

Human Mortality and Resilience – Severe Weather, Building Efficiency, Resilience, and Human Mortality

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ABSTRACT

This paper identifies key building characteristics that impact human mortality and health and makes the case that building energy codes should account for health impacts. Building energy efficiency brings energy savings as well as the potential for substantial health benefits to building occupants. Additionally, passive energy efficiency measures can address building energy resilience and reduce human mortality in electricity outages that coincide with severe temperatures. Severe weather events have been increasing in frequency and intensity. The Pacific Northwest heat event in June 2021 resulted in almost 1200 excess deaths as temperatures reached record highs. The Texas winter storm in February 2021 resulted in an estimated 755 excess deaths. The quality of housing stock is one among other factors that impacts the ability to respond to climate shocks and stressors. A recent multi-lab study funded by the Department of Energy; Building Technologies Office found that older housing lacks passive survivability during extreme temperature events due to inadequate energy efficiency. That study developed an approach to quantify energy cost savings and to monetize the reductions in human mortality resulting from improved passive energy efficiency measures. This paper provides a follow-on discussion of the applied methodology, which uses a damage curve developed for severe temperatures to estimate the change in excess deaths associated with mitigation measures. Additionally, we review existing literature to identify the impact of building characteristics on human health and propose a valuation method for including human mortality and health impact considerations in building energy codes cost benefit analysis.¹

Introduction

According to a World Health Organization report (McMichael et. al 2003), climate change will impact the risk and responses to human health; the adaptive capacity of these potential risks can be enhanced by designing flood control structures, air conditioning, building insulation and building codes to reduce vulnerability to climate variability. Severe weather events have been increasing in frequency and intensity. The Pacific Northwest heat event in June 2021 resulted in almost 1200 excess deaths (Washington – 450, Oregon – 160, British Columbia – 569) as temperatures reached record highs (Aldhous and Hirji 2022b, BC 2021, Popovich and Choi-Schagrin 2021). The Texas winter storm in February 2021 resulted in an estimated 755 excess deaths (Aldhous and Hirji 2022a, Aldhous and Hirji 2022b). Additionally, a forthcoming study by three US Department of Energy laboratories² (called Tri-lab hereafter) found that

¹ Enhancing Energy Resilience in Buildings: Development of a Standardized Methodology to Quantify Efficiency Benefits. Publication pending (Franconi et.al. 2022).

² Pacific Northwest National Laboratory, National Renewable Energy Laboratory, and Lawrence Berkeley National Laboratory.

passive energy efficiency measures³ can increase resilience and reduce human mortality when electricity and power outages or natural gas pipeline disruptions coincide with severe temperatures.

Building energy efficiency enables substantial health benefits to building occupants such as reduced mortality during extreme events, hospital visits and lost productivity (Muldavin et al 2017) as well as energy savings. In addition to the risks posed by severe temperature events, existing literature identifies a strong correlation between building characteristics and occupant health. Building related causes of health hazards include exposure to dampness and mold, exposure to extreme cold or heat, exposure to fine particulate matter and exposure to chemicals like radon, lead and formaldehyde. Additionally, buildings can indirectly impact occupants' cognitive performance, productivity, absenteeism, comfort, and general well-being.

In this paper we identify key building characteristics that impact human health and mortality. The goal is to identify how and why current and future building energy codes should consider impact of building characteristics on human health and mortality. We present findings from existing literature on building-related factors impacting health and mortality and valuation methods to quantify the impacts. In this paper we propose a methodology to account for health considerations in code development. To do this we develop a novel method based on damage curves for severe temperatures to estimate the change in excess deaths associated with energy efficiency improvements. Finally, we provide recommendations for health considerations in future energy codes and suggest further research needs to provide appropriate valuation of health benefits during energy code implementation and adoption.

Literature Review

In the following section we review the literature for impacts on human health from extreme temperature, dampness and mold exposure, and particulate matter exposure. Severe temperature impacts human mortality (death) and morbidity (illness). Morbidity can lead to hospitalization; emergency room visits and lost productivity from illness.

Extreme Temperature

Exposure to temperature extremes is associated with hypertension, increased risk of cardiovascular or cerebrovascular events, respiratory stress, hypothermia, hyperthermia, and mortality. Human mortality associated with severe temperature is a substantive area of public health research.

The studies reviewed evaluate the exposure and resistance of the population to severe temperatures, both hot and cold. The impact of severe temperature on human health is discussed in literature in terms of mortality, hospitalization, emergency room visits and self-treated illness. Factors that influence health outcomes are hazard, population resistance, exposure, damage and consequence and their probabilities of occurrence. Hazard is an extreme event such as hurricane, seismic event, heat wave or severe cold. Population resistance measures the tolerance of a population to an exposure by a hazard. As applied in this paper, resistance is specific to the ability of occupants to adapt to indoor conditions during extreme heat and cold events coinciding with power outages. The extent to which extreme temperatures can impact the indoor

³ Passive energy efficiency measures include improved envelope insulation (opaque and window), envelope tightness and cool roof.

temperature and affect building structure and occupants is exposure. The damage to the population is dependent on age and socio-economic factors including income, and access to health care. These factors can vary across states and counties in a hazard/climate region and influence local health impacts and death rates. Thus, the damage curve⁴ for the population can be is specific to unique in each city/county in the United States. The number of deaths, hospitalizations, emergency department visits are the consequences and can be valued for use in benefit cost analyses. Thus, the health models needed to evaluate the impact of buildings must be based on location-specific mortality and morbidity data, which consider the adaptive capacity of the local population to extreme temperatures. Each climate region and area within the climate region will differ in its demographic composition based on 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.

The literature in a few cases provides the relationship between mortality and other variables of interest. Hot ambient temperatures can negatively affect mental health, reduce work capacity, and cause occupational health problems (Ebi et al. 2021). Socioeconomic circumstances also play a part in mortality with lower income people suffering more mortality than higher income people. People with existing diseases such as cardiovascular and respiratory issues also are more susceptible to severe temperatures (Jay et al 2021). In addition, the impact of severe temperatures increases when the heat or cold wave occurs early in the season before people have adapted to either higher or lower temperatures (Barnett et al. 2012). The Gasparrini et al. (2015) study provided relative risk curves (damage curves of how many people die at each temperature) with an “adequate” fit (although not perfectly) for the information required to determine the reduction in lives lost due to mitigation measures.

The impacts of climate change have been investigated in terms of human health. Liu et al. (2019) evaluated the impact of severe temperatures in Minneapolis/Saint Paul, Minnesota by calculating the impacts of temperature on three different age groups: 0-19, 20-64 and 65 and over. The literature indicates that mortality due to severe temperature has more impact on people 65 years of age or older and the very young aged 0-19 (CDC ca 2013). Using the value of a statistical life (VSL) to determine the cost of severe temperatures, they calculated a morbidity cost as sum of emergency department hospitalizations and the value of daily productivity lost. The study found that severe temperatures lead to \$2.70 billion loss annually.

Similarly, Carleton et al. 2020, in a 40-country study, evaluated temperature-mortality relationships under a climate change scenario. Their study, using survey data to value human life, found significant decreases in mortality due to severe cold temperatures in cooler climate regions relative to large increases in mortality due to severe cold in warmer regions. This study does not provide adequate information to determine damage curves associated with hospitalization, emergency room visits and self-treated illness as it relates to severe temperature.

One factor that has not been studied at depth is the impact that loss of air conditioning (AC) has on people who are accustomed to it, and therefore haven’t adapted to the higher temperatures when heat waves occur. There have been studies that controlled for AC disruption. Sera et al. (2020) explicitly evaluated the impact of AC on mortality. They found that due to increased AC installations, the excess deaths decreased from 1.70 percent to 0.053 percent over the 1975-2007 period. The relative risk declined from near 1.4 to near 1.1 because of AC penetration increasing from 49.4 percent to 82.8 percent. Joe et al. (2016), a California-only

⁴ A damage curve provides a relationship between a particular hazard’s impacts on an asset or a person. In this paper the relationship is between severe temperatures and human mortality.

study, found that AC availability lowers mortality. Regions with high AC penetration had lower relative risk rates than did areas with lower AC penetration rates. An inexpensive alternative to AC is using fans. Jay et al. (2021) indicate that electric fans and dousing may effectively alleviate human stress to heat. They found that fans provided a similar impact to AC in reducing temperature stress in humans below 45°C. However, cooling effects are less effective the older the individual. Neither AC nor electric fans are effective during an electricity outage. However, battery driven fans with an effective dousing process may reduce heat stress during an outage.

Guo et al. (2017) found that heat waves had more impact in moderately hot and moderately cold regions than they did in cold and hot regions. In addition, acclimatization to heat and cold has been investigated. Milojevic et al. (2016) investigated whether people acclimatize to changes in temperature by studying adjacent areas, some with heat island effects and others without. They found the relative risk differed very little between those that were accustomed to higher temperature and those living in areas that experience fewer extreme temperatures.

Hajat and Gasparrini (2016) found that the measure of winter deaths when comparing December-March average deaths versus all other months leads to biased results in terms of the health-related impacts of winter weather.⁵ When adjusted for cold temperature, the winter death index dropped from 1.19 to 1.07. However, there are some limitations in the Gasparrini study regarding impacts of cold temperatures on human mortality as it did not factor for thicker blood and higher blood cholesterol levels during the winter, which may lead to deaths during cold winter months rather than hypothermia.⁶

The physical location of exposure (e.g., inside or outside of the building and the climate zone) is important for this study to discern whether the mitigation measures will impact health. Location of exposure is primarily anecdotal with articles in journals about the location of exposure. In a 2012 heatwave that affected Maryland, Ohio, Virginia, and West Virginia 69 percent deaths occurred at homes with no air conditioning. Five of the deaths occurred outside of the home and were attributed to heat exposure (Fowler et al. 2013). In a California heat wave study, 66 percent died indoors (Joe et al. 2016). A study of people 65 and older in Houston (O'Lenick et al. 2020) found positive correlation between mortality and short-term occurrences of indoor heat exposure for people with circulatory disease. The CDC occasionally provides information on the location of death for hypothermia. In one paper, the CDC reported two people were found dead outside, while the third person was found dead in his house due to hypothermia (Murphy et al. 2006). Lane et al. (2018) indicated that 75 percent of mortality from hypothermia were exposed outside. Thus, based on these studies, anecdotally about 66-69 percent of people exposed to heat die inside while about 22-33 percent exposed to cold die inside.

Dampness and mold

Dampness and mold in buildings is associated with respiratory illnesses including cough, wheezing new or worsening asthma symptoms and skin conditions. Dampness combined with inadequate ventilation create the perfect breeding ground for microbial and viral pollutants like dust mites, fungi, bacteria, mold, and viruses. Survival rate of bacteria is known to be larger at higher rates of relative humidity; similarly, virus survive in very low and very high levels of relative humidity. In addition to biological pollutants, dampness can dynamically change the

⁵ This not how the Buzzfeed calculations were undertaken.

⁶ Personal communications with Kris Ebi, University of Washington.

structure of particulate matter emitted from building materials at a molecular level, thereby impacting the concentration of non-biological pollutants inside buildings.

Studies have found an increase in odds ratio of respiratory illness in buildings with higher percentage of mold (Fisk et al. 2007). Indoor dampness is believed to potentially impact about 50 percent of buildings (WHO 2009). Most epidemiological studies focus on evaluating costs associated with outdoor sources of mold; but more recent ones have emphasized the need to recognize mold and dampness as a cause of serious concern for indoor environments (Gilbert et al. 2018); particularly for vulnerable populations (Kim et al. 2019). Mudarri attributes dampness and mold to cost the society \$3.7 billion for allergic rhinitis, \$1.9 billion for acute bronchitis and \$16.8 billion for asthma (Mudarri, 2016). Reasons for mold in buildings include moisture build-up due to higher occupancy (latent heat from occupants), poor maintenance due to tenancy vs homeownership, poor insulation, ventilation, age of buildings, inadequate space heating associated with fuel poverty, the general state of repair and maintenance and increased exposure to sea level rises, floods and storms aggravated by climate change. (Taptiklis 2021, WHO 2009).

Particulate Matter Exposure

Particulate matters are extremely small particles in solid or liquid form. Exposure to particulate matter is associated with cardiovascular, respiratory, reproductive, metabolic, and psychiatric disorders and certain types of cancer (NAE 2022). Most studies on health impacts are focused on outdoor sources, but there is increasing evidence of higher exposure to particulate material indoors. Indoor sources of fine particulate matter include building materials and finishes, tobacco smoke, cooking emissions and infiltration of outdoor sources into the buildings. Adhesives and bindings used in common building materials contain formaldehyde, a chemical that aids in the formation of fine particulate matter. Two main sources of particulate matter are associated with cooking – the heat source used and the food itself. According to a study conducted in 2014, use of solid fuels for cooking is estimated to have caused 3.5 million to 4 million deaths worldwide (Chafe 2014). Another study (Patel 2020) the particulate matter concentrations with gas stove cooking are 4 -7 times more than that of electric cooktops. Infiltration of outdoor borne particulate matter occurs via leaky envelopes and mechanical or natural ventilation. Studies show disparity in exposure to particulate matter; with higher exposure in low-income communities; due to the closer proximity to commercial and industrial sources of particulate matter (Goldstein 2021). Higher rates of outdoor particulate matter infiltration are also seen in regions with frequent wildfire events (Pantelic 2019). Building envelope; particularly infiltration levels hence have a health impact by virtue of preventing the entry of outdoor particulate matter.

Building characteristics that impact particulate matter concentrations include infiltration, mechanical ventilation and filtration efficiency. Ventilation via mechanical or natural methods is crucial for diluting the concentration of particulate matter concentration. However, it can also act as carriers of outdoor sources to indoors if the outdoor air is not filtered sufficiently. Ventilation filters are believed to be highly effective in containing particulate matter; however, they are utilized only when the HVAC system is in operation; hence the system runtime can impact the effectiveness of a ventilation filter. In the US, the mortality burden associated with particulate matter exposure is estimated to be approximately 300,000 deaths per year. Of this about 40 percent to 60 percent is believed to be due to indoor exposure of particulate matter of outdoor origin (NAE 2022, Kim 2019).

Valuation of Health Impacts

Building energy codes help reduce energy use in buildings; help reduce greenhouse gas emissions and help meet energy independence goals of the nation. In addition, climate change is causing more severe weather including both severe cold and severe heat. Therefore, valuation of mitigation measures in building energy codes could also benefit from including the value of human health when evaluating the benefit cost of energy codes.

A number of pieces of literature have attempted to provide health valuation measures. The Federal Emergency Management Administration provides a benefit-cost tool that is used to justify FEMA grants (FEMA 2009) and (FEMA 2020). The tool provides values for human life, hospitalization, and emergency department visits. The tool, however, requires the entity using the tool to determine the potential losses that will occur during the severe weather event.

Several studies have attempted to quantify the productivity gains of building improvements. Fiske (2002) found that improvements in ventilation could reduce acute respiratory illness 9 percent-20 percent, providing productivity gains of \$6-14 billion in the United States. He also found that sick building syndrome could be improved with ventilation improvements costing about \$60 billion annually in production losses. He estimated that improved ventilation could reduce the losses by 20-50 percent. He also evaluated lighting and temperature affects finding \$20-\$160 billion in savings.

Muldavin, Miers and McMackin (2017) develops a methodology to assess the financial performance of buildings that met the WELL standard (WELL 2018). A primary point of their paper was that employers spend 112 times more on salaries than they do on energy costs and therefore healthy buildings could boost the bottom line for most companies. Their approach follows the profit motive using an ROI model that applies improvements to a hypothetical building to improve productivity and reduce absenteeism. They found that including WELL health standards could reduce insurance premiums, employee turnover, and in return, reduce recruiting costs as well as increase productivity.

In their 2020 research report (Hayes 2020), 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. They use a generalized formula based on number of households, number of vulnerable occupants, incidents or harms avoided through intervention and dollar value of voided health harm.

Impact of Building Energy Codes on Health

Building characteristics that could impact the three health hazards described in the literature review (temperature, dampness and particulate matter) include building envelope air tightness, building materials, insulation, HVAC system runtime, humidification, ventilation rates, filtration efficiency of ventilation equipment and cooking fuel source. In the US, model energy codes -ANSI/ASHRAE/IES Standard 90.1 and IECC and state codes like California's Title -24 have mandatory and prescriptive requirements that set minimum standards for the above-mentioned building characteristics. Though the primary intent of the energy codes is to reduce energy consumed by buildings; findings from the literature review provide evidence that they also have a significant impact on the health of people occupying these buildings.

Energy codes are applicable to newly constructed and renovated buildings and do not directly regulate building operation. There are several technical guidelines and rating systems available for building operation but currently they are not as well enforced as model energy

codes. This limits the impact energy codes can have on existing buildings. Additionally, enforcement of energy codes varies by jurisdiction, which results in energy efficiency requirements being installed or operated below the requirements set by the standards (Xie 2019). Improper installations can worsen indoor air quality; for example, a poorly installed insulation assembly may impact health by emitting volatile organic compounds, by increasing particulate matter concentrations, by trapping excess moisture, and may even impact the overall energy performance. Another challenge for health considerations in energy code development and enforcement is the potential tradeoff between energy efficiency and health at individual measure levels. For example, increased envelope airtightness reduces energy use in cold climates; however, an airtight building that is not properly ventilated is detrimental for occupant health (Carmichael 2020).

Yet another challenge lies in the current process of energy code development. Like most other policies, energy code development is based on the assessment of a “typical” building in each climate or region. Even though it considers variability in climate and building type; it is not meant to account for every change in microclimate or occupant behavior. Energy and health impacts of measures on normal days may vary significantly, particular for health on extreme weather days. Additionally, the health impact of energy measure packages may differ from that of individual measures, for example, higher envelope insulation and air tightness will reduce energy use and increase thermal comfort on normal days; however, if there is insufficient ventilation and air-movement, indirect negative impacts on health in extreme hot weather days are plausible.

Despite the complexities, factors other than cost effectiveness can be considered when evaluating proposed changes as part of energy code development. These factors include occupant safety, security, comfort, and functionality. Yet, economic cost-effectiveness is an integral part of Standards’ development, such as ASHRAE Standard 90.1, which is referenced by the International Energy Conservation Code (IECC). The ability to quantify the cost benefits of proposed changes to the standard can inform decision making and aid in reaching adoption consensus. In this paper we propose a methodology that can be applied in code change proposals to quantify the impact of efficiency improvements on health considerations. The approach integrates building performance simulation analysis with a health impact model. The method allows health impacts to be tied to efficiency improvements affecting the building envelope air tightness, building materials, insulation, humidification systems, ventilation rates, filtration efficiency of ventilation equipment and cooking fuel source. By including human health considerations, the added benefit could provide sufficient economic justification for adopting the proposed code change.

The valuation methodology we propose utilizes the value of statistical life at risk. We determine the risk based on event-specific damage curve. The proposed methodology is based on damage curves presented in Gasparini et al. (2015) for mortality associated with severe temperature events. We test the applicability of the proposed methodology with a case study. The proposed methodology can be extended to other hazard types (for example wildfire or hurricane) and health outcomes (for example hospitalizations, loss in productivity or emergency department visits) in future studies by developing case appropriate damage curves.

Value of Lives Saved

To incorporate a valuation of the impact of building codes on human mortality, a value of human life is required, and as such the value of a statistical life (VSL) is used. This metric has

been used to calculate the value of each human life. For example, Viscuzzi (2020) calculated the VSL of health risks from the COVID-19 pandemic at \$11 million (2019\$) while estimating the total US cost of the covid pandemic. The Viscuzzi VSL value was composed of a set of estimates: a sample of all VSL estimates at \$13.2 million (2019\$); and a best set sample at \$13.3 million (2019\$). 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 uses a VSL estimate of \$11.6 million (2020\$) (Putnam and Coes 2021). FEMA provides a VSL estimate of \$7.6 million (2020\$) (FEMA 2020). Their BCA model includes estimates for hospitalization (\$1.3 million), treat and release (\$0.1 million), and self-treat (\$0.01 million) (FEMA 2009). Based on these examples, we estimate the VSL at \$10 million per life saved as attributable to mitigation measures in buildings that impact human health.

A Risk Approach to Valuing Human Mortality for Code Development

The proposed benefit-cost analysis (BCA) approach follows the probabilistic methodology discussed in Weimar (2022) where hazards, vulnerability and consequence are evaluated separately. However, when evaluating human health considerations, we found we needed to directly account for the exposure (which wasn't in Weimar's (2022) probabilistic approach) as previously discussed in the literature review above. The BCA analysis evaluates the discounted present value of all the value streams associated with the mitigation measures being evaluated. The benefit-cost analysis is divided into two parts: the energy life cycle costs and the resilience to mortality value of mitigation. An energy life cycle cost savings approach was used for valuing energy savings. For the mortality resilience valuation, the value at risk is calculated for the baseline for each housing type and re-evaluated with the impact of each set of passive mitigation measures modelled based on PHIUS standards (PHIUS 2022). The approach can be simplified to evaluating the difference between the baseline and the mitigation measures with reductions in human mortality and avoided property damage measured as a dollar benefit and compared with additional cost of the mitigation measure.

Equation 1 is used to determine the value at risk based on the joint probability of the five risk factors indicated below. The equation accounts for the probability of the hazard given the climate zone/region, the probability of the resistance to severe temperature associated with the housing stock and the population, as well as the probability of the associated damage. The dollar value of the loss is based on the damage incurred. For damages that can be quantified, monetary values can be used. For non-quantitative values for example, aesthetics of the building, ratings such as high, medium, low can be applied.

$$V = Prob(H|S) * Prob(R|H) * Prob(E|R) * Prob(D|E) * Prob(L|D) \quad \text{Eq. (1)}$$

where:

- V = Value at Risk
- Prob = Probability
- H = Hazard (joint temperature/electricity outage)
- S = Region/climate Zone)
- R = Resistance to indicated hazard
- E = Exposure to severe temperature
- D = Damage that occurs to the housing and population
- L = Dollar value of the loss that occurs due to damage

Using the equation, the baseline annualized value at risk or the resilience value was calculated. To establish the benefit of mitigation measures, the differences in cost values were calculated between the baseline and mitigation measures. The information pertinent to the life cycle cost calculation, included: annualized investment costs of mitigation measure, lives lost, equipment lost, broken pipes, repair for mold (remediation), energy saved, and carbon emission changes. Changes in the value of illnesses, hospitalizations, emergency room visits were not calculated as more work is required for the development of damage curves for these outcomes.

Case Study – Houston Winter Storm

For this paper, a case study was developed to evaluate the effectiveness of using the Gasparrini damage curves with the proposed methodology above for predicting human mortality from severe temperature. The Texas winter storm of 2021 was used to calculate the mortality associated with indoor improvements achieved by implementing the mitigation measures based on passive measures associated with PHIUS (2022). The Texas 2021 winter storm event provides a good case study to indicate whether the Gasparrini study damage curves with respect to cold temperatures and human mortality closely represent values to those associated with actual outcomes. The excess deaths associated with the event can be matched with the study's outcomes to understand whether application of the study to mitigation measures can be used to measure the mortality outcomes. In addition, comparison of efficiency measures' impacts on indoor temperatures can be used to determine how much the indoor temperature changes reduced human mortality.

The Gasparrini study fitted a Poisson model for each of 384 locations in 13 countries including 135 US cities in most regions of the U.S. The model controlled for air pollution, humidity trends, and days of the week mean daily temperature. The model also contained a 21-day lag to capture the effects of cold and to remove deaths that were advanced by only a few days. The Gasparrini study has some limitations in its applicability. However, the study is currently the only one that provides a relationship between mortality to severe temperature for the regions evaluated. The primary limitations of applying the Gasparrini et al. (2015) to buildings are that it does not: 1) account for indoor temperatures: 2) control for air conditioning, and 3) specify the location of exposure (indoors versus outdoors). Our case study implements passive efficiency measures associated with the Passive House Institute US (PHIUS) (ca 2022), to affect indoor temperature during the extreme cold event through whole building energy simulations using weather files representing the Texas 2021 winter storm event.

Winter Storm Uri caused nearly 10 million people to lose power in February 2021. Texas was hit the hardest with three-quarters facing rolling blackouts. Freezing temperatures caused natural gas generators that weren't winterized appropriately to fail requests for generation (Postelwait 2022). In Texas, the storm left 4.5 million homes without power. The storm's property damage reached \$295 billion. Several Texans lost power for an average of 42 hours between February 14 and 20th and one-third suffered water damage (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 (Aldhous and Hirji 2022). The values from these studies were used to compare with the results from simulated indoor temperatures and the Gasparini damage curves to estimate mortality.

Figure 1 provides the Gasparrini damage curves for human mortality for Houston shown as relative risk. The figure indicates the relative risk rate at each temperature. The dashed vertical

lines are the 2.5 percent and 97.5 percentiles for Houston. Table 1 shows an example of the relative risk (RR) values that were interpolated for Houston from the Gasparrini study. The relative risk can be converted to an attributable death fraction by using the formula (equation 2):

$$AF = (RR-1) / RR \quad (\text{eq. 2})$$

Where:

AF = Attributable fraction of deaths due to severe heat or severe cold

RR = Relative risk of mortality compared with normal circumstances

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. In Table 1 the relative risk rate for both the existing housing stock and PHIUS measures are evaluated.

ResStock (Wilson 2016) was used to calculate the simulated indoor temperatures for existing single family residential housing for the baseline and PHIUS measures for the Houston weather event. The temperatures were then averaged by day for each day of the cold wave to get the average daily temperature. The indoor temperatures were used to calculate the indoor mortality for the baseline and the PHIUS measures as shown in Table 1.

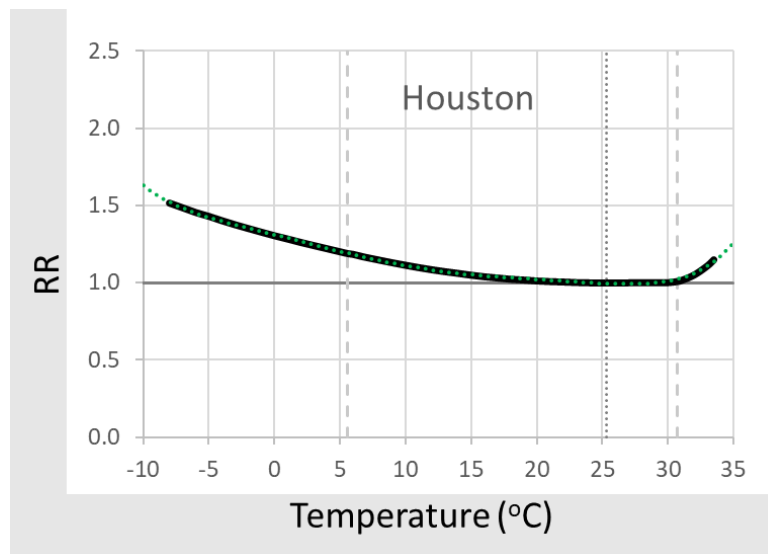


Figure 1. Relative risk rates for the Houston. The graphics were recreated from Gasparrini et al. 2015.

Analysis and Comparison

The updated excess death analysis indicated that 755 people died in Texas during the week of the February winter storm. The total number of people who died was determined for Harris County by assuming the same rate and adjusting that value based on its population relative to state population, which is 33 percent. That results in an estimate of 246 deaths. Thus, the 206 average deaths estimated using the damage curves developed from the study is directly comparable. The numbers calculated would have been higher had the ambient outdoor

temperature been included rather than the indoor temperature. However, the study compares differences in mortality between the two efficiency conditions, and not absolute values. Thus, the bias of outdoor ambient temperature versus indoor ambient temperature has been reduced. Based on the analysis above, the upgrade to the beyond-code efficiency measures could save, more than 68 lives on average, worth more the \$687 million if the event occurred. The annualized amount that accounts for event probability is about \$23 million based on Table 2.

Table 1. Relative Risk rates associated with specific indoor temperatures for Houston, Texas for existing buildings in the 5th percentile with calculated mortality for baseline and PHIUS improved buildings

Temp. (°C): base	RR	Temp.(°C): PHIUS	RR	Base Deaths	PHIUS Deaths	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
...	...	..	...	...	...	...
21	1.025	21	1.025	3	3	-
Total				246	198	48
Joint Probability		3.3 percent		Expected Deaths →		1.57

Table 2. Mortality results using Gasparrini mortality curves for Harris County Texas

	Base PHIUS Chg.			Base PHIUS Chg.			Base PHIUS Chg.		
	Cold 95 percentile			Cold 50 percentile			Cold 05 percentile		
Cold event deaths	166	80	85	202	128	73	246	8	48
Joint Probability	3.30 percent			3.30 percent			3.30 percent		
Annualized Deaths	2.8			2.4			11.6		

Conclusion

The authors present a literature review on the relationships between building codes and human health to determine damage curves related to health outcomes and human mortality. There is significant literature relating temperature and indoor contaminant sources to human health. For temperatures, the relationship is dependent on acclimatization and adaption. People from areas with warm weather tend to adapt to hotter temperatures than people from cooler

regions, while people from cooler climates can better adjust to below-normal cold temperatures. In addition, studies found that people 65 years and older and the very young were more susceptible to severe temperatures than others. The literature also revealed that socioeconomic status played an important role in mortality. Lower-income individuals fair less well than middle- and upper-income individuals. One study by Gasparrini et al. (2015) provided damage curves for 135 US cities considering the differences between cities with different acclimatization, socioeconomic status, and age demographics. That study provided damage curves for our case study and the tri-lab Efficiency Resilience Nexus study⁷ results. In this paper we presented a method to use damage curves to value human mortality reductions associated with energy efficiency. The proposed approach can also calculate the annual value of mitigating health hazards associated with exposure to indoor sources of triggers for asthma, respiratory, cardiac, and other health conditions. However, future studies to develop health outcome specific damage curves are needed.

Economic cost-effectiveness analysis is an integral part of the building construction standard's development, such as ASHRAE Standard 90.1 and 90.2. The methods developed in this study can be applied to expand the typical scope of the economic analysis to quantify the value of the code change to health as indicated by the reduction in excess death during extreme temperature events. As changing climate impacts on building infrastructure and global health becomes an increasingly important concern, health considerations in the energy equation will become essential. As model energy codes have the power to impact entire populations of buildings; there could be potential to develop synergistic goals if future energy codes account for health considerations in the development process.⁸

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⁷ Enhancing Energy Resilience in Buildings: Development of a Standardized Methodology to Quantify Efficiency Benefits. Publication pending (Franconi et al. 2022).

⁸ These documents are referenced by Energy Conservation and Production Act as modified by the Energy Policy Act of 1992 as the minimum requirements for states adopting energy codes (<https://www.govinfo.gov/content/pkg/USCODE-2011-title42/pdf/USCODE-2011-title42-chap81-subchapII.pdf>).

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