimated excess mortality determined using the Gasparrini fragility curve for Houston is just over 200. This is about 80% of the anticipated value based on excess mortality data reported for the event (Aldous and Hirji 2022). This implies that follow on research should include the following:

- Conduct additional studies to compare published excess death data to values estimated using the Gasparrini models. Use the results to inform the appropriate time duration to be applied with Gasparrini for efficiency resilience purposes.

Mitigation Valuation

The continued research areas listed above that affect cost effectiveness calculations include coincident risk and mortality estimates. To improve the robustness of these methods, the following should be addressed:

- The data used to estimate property damage monetary losses appears to underestimate actual event losses. Better data sources should be identified and referenced.

Continued Advancement through Industry Collaboration

This research project was a joint effort of several teams from three national laboratories. The underlying research methods are based on a sophisticated multi-component multi-phase workflow. To share the foundational work completed as part of this study, PNNL is creating an open-source development environment on GitHub to openly share and communicate the research progress, data, and methodologies with different parties within the research teams and to the general scientific community. Proprietary data, vast amount of simulation cases, and intermediate computation results won't be included in this repository. However, contents being collected and shared include research design and methodology documentation, meta information to support the instantiation of research design, research methods implementation code, key results, and findings. By standardizing the structure of contents being included as components in this open-source repository and deploying a landing page to summarize the included items, we expect the repository to also serve as an information hub for supporting the collection, distribution, collaboration, and documentation of building energy efficiency for energy resiliency related research resources.

Conclusion

The study expands the traditional scope of building performance simulation analysis to also consider efficiency benefits on building energy resilience. The developed methodology reveals the relationship between the multi-disciplinary analysis components and associated data requirements. Some analysis components have shortcomings since they rely on methods not developed specifically for building energy resilience applications and/or utilize deficient data sources. For example, the research includes a net present value assessment, which involves the monetization of annual energy savings, carbon emissions, excess mortality, and property damage. However, the authors do not consider the resilience contribution to the metric to be robust. It relies on the determination of the annual coincident risk probability (of extreme events coinciding with a power outage), which is difficult to determine using available data sources.

While there are opportunities to improve the valuation methods, the calculated resilience metrics are informative and can be used in comparative assessments. At the metric level, the comparisons can reveal the relative impact of building efficiency measures or energy code adoption on indoor comfort conditions, occupant exposure, and potential damages. The metrics can also be applied more broadly to inform efficiency investment decision-making using an efficiency-resilience decision matrix.

To continue method development and refinement, recommended future work includes standardizing extreme temperature event weather data, establishing industry acceptance for thresholds of habitable conditions, and identifying a better source of property damage data. Also, applying the methods using projected future weather data will demonstrate the increased value and importance of energy efficiency for energy resilience in new building design. Continued development and application of the methods will benefit from multi-disciplinary, collaborative research efforts. The open-source GitHub repository, which is under development, will support such an endeavor.

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