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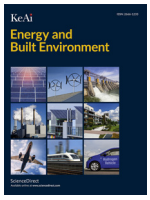
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Full Length Article

High-performance windows improve thermal survivability of occupants during cold snaps ☆

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ABSTRACT

Exposure to low indoor air temperature is a major contributor to temperature-related mortality during extreme cold events, especially when power outages disrupt operation of space heating systems. This study explores the impact of high-performance windows on the thermal resilience of residential buildings during extreme cold weather and grid power outages, as well as their long-term benefits through energy efficiency and reduced risk of property damage. Building performance simulations were conducted for reference residential buildings in three construction vintages and two major U.S. cities located in cold climate zones, considering two types of extreme cold events: short and severe, and long and milder. Our research found that even houses compliant with current energy codes struggle to maintain safe indoor temperatures for more than a few hours during power outages, necessitating rapid evacuations. High-performance windows can extend the thermal survivability time by up to 3.8 days within a 7-day cold snap and significantly reduce risk of bursting frozen water pipes, depending on the building's insulation and infiltration level, cold event severity, and occupant vulnerability. This extended thermal safety time is crucial in scenarios where reduced mobility complicates emergency responses in senior housing. In addition to boosting thermal resilience, upgrading older homes with high-performance windows can reduce heating energy consumption by over 18 % and cooling energy by 15 %. Our findings highlight the need to incorporate thermal resilience assessments into new designs or major retrofits, including the use of typical and extreme weather scenarios and advanced technologies like high-performance windows.

1. Introduction

Increasing greenhouse gasses (GHG) emissions disrupt established weather patterns, resulting in more unpredictable and severe weather [1]. Warmer ocean temperatures can result in heavier snowfall, and extreme low temperatures can extend further south due to warmer and weakened Arctic air jet streams [2]. These extreme cold events, paradoxically linked to a warming world, highlight the complex ways in which shifting climate patterns are increasing climate variability, posing significant challenges for communities and infrastructure unprepared for such extremes [1].

Power outages during extreme cold events have become an increasingly critical issue in the United States. Bhattacharyya et al. [3] analyzed historical data from 2000 to 2016 and found that 75 % of power outages in the U.S. were caused by severe weather events. During extreme cold periods, the demand for electricity spikes as the heating load increases significantly while heating system efficiencies decrease, straining the grid beyond its capacity [4]. Ice accumulation on the power grid components, such as insulators, during cold events can cause flashover faults and hinder power transmission [5]. Beyond the direct impact on grid components, cascading failures—which can lead to subsequent disruptions—are often triggered and exacerbated by extreme weather events [6,7]. The damage caused by extreme weather on buildings, water systems, and air quality also challenges recovery efforts [8]. For example, very low temperatures can freeze the water within pipes, leading to expansion that may cause the pipes to split or break [9]. In fact, burst pipes are one of the most frequent causes of property damage during cold events in the United States, requiring thousands of dollars to repair [10].

Abnormal ambient temperatures significantly contribute to excess mortality. While most of the previous research has emphasized heat-related effects, Gasparrini et al. [11] estimate that low temperatures are responsible for the majority of temperature-related deaths across 384 locations worldwide. Cold spells are associated with increased incidence of various diseases, including respiratory, circulatory, digestive, endocrine, and nervous system diseases. The cumulative impacts of cold spells are also intensified by longer periods of exposure [12]. During the eight-day Great Texas Freeze in 2021, nearly 10 million people were left

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without power, lacking both warmth and the means to cook food [13]. During such conditions, buildings serve as a buffer to protect occupants from the severity of the outdoor environment [14].

Despite representing a small portion of the building envelope, glazing elements can significantly affect the energy use for cooling and heating buildings, as well as peak electric demand and occupant comfort [15]. Also, older homes often have poor and leaky windows that contribute to significant heat loss during winter, making them less energy-efficient and more vulnerable to extreme cold events. In the U.S. building stock, infiltration was identified as the largest contributing component to heating loads [16].

Advanced glazing technologies can optimize heat transmission by managing solar radiation through absorption, transmission, and reflection, tailored to the materials used [15]. Available static solutions include triple-pane glazing, low-emissivity (low-E) coatings, and gas-filled insulated glazing units. There are also dynamic glazing solutions (e.g., electrochromic and thermochromic), but these are still expensive and only offered by a limited number of manufacturers worldwide [17]. Triple-pane glazing involves three layers of glass with air or gas-filled spaces in between, providing superior insulation compared to single or double-pane windows. Gas-filled insulated glazing units, often filled with argon or krypton, further reduce heat transfer between the indoor and outdoor environments by enhancing the insulating properties of the window [18]. However, the costs associated with these technologies still impact broader adoption, particularly when retrofitting existing buildings, with high-performance windows being more expensive than other retrofitting options, such as weather stripping and insulating cellular shades [19]. Nonetheless, prices of window products vary considerably within performance levels and technologies, indicating that performance is not the key factor driving cost [20]. Given the strong impact of window technologies on building thermal performance, exploring their co-benefits beyond energy efficiency is paramount to driving broader adoption.

1.1. High-performance windows in codes and standards: drivers of broader adoption

Building energy codes and standards can significantly influence the adoption of new technologies in construction by mandating certain requirements. The primary types of policies addressing glazing technologies are either prescriptive or performance-based. Prescriptive policies specify minimum/maximum values for Solar Heat Gain Coefficient (SHGC), thermal transmittance, and window-to-wall ratio, among other desirable characteristics. The window industry and fenestration organizations have developed rating and certification systems to assess and communicate the energy efficiency of window products [21]. In the U.S., the National Fenestration Rating Council (NFRC) has established performance ratings to characterize window, door, and skylight products. ENERGY STAR utilizes the NFRC ratings to define appropriate above code transmittance and SHGC values depending on the climate zone [22]. Similar labeling systems can be found across the globe [23,24]. For instance, ENERGY STAR for residential windows, version 7.0, prescribes windows with thermal transmittance lower than 1.25 W/(m^2.K) and SHGC higher than 0.17 for the Northern—colder—U.S. regions [22]. A window market share study [25] conducted in this region verified that only a very small percentage of windows sold in 2022 (2–4 %) would have met ENERGY STAR version 7 requirements which became effective in October 2023, even though about 90 % of the windows sold in 2022 met the requirements of ENERGY STAR version 6. Still, the study [25] highlights that such rating is one of the top five criteria for window selection among consumers, indicating that codes and standards create a demand for compliant materials and technologies, pushing the market to wider adoption as they are applied to new buildings and major renovation projects.

A more flexible approach for code compliance is through whole-building performance-based approaches, which typically allow any window technology to be applied as long as the overall building performance goal is met. This is the case of the performance paths from ASHRAE Standards 90.1 (energy efficiency for commercial buildings) [26] and 90.2 (energy efficiency for low-rise residential buildings) [27], for example. On one hand, performance analyses—particularly through simulation—account for the relative importance of each building component and lead to a more robust assessment of building technologies. On the other hand, modeling assumptions can lead to high uncertainty. Also, most current building codes focus on energy efficiency, not accounting for potential benefits of window technologies in enhancing thermal safety of occupants during extreme weather events and infrastructure disruptions [28,29]. As such events are projected to happen more frequently in the future [30,31], there's a gap in understanding how building technologies can help enhance thermal resilience.

The Leadership in Energy and Environmental Design (LEED) pilot credit "Passive Survivability and Backup Power During Disruptions" [32] provides a structured framework for assessing a building's capacity to maintain livable conditions during extended power outages or fuel disruptions, particularly under extreme weather conditions. One core aspect of this credit is the evaluation of **thermal survivability**, defined as a building's ability to passively maintain safe indoor temperatures during extended power outages or loss of heating fuel, ensuring occupant safety without relying on mechanical systems. This approach encourages the use of passive design strategies—such as high-performance windows—to ensure buildings remain habitable during emergencies.

1.2. Major efforts to assess and improve thermal resilience of buildings worldwide

Indoor overheating risk, due to lack of air-conditioning or during heat waves without grid power, has been studied recently, aiming to provide a reasonable assessment of heat vulnerability and more importantly to identify mitigation measures for informing decision makers on heat policy or programs. An example is the 5-year international collaborative project Annex 80—Resilient Cooling of Buildings—under the International Energy Agency's Energy in Buildings and Communities Programme [33]. The follow up Annex 97—Resilient Cooling in Cities—expands the cooling study to the urban or city scale including the built indoor environment and the outdoor urban environment. A recently approved Annex 93—Energy Resilience of Buildings in Cold Climates [34]—will focus on the cold resilience issues, technologies, building design and operation, as well as building energy codes and policies.

1.3. Scope and contributions

This article aims to quantify the co-benefits of high-performance windows in improving the cold resilience of residential buildings by minimizing indoor temperature drops and associated risks during extreme cold events. Such improvements are known to contribute to reduced mortality risk, better occupant health, and lower property losses. For a comprehensive assessment of these window technologies, we also investigate the building annual energy performance and potential overheating risks during summertime. Findings from the study could:

- Support the promotion of high-performance windows for new building design or major retrofits to improve thermal resilience while reducing energy use.
- Demonstrate how thermal resilience analyses can help prioritize emergency response efforts during extreme cold events compounded by power outages.
- Demonstrate the potential to reduce property damage by maintaining safer indoor temperatures during heating system shutdown.
- Provide insights into overheating risks during warmer months, ensuring balanced year-round thermal performance.
- Inform codes, standards, and incentive programs by presenting performance-based evidence that can guide design decisions.

2. Method

To assess the low temperature risk and evaluate how high-performance windows improve the thermal resilience of occupants and properties, we chose the building performance modeling approach and scenario analysis using prototype single-family buildings in typical U.S. cold climates.

Five window technologies were evaluated considering two scenarios with different performance metrics:

- **Thermal resilience during extreme cold events:** Explores how different window technologies can help buildings to guarantee occupant's survivability in the event of cold snaps compound with power outages lasting 3 or 7 days.
- **Annual energy performance:** Explores annual energy impacts of different window technologies in a typical year. We also analyzed the effect of these technologies zooming in typical hot summer days to verify potential trade-offs between energy use, and overcooling and overheating risks.

For each scenario, a combination of two climates, three building vintages, and two infiltration conditions were considered. Fig. 1 summarizes the workflow, which is described in detail in Sections 2.1 through 2.5.

2.1. Weather data curation

Two of the largest U.S. cities with very harsh winters were selected: Chicago, Illinois, and Minneapolis, Minnesota. Their climates are classified by ASHRAE 169 [35] as 5A (cool humid) and 6A (cold humid). Section 2.1.1 describes the process of identifying extreme cold events within historical weather records for these two locations. Section 2.1.2 presents the weather files used for the annual energy performance scenario to represent typical meteorological years.

2.1.1. Extreme cold events for thermal resilience assessment

Extreme cold events (cold snaps) curated from historical weather records in each city were adopted to understand the thermal resilience of buildings under given conditions in the short-term scenario. A cold snap generally refers to a sudden period of significantly lower-than-average weather that may last a couple of days. Therefore, rather than directly using the minimum temperature as a metric, the duration, intensity, and severity should be considered to characterize cold snaps [36]. In this study, we adapted the methodology developed by Ouzeau et al. [37] to detect heat waves, which utilizes percentile-based thresholds of historical daily temperature distributions: Spic for detection, Sdeb for the start and end of the event, and Sint for event interruptions. Specifically, for identifying cold snaps, the three percentiles of the daily average outdoor dry-bulb temperature used in this study were 0.5 % for Spic, 2.5 % for Sdeb, and 5 % for Sint. To comprehensively understand climate variability, we utilized 42 years (1980–2022) of historical weather records for each city from SPtMaster [38] (1980–2000) and NASA Power [39] (data only available from 2001 onward). Each calculated threshold and identified event is specific to the location of the temperature records.

Fig. 2 demonstrates the daily dry-bulb temperature for historical weather records (in purple), curated cold snaps (in red), and the calculated Spic, Sdeb, and Sint in both Chicago (5A) and Minneapolis (6A). To better reflect evolving climate conditions, the 42-year historical weather record was divided into two periods—1980–2001 and 2002–2022—for the cold snap curation process. Thresholds were calculated separately for each period, and cold snap events were identified using the thresholds specific to their respective timeframes. This approach allows the percentile-based method to adapt to long-term shifts in temperature distributions, resulting in thresholds that evolve with climate variability. As a result, the selected cold snaps are more representative of the changing nature of extreme cold events over time. After analyzing historical weather records to identify cold snaps, we compared the duration and the average daily temperature for those events. From this comparison, we selected the event with the lowest temperature and a duration of three days to represent shorter but colder snaps. Additionally, we chose the event with the highest temperature and a duration of seven days to represent longer but milder events. Selected cold snaps are described in Table 1. Also listed in Table 1 are the Mean Daily Temperature, which is the average of the daily temperature of the selected cold snaps, and the winter design day temperatures from ASHRAE [40] used for sizing the HVAC system in the prototype models.

Fig. 3 shows the hourly comparison of dry-bulb temperature with wind speed and global horizontal irradiation (GHI) in Chicago and Minneapolis before, during, and after the selected cold snaps. In Fig. 3, the dashed vertical lines and arrows help us see the start and end days of the selected cold snaps, while we noticed that there were two additional cold snaps that occurred near the selected one. Finally, the red markers in the left-hand side plots indicate the highest wind speeds during the entire displayed period. Analyzing Fig. 3, several observations can be made. First, it is evident that during the 3-day cold snap, the temperature usually drops sharply, although there are some slight rebounds. However, such temperature declines in a 7-day cold snap were much gentle and could span 1–2 days for the temperature to reach lower-than-normal temperature. In addition, after the temperature drop, the 7-day cold snaps either remained consistently low (in Minneapolis) or had several transient, gentle temperature rises (in Chicago). Secondly, the highest wind speeds consistently occurred during cold snaps, indicating a gusty wind passed. This might be caused by the large difference in temperature and pressure in a short geographic difference during the cold snaps [41]. Third, a clearing sky is usually behind the sharp temperature drop during cold snaps, and such phenomena are more obvious when the wind speed is higher. This might be caused by the fact that cloud evaporation was promoted by the appearance of sinking cold air in cold snaps, which promoted clearing skies [42].

2.1.2. Typical meteorological year for annual energy performance assessment

Meteorological years representative of the long-term climate in each city were adopted to understand the typical annual energy consumption for heating and cooling. Fig. 4 shows the hourly dry-bulb temperature throughout a typical year (TMY3) in Chicago and Minneapolis, with annual average values of 10.0 and 7.7 °C, respectively. The areas highlighted in Fig. 4 allow to visualize the frequency in which temperatures fall below cold survivability thresholds, 4.4 °C and 10 °C, further discussed in Section 2.3.

Within the typical year, we also analyzed the building performance specifically during typical hot summer days to see whether high-performance windows cause increased indoor overheating risk. The climates of Chicago and Minneapolis are particularly interesting for this type of analysis because they exhibit both extremes, very cold (as low as −31.1 °C) and very hot temperatures (up to 37.2 °C) even in a typical meteorological year.

2.2. Power outage definition during extreme cold events

This study focuses on a worst-case scenario in which extreme cold events coincide with power outages, recognizing while such overlaps may not be frequent, they pose significant risks to occupants and infrastructure when they do occur. Although winter power outages are often triggered by specific conditions such as heavy snowfall or freezing rain, rather than low temperatures alone, these events are increasingly influenced by shifting climate patterns that contribute to grid stress and cascading failures.

We assumed the power outage events started at the beginning of the first day (midnight) and lasted for the full extreme cold periods. Besides the outage days, the simulation period included one week before and one week after the cold events to correctly represent the indoor thermal conditions and the recovery process post-disruption. For these weeks

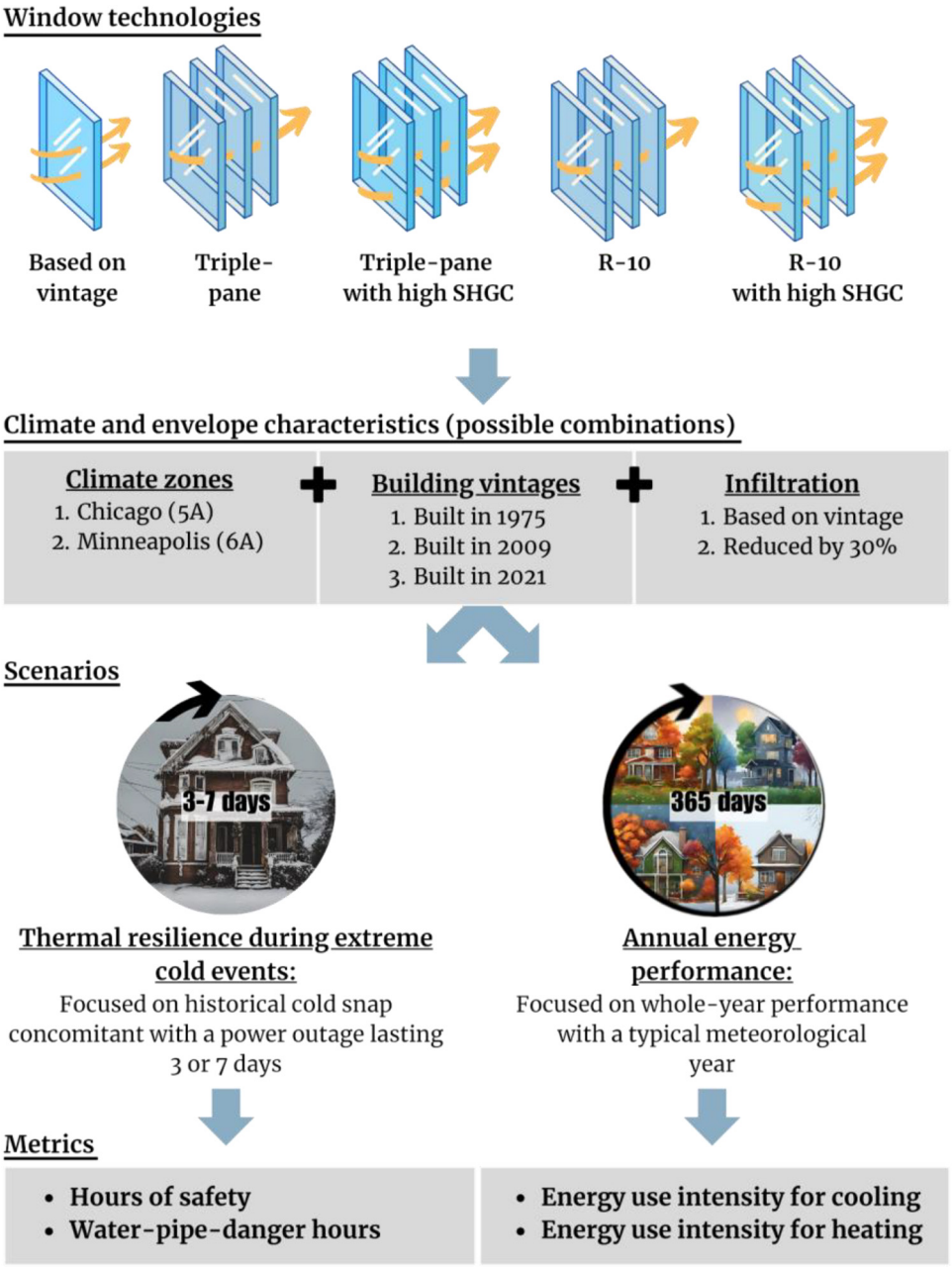


Fig. 1. Method and workflow overview.

Table 1
Cold snap events selected for Chicago and Minneapolis.

Location	Event Type	Start [month/ day/ year]	End [month/ day/ year]	Duration [day]	Mean daily temperature [°C]	ASHRAE heating design condition at 99.6 % [°C]
Chicago (5A)	Shorter, colder	1/19/1985	1/21/1985	3	−20.86	−20.0
	Longer, milder	2/22/2015	2/28/2015	7	−10.49	
Minneapolis (6A)	Shorter, colder	1/21/2014	1/23/2014	3	−23.89	−25.2
	Longer, milder	12/25/2017	12/31/2017	7	−20.16	

surrounding the event, normal occupancy and operation of the building systems and equipment was considered. During the power outage period, we modified the schedules of electricity appliances, HVAC system availability, and occupant behavior to turn off any energy consuming device or equipment.

2.3. Performance metrics

We used tailored performance metrics for each scenario, aligned with their specific objectives. Under the short-term scenario, focused on extreme cold events, metrics should reflect whether residents' health might be in danger due to low indoor temperatures without the support of mechanical systems (e.g., if power goes off). Another relevant impact during these events is the risk of property damage. These two dimensions of impact (to occupants and to properties) were analyzed through two metrics:

- **Hours of Safety (HOS) (in hours):** Describes how long a building can sustain safe indoor thermal conditions in the absence of power supply during extreme cold events [2]. Considering that risks of cold

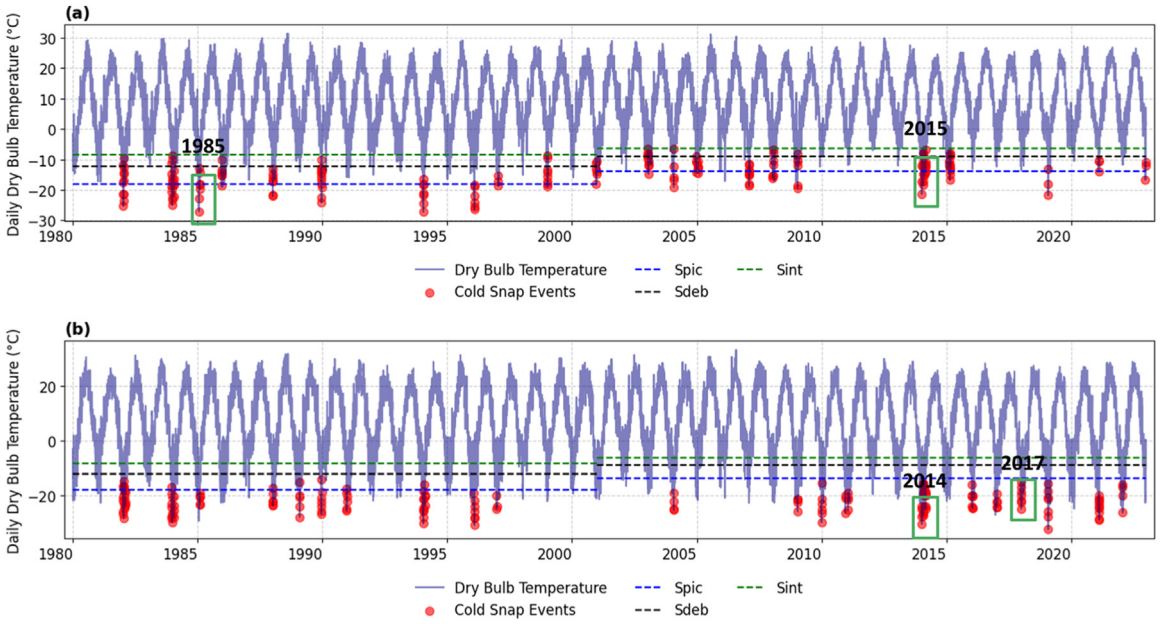


Fig. 2. Daily dry-bulb temperature of 42-year weather record and curated cold snaps in (a) Chicago and (b) Minneapolis.

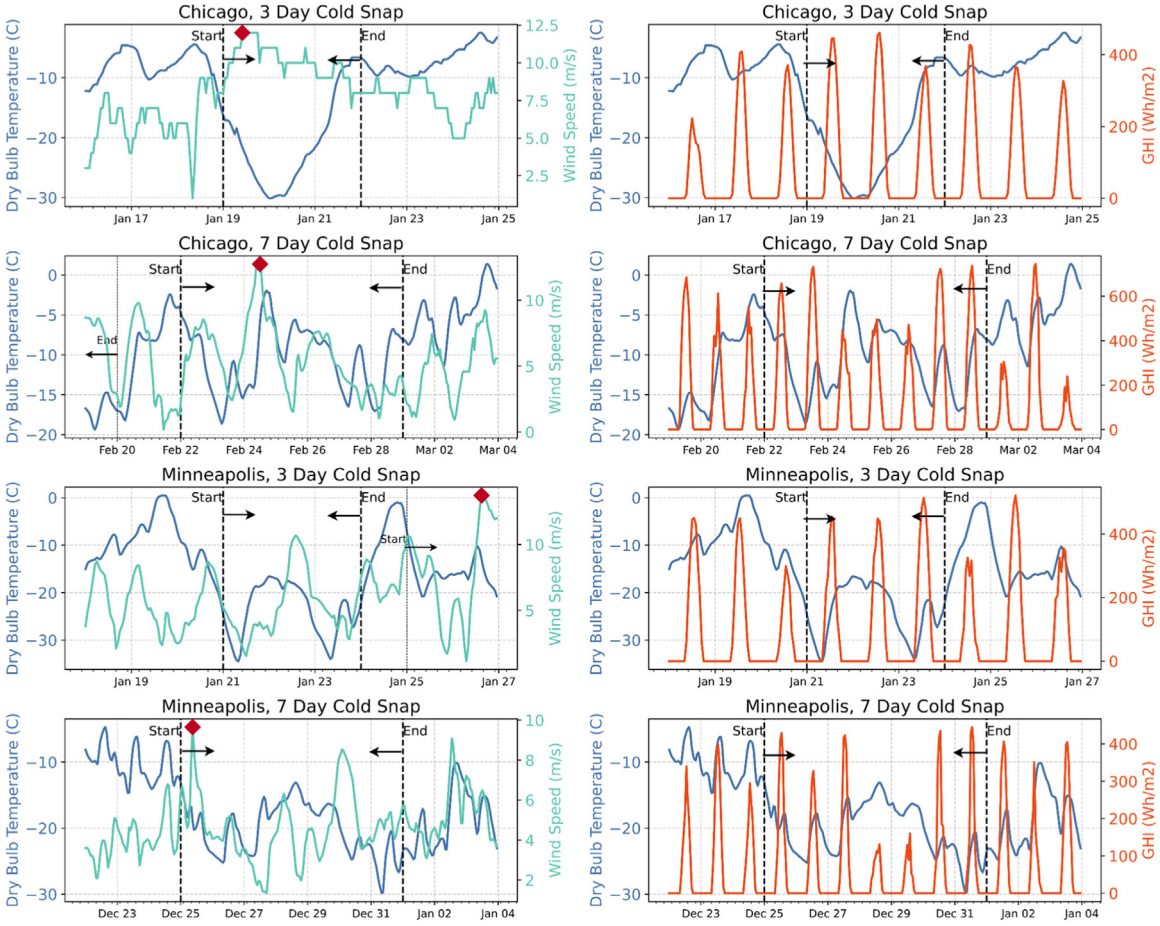


Fig. 3. Hourly comparison of weather data during selected cold snap events in Chicago and Minneapolis.

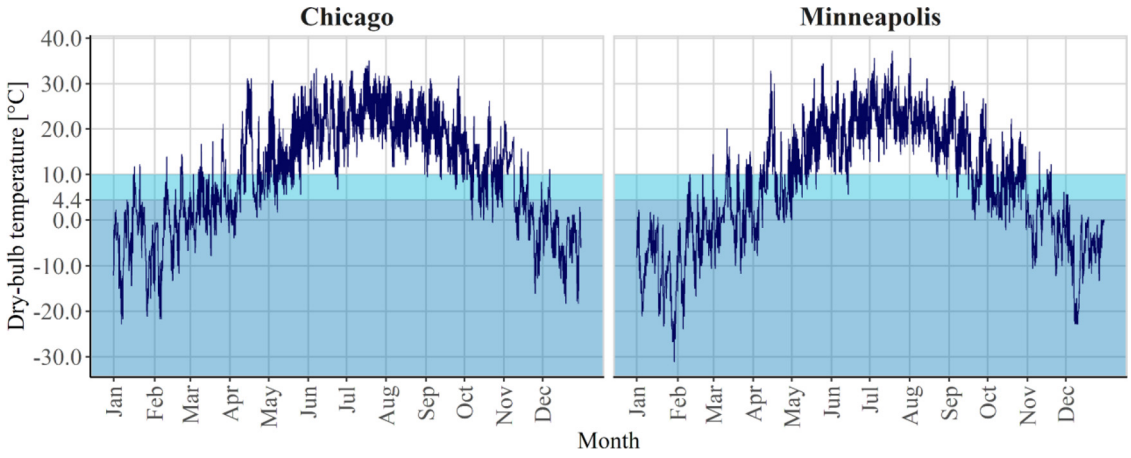


Fig. 4. Hourly dry-bulb temperature of a typical meteorological year in Chicago and Minneapolis.

Table 2
Cold stress scale according to [2].

Minimum safe temperature for vulnerable populations	Minimum safe temperature for healthy populations	Mild cold stress for healthy populations	Moderate cold stress for healthy populations	Severe cold stress for healthy populations
> 17.78 °C	15.56 °C	15.56 – 10 °C	10 – 4.44 °C	< 4.44 °C

exposure vary with population groups, we considered two thresholds within the cold stress scale described in [2] (Table 2) to delimit thermal safety:

- Threshold for healthy populations, indoor air temperature equals 4.44 °C.
- Threshold for vulnerable populations (e.g., the elderly and young infants), indoor air temperature equals 10 °C.

- **Water-pipe-danger hours (in hours):** Defined as the number of continuous hours with indoor air temperature below −6.7 °C. This threshold was established by Gordon [43] as the temperature alert threshold for freezing water pipes.

Under the long-term scenario, we focused on evaluating how window technologies can impact the energy burden on occupants throughout the year, particularly looking at the interplay between energy consumption for heating and cooling. Thus, selected metrics are:

- **Energy Use Intensity for cooling (EUI_c) (in kWh/m^2):** Electricity consumption to cool the building throughout the year divided by the conditioned floor area.
- **Energy Use Intensity for heating (EUI_h) (in kWh/m^2):** Natural gas consumption to heat the building throughout the year divided by the conditioned floor area.

2.4. Building performance model

We used a representative single-family residential building based on the U.S. Department of Energy (DOE) residential prototype models [44] (see Fig. 5) complying to the International Energy Conservation Code (IECC) [45] under two climate zones (5A and 6A) and three vintages: 1975, 2009, and 2021. This is a two-story south-facing detached home with 220 m^2 of conditioned area (110 m^2 per floor). The house was modeled as a single thermal zone, while the attic was represented as a separate unconditioned thermal zone. This prototype model was originally developed for the DOE's Building Energy Codes Program (BECP), and is extensively used to simulate energy savings from changes to building energy codes and standards [44]. By adopting this well-established prototype, we are able to leverage a validated framework for assessing

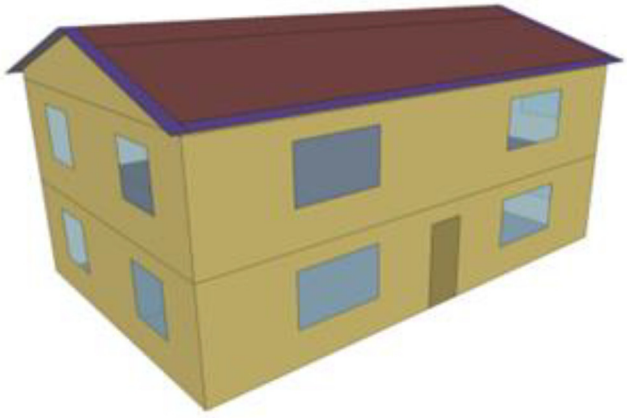


Fig. 5. Illustration of the single-family residential building model.

envelope performance across vintages and climate zones, ensuring consistency, reproducibility, and alignment with national benchmarks.

The window-to-wall ratio varies from 13.1 % (North and South orientations) to 17.5 % (East and West orientations). Table 3 describes the building envelope in each vintage, which represent the baseline conditions in this analysis. The U-factor and SHGC values in Table 3 correspond to the entire window, including the glass and window frames and dividers. Building performance modeling and simulation were performed using the physics-based software EnergyPlus, version 23.1, which is a tool widely utilized across industry and academia; and has been validated by multiple parties (e.g., [46]).

Exterior walls are composed by stucco (outermost layer), followed by sheathing, oriented strand board (OSB), insulation with different thermal resistances depending on the vintage, and drywall. The roof is composed of asphalt shingle tiles and OSB, and the ceiling consists of drywall and insulation. Thus, the overall building envelope has low thermal mass, which limits heat retention and can cause rapid indoor temperature drops during extreme cold events if a heating system is not available.

Table 3
Thermal properties of the building envelope in the baseline model, considering three building vintages.

	Vintage	U-factor [W/(m²-K)]	Solar Heat Gain Coefficient (SHGC)
Exterior walls	1975	0.526	
	2009	0.340	
	2021	0.271	
Roof and ceiling (attic floor)	1975	3.086 (roof) and 0.294 (ceiling)	
	2009	3.086 (roof) and 0.171 (ceiling)	
	2021	3.086 (roof) and 0.132 (ceiling)	
Windows	1975	4.770	0.435
	2009	1.988	0.334
	2021	1.704	0.334

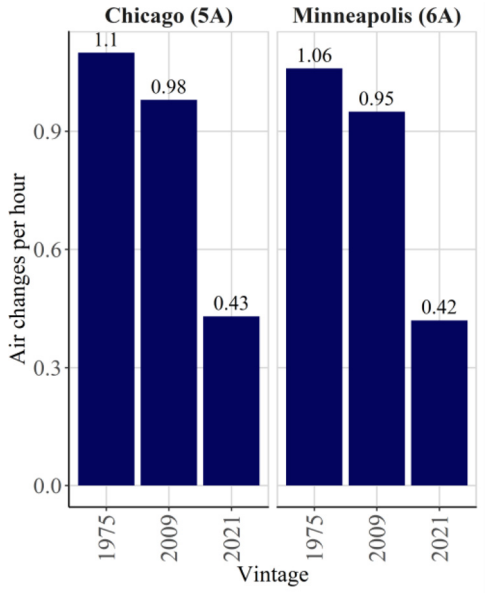


Fig. 6. Average air infiltration across buildings vintages and climate zones.

Besides thermal properties, the vintage of houses influences air infiltration. This is associated with improvements in building standards, codes, and materials to reduce air leakage through joists, cracks and gaps in the building envelope. Fig. 6 illustrates average air infiltration during occupied hours in buildings in different vintages and climate zones. Additionally, we explored what would be the impact to the building thermal performance if reduced air infiltration by 30 %, compared to the baseline condition in each vintage. This is particularly relevant in the context of extreme cold conditions to help buildings retain heat more effectively, preventing cold air from entering and warm air from escaping. Such reduction of air infiltration could be achieved through a combination of strategies focused on sealing and insulating the building envelope, like applying weatherstripping and caulking around windows and doors to close gaps and cracks.

By combining two climates, two types of cold snaps (more extreme and milder), three building vintages, and two air infiltration levels, we aim to capture some of the main uncertainties in building performance and broadly illustrate the impact of high-performance windows in multiple conditions.

Buildings are assumed to be fully air-conditioned (heating and cooling) throughout the entire year, except during power outages, as described in Section 2.2. Heating is provided by a natural gas furnace, with a set point of 22.2 °C. The set point for cooling is 23.9 °C. The HVAC system was sized based on the building in its baseline condition (Table 3) in each climate. That is, buildings equipped with high-performance windows have the same HVAC system as their correspondent baselines to isolate the effect of windows and allow comparability of results.

To accurately assess thermal comfort and mimic occupant behavior during winter, adjustments were made to both the clothing insulation and work efficiency parameters throughout the simulation period. The clothing insulation was set to 0.87 clo to represent occupants wearing slightly thicker clothing at home, as tested and reported in [47]. The work efficiency parameter was set to 0 to indicate that energy produced by the human body is all transformed into heat instead of mechanical energy, which represents that no critical activities are performed during extreme cold weather.

2.5. Selection of window technologies

High-performance windows—which are one of the emerging solutions to reduce energy consumption and meanwhile improve safety, soundproofing, and comfort in buildings—were recently found to improve building resilience during extreme cold events [48]. In this study, we selected two high-performance window technologies that are primarily focused on improving the thermal insulation of the building: (1) standard triple-pane window and (2) R-10 window. The triple-pane window consists of three layers of glass panes with spacers filled with gas, providing superior insulation and reducing heat transfer (i.e., reducing U-factor) [49]. An R-10 window refers to windows with an insulation rating of R-10 (i.e., with an R-value equal to 10 $ft^2 \cdot °F \cdot h/BTU$ [1.76 $m^2 \cdot K/W$]). To achieve an R-10 window, innovative materials [50], innovative design [51], or an effective combination of manufacturing technologies [52] are often necessary, as single-pane windows and double-pane windows typically have R-values between 1 and 3 $ft^2 \cdot °F \cdot h/BTU$ [49]. National Fenestration Rating Council (NFRC)-certified full-frame R-10 windows are commercially available since about 2016 [53]. For comparison, a list of the ENERGY STAR Most Efficient 2025 windows is available in [54], with R ratings varying from 5 to 9 $ft^2 \cdot °F \cdot h/BTU$.

This study investigates window technologies that are already available in the U.S. market but still have limited adoption, particularly in existing residential buildings. While triple-pane windows are recognized in energy regulations and used in new or refurbished buildings, they are far from being the market standard in most of the existing building stock [55]. Our goal was to highlight additional benefits—beyond energy savings—such as improved thermal resilience, which could help justify the higher initial costs and encourage broader adoption. We chose not to focus on emerging technologies like smart glazing, as these solutions, while promising, are not yet mature enough for widespread deployment and practical application at scale.

Table 4 compares the thermal transmittance (U-factor) and SHGC of each window technology, each of them based on NFRC ratings of typical real products available on the U.S. market that meet Energy Star “Most Efficient” criteria for “Residential Windows and Sliding Glass Doors”

Table 4
Thermal properties of window technologies.

Window technology	Vintage	U-factor [W/(m^2-K)]	Solar Heat Gain Coefficient (SHGC)
Baseline windows	1975	4.770	0.435
	2009	1.988	0.334
	2021	1.704	0.334
Standard triple-pane		1.136	0.280
Standard triple-pane with high SHGC		1.192	0.450
R-10		0.568	0.280
R-10 with high SHGC		0.568	0.450

[56]. The U-factor and SHGC values in Table 4 also correspond to the entire window, considering glass panes, window frames and dividers. Also included in Table 4 are the properties of windows in the baseline conditions. The performances of baseline windows come from the original prototype models. Both triple-pane and R-10 windows were explored in two alternatives, with low Solar Heat Gain Coefficient (SHGC), and with high SHGC, resulting in four high-performance window alternatives investigated. The choice of U-factor and SHGC (both low and high) of the high-performance windows are based on the typical product performance, with the Energy Star Most Efficient criteria as a basis [56]. In total, we analyzed five window technologies, including the baselines.

The SHGC reflects the amount of solar radiation transferred through the fenestration. Windows with low SHGC are especially beneficial during summer time, or in hot climates, to block solar heat more effectively, reducing cooling loads. Windows with high SGHC allow more solar heat indoors, which benefits cold climates by reducing heating demand.

3. Results

There are myriad uncertainties during building design and retrofitting aided by performance simulations. Occupants move (particularly renters), the climate varies, the power supply is interrupted by extreme events, and even infiltration levels are influenced by building operation and maintenance. Fig. 7 captures the range of building performance outcomes for different combinations of window technologies across three building vintages, using two complementary metrics: hours of safety during power outages (left y-axis) and annual site energy use intensity for HVAC (right y-axis).

The boxplots represent a distribution of HOS values, which results from simulating each scenario under varying conditions. Specifically, each box reflects the range of HOS across:

- Two power outage durations (3-day and 7-day);
- Two infiltration conditions (baseline and 30 % reduced);
- Two occupant vulnerability levels (healthy and vulnerable).

Thus, each boxplot aggregates eight different simulation cases per window technology and building vintage. This approach highlights both the central tendency and variability in thermal resilience due to uncertainties in occupant condition and building operation.

High-performance windows consistently improve thermal resilience during extreme cold events, irrespective of said uncertainties, by increasing the hours of safety. The lengths of such improvements are detailed in Section 3.1. Overall, the best results are obtained through the installation of R-10 windows with high SHGC, particularly in a very cold climate like the one in Minneapolis with a 2021 building vintage. This technology nonetheless penalizes cooling consumption while significantly reducing heating loads, which is described in greater detail in Section 3.2. The energy consumption shown in Fig. 7 only considers baseline infiltration.

To improve the visualization of Fig. 7, the scale in the primary y axis shows results up to 125 hours of safety, hiding a few data points that exceeded this margin. These hidden results show that healthy populations might be able to shelter in a 2021 vintage home in Chicago throughout a 7-day power outage during a less intense cold event, irrespective of the window technology installed.

3.1. Thermal resilience during extreme cold events

Prior to exploring the performances of high-performance windows, Fig. 8 illustrates the potential of the building envelope in three vintages to contain the degradation of indoor thermal conditions during an extremely cold event in Chicago concomitant with a 3-day power outage. Results evidence the dangers of such events, particularly for houses in older vintages, which would require the timely evacuation of their residents in as little as 1.2 hours. Within just over a day, indoor temperatures can drop as low as −15 °C. Improvements in the building envelope in newer vintages (i.e., 2021) increase the hours of safety by a scale of six for vulnerable populations. Still, this is not safe enough to allow them to shelter-in-place, but rather to increase evacuation time. Healthy populations might be able to take shelter at a newer home for longer, but evacuation would still be necessary within 18.2 hours after power goes off at midnight of the first day of the event. The vertical blue dotted lines in Fig. 8 illustrate when indoor temperatures cross the 4.4 °C threshold for healthy populations, marking the end of the safe period and consequently determining the hours of safety for each building vintage.

Fig. 9 and Fig. 10 show the impact of high-performance windows when installed in 1975 and 2021 vintages, respectively. Again, when facing the most extreme cold events, the impact of improving windows is directly linked to saving lives by gaining within 1 hour to nearly 9 hours for a proper evacuation of vulnerable occupants. Considering less intense cold events with a longer power outage period of 7 days, a standard triple-pane window can increase the evacuation time of vulnerable occupants in 1975 houses in Chicago by 10.5 hours.

Overall, reducing the thermal transmittance of windows in cold climates is the most effective strategy, which is highlighted by the performance of R-10 window technologies in this study. Nonetheless, the combination of low U-factor with higher SHGC values is also beneficial and is particularly evidenced during the 3-day outage in Chicago for vulnerable populations in the 2021 vintage (see Fig. 11). In this particular case, the more insulated envelope slowed the rate of indoor temperature decline, keeping it nearly stable above the 10 °C threshold for a few hours during peak solar heat gains through the high-SHGC window. We do not observe this significant improvement in HOS for the same window for healthy populations because, by the time the temperature reaches their threshold (4.4 °C), the sun has already set, and the extra accumulated heat is lost. Leakier and less insulated buildings in older vintages (i.e., 1975 and 2009) became uninhabitable for vulnerable populations on the first night, regardless of window technology, and were unable to benefit from the high SHGC window technologies. Thus, there's an important role of timing in the analysis, particularly the start time of the power outage (i.e., midnight).

Across Fig. 12 through 14, the dots over each bar represent the hours of safety if air infiltration is reduced by 30 %. Such a strategy could increase the hours of safety even further by up to 24 hours (5.5 hours on average, 68.8 hours as an outlier) across all climates, window tech-

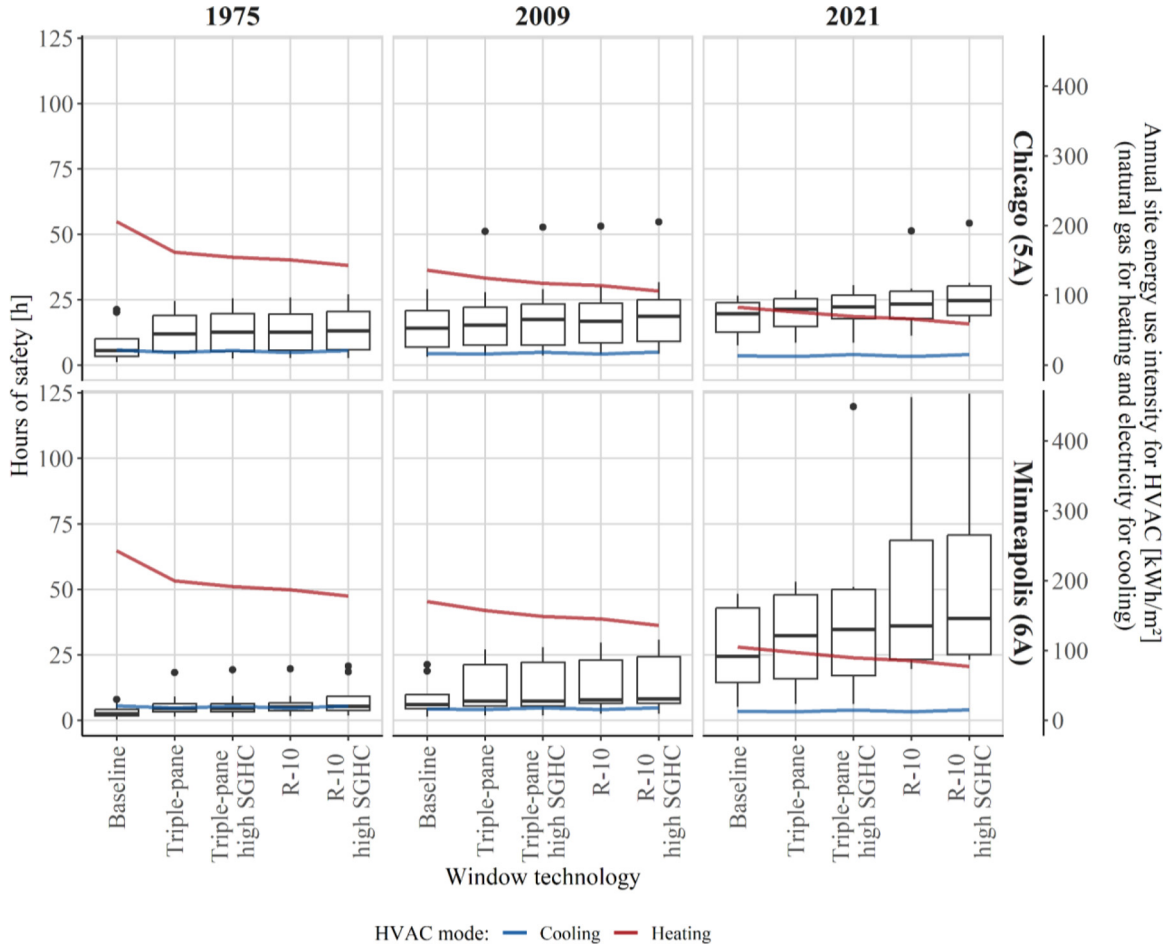


Fig. 7. Summary of results for hours of safety and energy use across climates, building vintages, and window technologies.

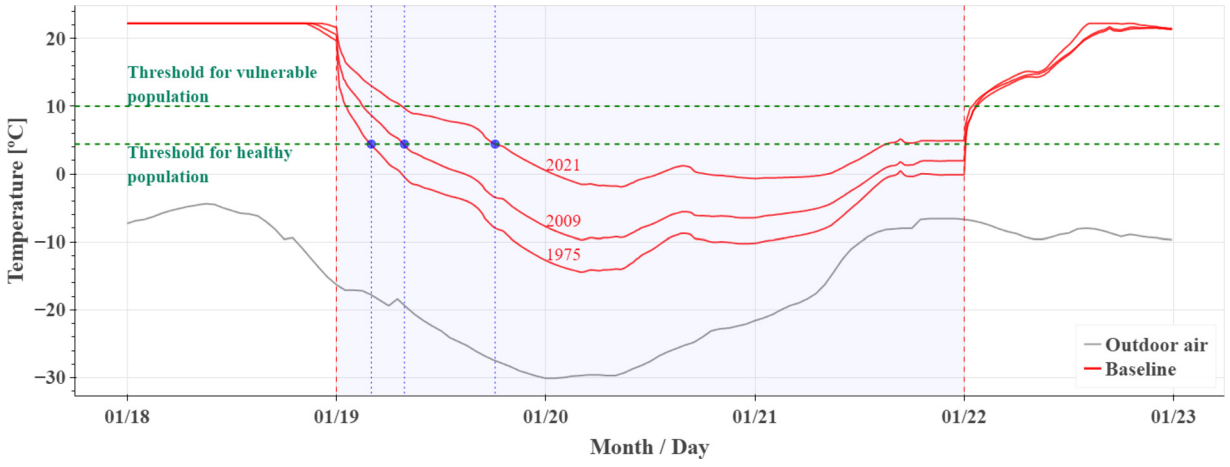


Fig. 8. Indoor temperature decline during an extreme cold event in Chicago, coupled with a 3-day power outage, in buildings of three different vintages.

nologies, power outage duration, occupant type, and building vintage (Fig. 13).

When considering even colder climate zones, like the one in Minneapolis, high-performance windows help extend the time for evacuation, especially when installed in already well-insulated and air-tight envelopes (i.e., 2021 vintage). The R-10 windows with high SHGC increase the hours of safety during extreme cold events by 18 hours (see Fig. 14).

For shorter and colder events (i.e., the 3-day power outage scenario), high-performance windows can reduce the water-pipe-danger hours by 10 % to 70 %, as shown in Fig. 15. During longer and milder events (i.e., the 7-day power outage scenario), R-10 windows with high SHGC can reduce the number of hours below −6.7 °C from 23 hours to less than an hour in 1975 vintages in Minneapolis, nearly eliminating the risk of bursting pipes. Note that vintages and outage events not included in Fig. 15 had no hours lower than −6.7 °C, which includes all cases in the

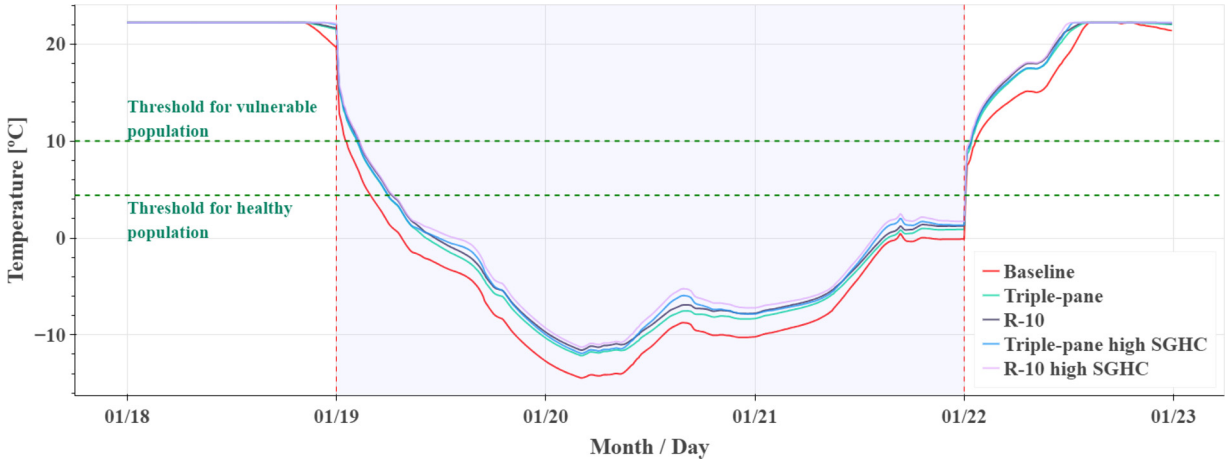


Fig. 9. Indoor temperature decline during an extreme cold event in Chicago, coupled with a 3-day power outage, in a building constructed in 1975 and equipped with various window technologies.



Fig. 10. Indoor temperature decline during an extreme cold event in Chicago, coupled with a 3-day power outage, in a building constructed in 2021 and equipped with various window technologies.

2021 vintage, all cases under the 7-day power outage in Chicago, and all cases in the 2009 vintage in Minneapolis under a 7-day power outage event.

Comparing the results for the 1975 and the newer vintages (2009 and 2021) during the 7-day power outage scenario in Minneapolis, we can observe the significant impact of improving windows performance. The reduction in risk of bursting pipes by upgrading the entire envelope could be comparable to the effect obtained by simply improving the windows alone (e.g., installing R-10 windows with high SHGC).

3.2. Annual energy performance

By comparing heating and cooling loads in buildings, we can observe the possible compromises when choosing between window technologies. From the heating perspective, adding insulation helps reduce heat losses through the building envelope, especially through transparent surfaces such as windows. A complementary strategy to reduce heating loads is combining low thermal transmittances with high SHGC values, which allows not only to keep the heat inside, but also to allow more through the windows. This is clearly observed in Fig. 16, as lower transmittances and higher SHGCs progressively reduce natural gas consumption for heating up to 31 % in the older vintage.

Fig. 17 shows annual electricity consumption for cooling, which can be reduced by up to 15 % in older vintages by reducing thermal transmittance in windows. Such effect is minimized in newer vintages with more insulated and air tight envelopes. Comparing the performances of baseline and triple-pane windows in Chicago as an example, we can observe that SHGC values have a higher impact on cooling consumption than thermal transmittance. By reducing the SHGC by 42 % and transmittance by 77 % in standard triple-pane windows, compared to the baseline, cooling consumption was reduced by 15 % in the 1975 vintage. However, if we were to keep SGHC values at similar levels than those of the baseline (between 0.44 and 0.45) in triple-pane windows with high SHGC, cooling consumption would be reduced by only 3 % even with more insulated windows. This is also evidenced by observing that higher SHGC values actually make buildings consume between 11 % and 15 % more energy for cooling in 2009 and 2021 vintages in spite of reducing thermal transmittance.

3.3. Potential overheating risk during typical summer days

From the cooling perspective, lower thermal transmittances can have two major impacts. If buildings are fully air-conditioned with sufficient HVAC capacity, insulation reduces heat gains through the enve-

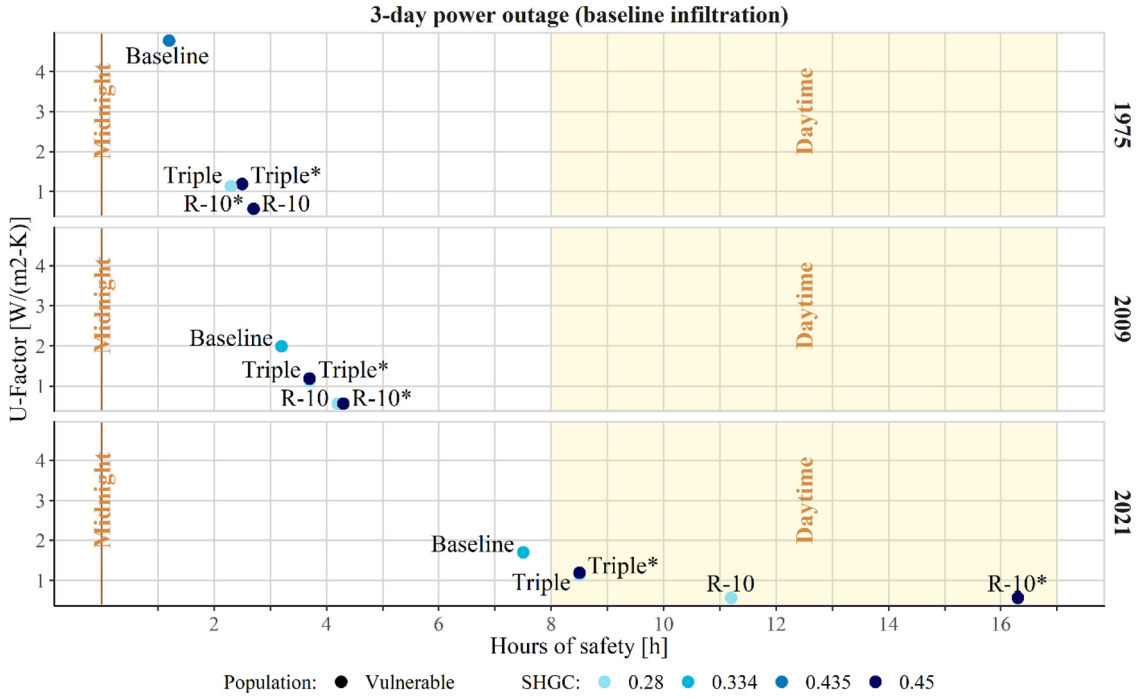


Fig. 11. Performance of window technologies compared to their thermal properties in Chicago during the 3-day power outage event with baseline infiltration (* indicates windows with high SHGC).

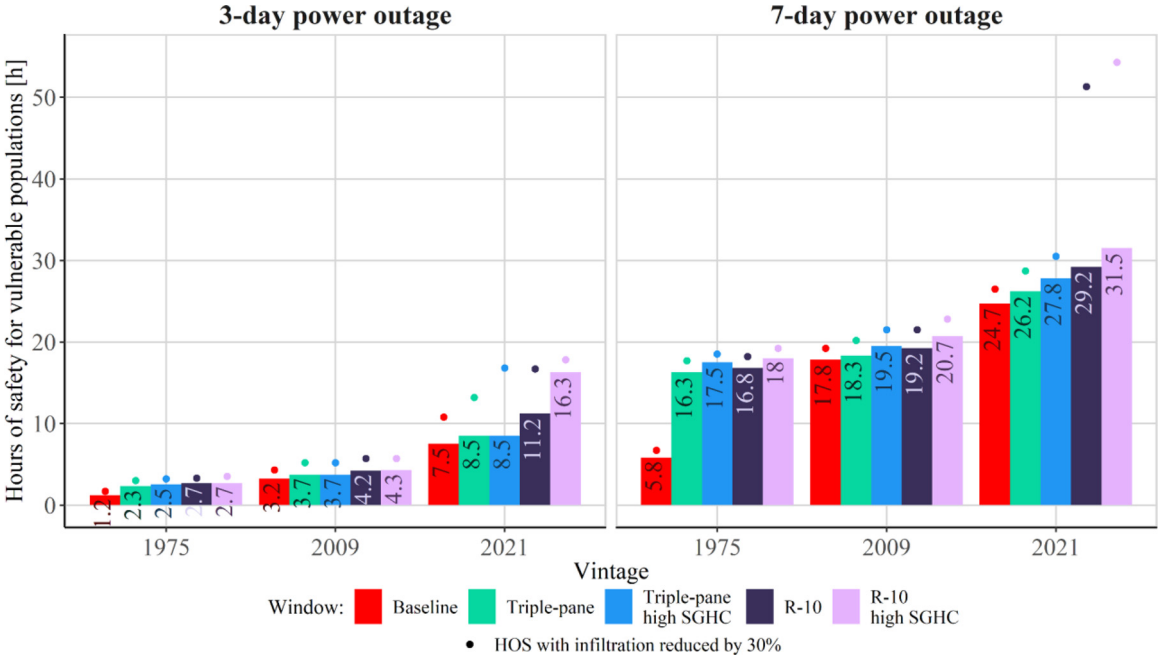


Fig. 12. Comparison of window technologies in 3- and 7-day power outage events in Chicago for vulnerable populations.

lope, thus leading to lower cooling loads. On the other hand, in naturally ventilated and hybrid buildings, buildings with insufficient HVAC capacity, or during power outages, insulation can cause overheating by trapping heat inside. We briefly explored this scenario by considering the possibility of a power outage during a typical hot summer day.

Fig. 18 shows the hourly outdoor heat index during a typical summer week containing the highest annual temperatures from the TMY3 weather data. The heat index represents what temperature feels to people by combining relative humidity with air temperature [57]. Each colored region of the graph represents levels of potential impacts of heat on occupant's health: safe conditions (up to 26.7 °C of heat index), caution (26.7–32.2 °C), extreme caution (32.2–39.4 °C), danger (39.4–51.1 °C, and extreme danger (higher than 51.6 °C, not included in the graph) [57]. Three extreme heat days within this week were selected to evaluate the overheating risk during typical summers.

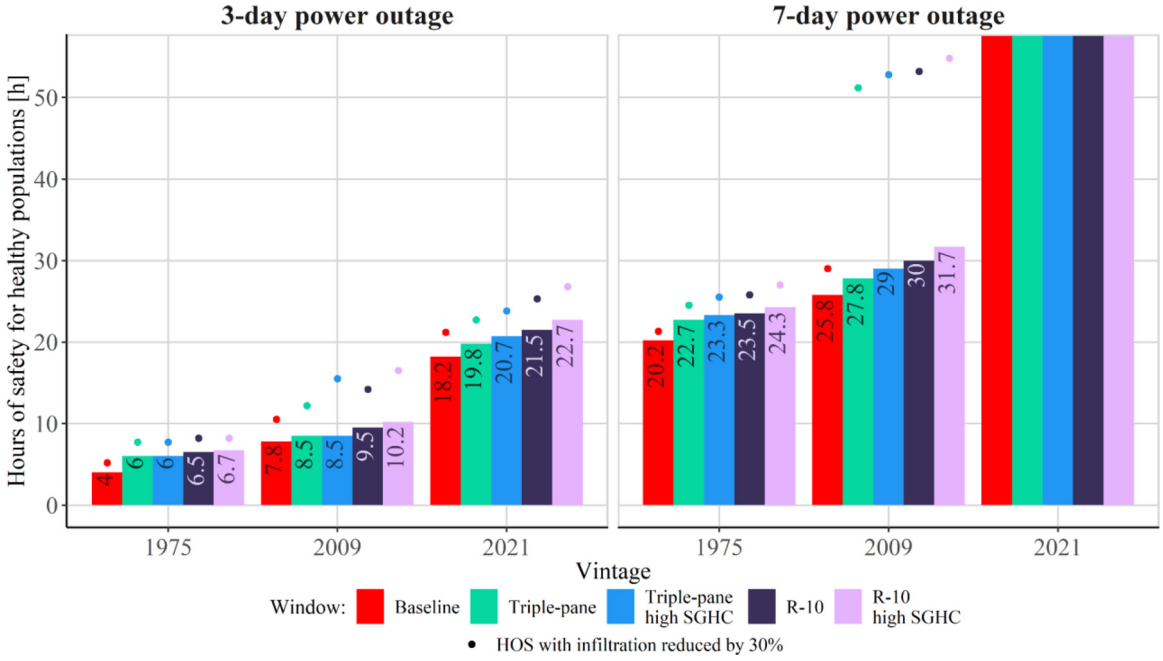


Fig. 13. Comparison of window technologies in 3- and 7-day power outage events in Chicago for healthy populations (note: the 2021 vintage remained safe throughout the entire 7-day power outage event irrespective of the window type).

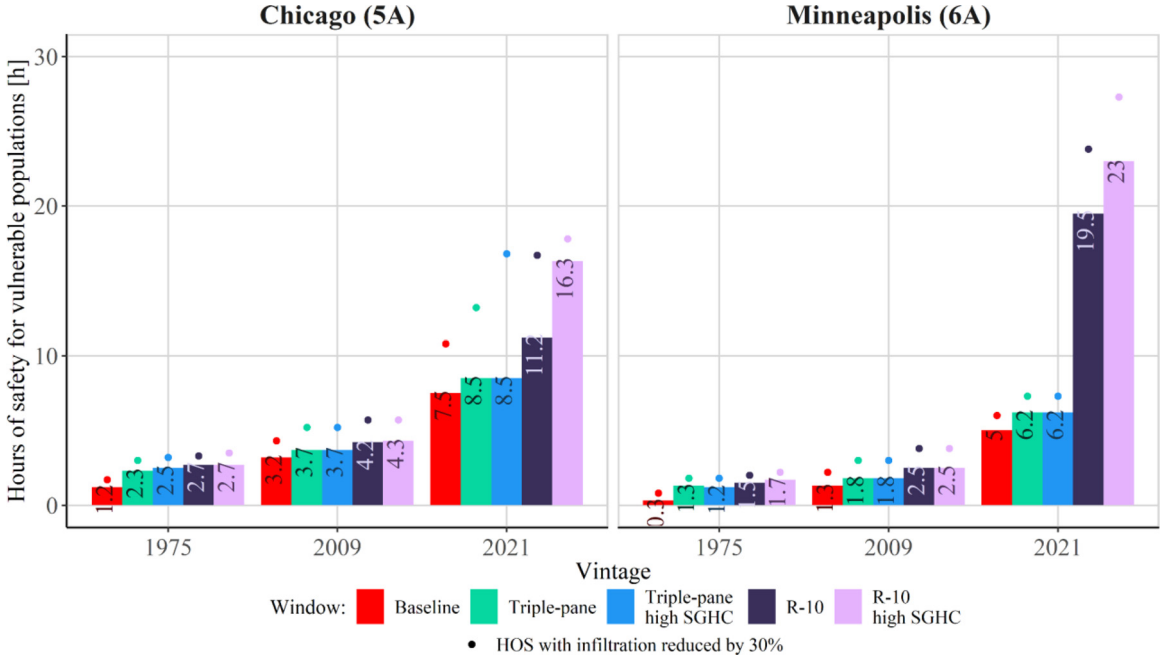


Fig. 14. Comparison of window technologies in 3-day power outage events in Chicago and Minneapolis for vulnerable populations.

Fig. 19 shows the hourly heat index inside buildings in each vintage in Chicago, comparing the performance of all window technologies during a 3-day power outage. Solid lines represent building performance if windows were kept closed during the event. Dashed lines represent building performance if windows were openable to enhance natural ventilation when the indoor temperature is 2 °C higher than the outdoor temperature. Results highlight the potential risks of higher insulation during very hot days if occupants have no adaptive alternatives. However, by only allowing them to open the windows, indoor overheating is significantly mitigated, with the heat index mostly under cautious conditions (26.7 to 39.4 °C) throughout the event, instead of dangerous conditions (over 39.4 °C). In such circumstances, improving natural ventilation is even more important in newer buildings with air-tight and highly insulated envelopes that would not allow heat to be released if mechanical systems are unavailable. This observation aligns with the findings of Baba et al. [58], who concluded that the risk of overheating in new energy-efficient buildings in Canada depends on providing adequate ventilation rates.

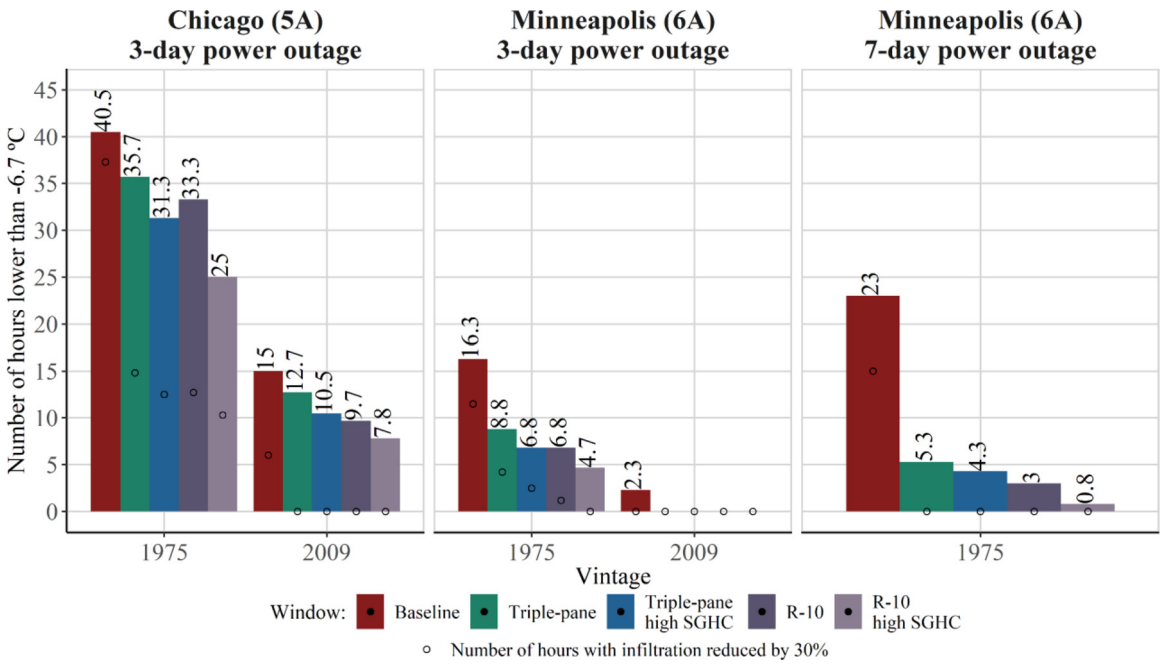


Fig. 15. Water-pipe-danger hours during 3-day and 7-day outage events in Chicago and Minneapolis (note: excluding vintages and outage events with zero hours lower than −6.7 °C).

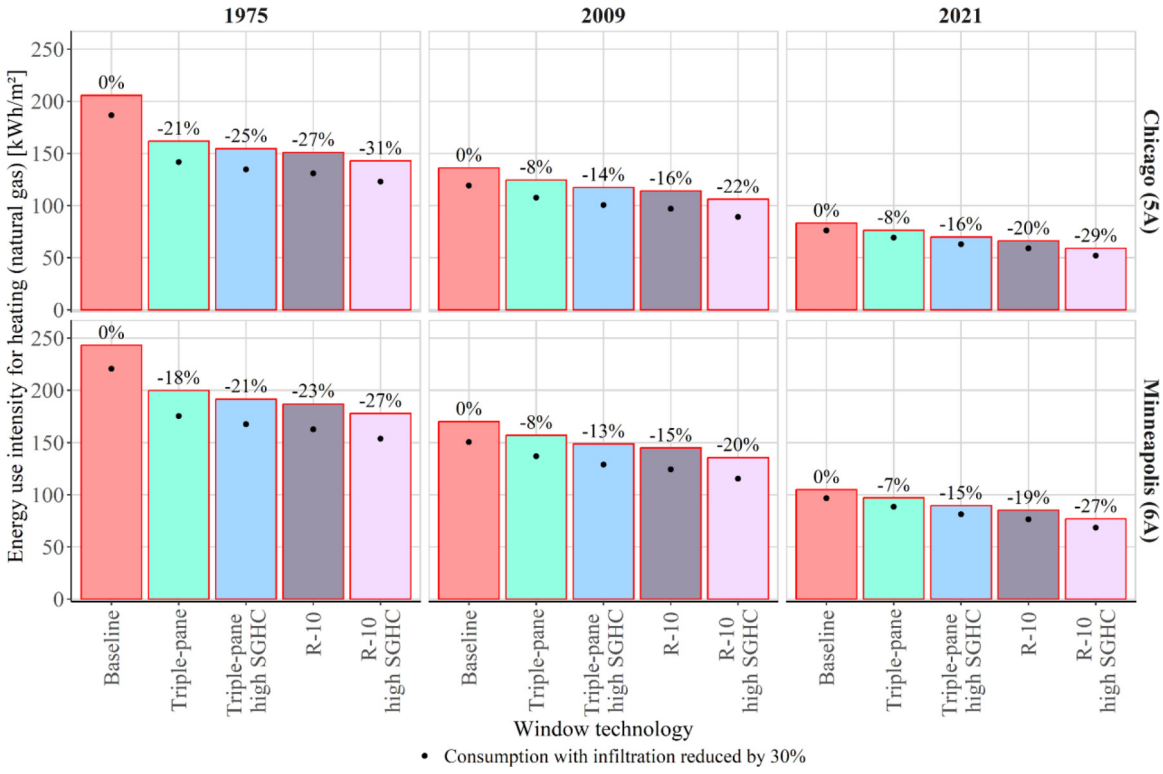


Fig. 16. Annual natural gas consumption for heating in Chicago and Minneapolis.

Additional adaptation measures could be adopted to mitigate the overheating risk, especially dynamic solutions that allow adjusting to climates with wide temperature variations between seasons—i.e., experiencing very hot summers and very cold winters. A few examples are thermochromic windows [59], smart solar shading [60], and operable windows [58]. However, studies addressing overheating in buildings through multiple strategies are abundant in literature due to worsening impacts of changing climate patterns (a few examples are [17,61,62]). Thus, we focused on addressing underheating challenges while ensuring that selected strategies would not compromise the building's overall performance throughout the year.

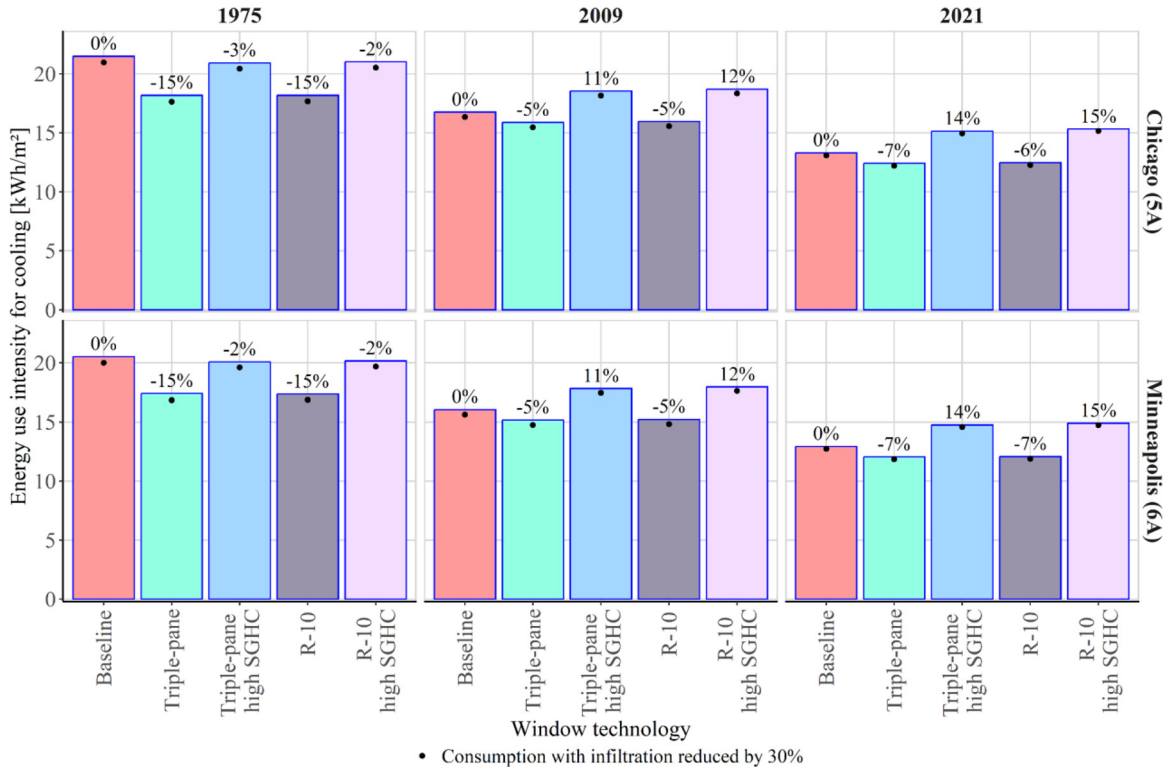


Fig. 17. Annual electricity consumption for cooling in Chicago and Minneapolis.

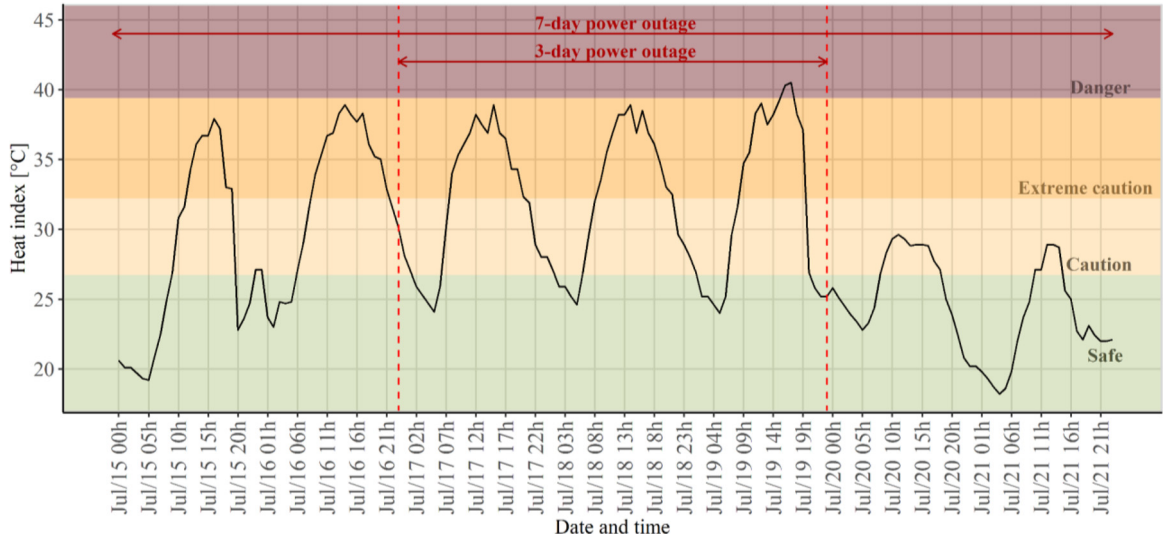


Fig. 18. Hourly outdoor heat index of a hot summer week in Chicago.

4. Discussion

4.1. Major findings and policy implications

Results from the resilience analysis flag the extreme vulnerability of homes to very cold events when power supply is lost. In the current (baseline) building stock conditions, major coordination might be necessary at the city or county levels to inform and coordinate evacuations within a timeframe as short as 18 min (e.g., for vulnerable residents in a 1975 vintage in Minneapolis) and no longer than two days (e.g., for healthy residents in a 2021 air-tight vintage in Minneapolis). High-performance windows do not solve the problem alone, but help double life-saving time, which can be vital in such extreme scenarios that typically compound with logistical and transportation issues. Icy, snowy, or blocked roads can impede evacuation efforts, making it difficult for emergency vehicles to reach affected areas and for residents to leave safely. Also, elderly individuals and those with disabilities may have limited mobility, making evacuation complicated and slow.

Upgrading windows in 1975 vintage homes with high-performance windows could save over 18 % of energy for space heating and 15 % for cooling, while increasing thermal resilience during extreme cold weather events. However, upfront costs are substantial and not quickly recovered through energy bill savings. Important considerations in a cost-benefit analysis are the window frame compatibility, potential wall modifications and reinforcements, and permitting. There are retrofit options that could provide comparable benefits as window replacements

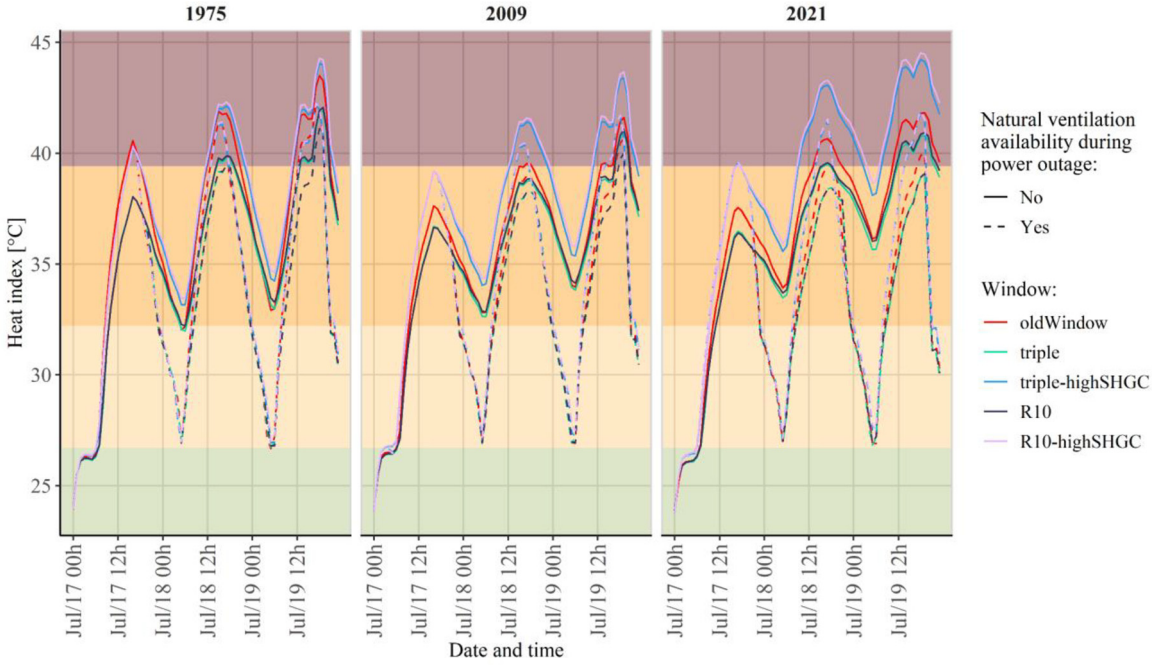


Fig. 19. Hourly indoor heat index during typical hot summer days concomitant with 3-day power outage in Chicago.

[19] that could be further explored in future analyses, such as insulating shades, and exterior storm windows.

High-performance windows should be considered in the design process of new buildings in combination with other strategies to improve energy performance and resilience even further. In fact, the alarming results reported herein highlight the need to include thermal resilience as a requirement in codes and standards, which should describe appropriate testing conditions such as extreme event datasets and assessment metrics (e.g., the hours of safety). It is necessary to define emergency procedures and strategies at the building level to reduce risks from increasingly frequent and severe weather. One option is selecting a room inside the home with optimized features (e.g., high-performance windows) to shelter occupants in place during cold snaps or heat waves. Low-cost backup power and storage could be designed to address reduced loads in this room to preserve occupant's health.

The impacts of cold events are often clearly defined and visible to the population and to decision makers, like disrupting infrastructure by causing pipes to freeze and burst, damaging roads and bridges, and obstructing public transportation. The impacts of extreme hot weather, on the other hand, are less evident. Nonetheless, with extreme heat events projected to increase globally, any new design prescriptions need to take the indoor overheating risk into account, ideally considering historical and future weather scenarios.

In this study, we found that heating-centered solutions, like windows with high SHGC, can hinder performance during summer and, now or in the future, can compromise vulnerable occupant's health if adaptive strategies are not available. Simple strategies can significantly reduce the overheating risk, like leveraging natural ventilation. Other low-cost solutions should be considered, such as ceiling fans and retractable exterior shading.

4.2. Future climate perspectives

As global temperature rises, many assume that severe winter weather will occur less often, potentially fostering a false sense of security and diminished readiness for extreme cold events. Such lack of preparedness can make populations more vulnerable when extreme cold events do occur, leading to greater disruptions and potentially higher costs [63].

A study estimated that the Arctic has been warming almost four times faster than the rest of the world—a phenomenon known as Arctic amplification [64]. This amplification is believed to lead to the "warm Arctic - cold continents" pattern [65], which paradoxically results in extreme cold events, such as cold air outbreaks and heavy snowfalls, particularly in mid-latitude locations [66]. Specifically, a part of the atmosphere called the polar vortex—which usually keeps cold Arctic air trapped near the pole—is being stretched out of shape. This happens because warming in the Arctic and changes like less sea ice disrupt the usual atmospheric dynamics. These disruptions send cold Arctic air farther south, leading to harsher and more widespread cold snaps [63,67].

Researchers are still working to fully understand the complex phenomena that could cause extreme cold events in a future warmer world. Comprehending the links between the polar vortex, sea ice loss, and mid-latitude weather patterns offers promising avenues for enhancing weather forecasting capabilities, especially for predicting extreme cold events [68]. In this context, analyzing buildings exposed to extreme cold events is equally critical in a warming climate, as it ensures resilience and efficiency amid shifting and increasingly unpredictable weather patterns.

4.3. Limitations of the study

This work is limited by the climates and scenarios analyzed, and could be expanded to cover a wider range of cold climates across the country. Quantification of the hours of safety is intrinsically linked to the time defined for the power outage to start in the building model, thus influencing the perceived performance. Starting time was defined at midnight, when temperatures are already low, thus not benefitting the building performance in significant ways by, e.g., gaining solar heat during daylight hours.

This study used historical weather data to curate the cold snap events. However, future extreme cold snaps can be very different in duration and intensity, so there is a need to consider future climate data in the cold resilience assessment. The results are based on simulation and have not been validated against measured data, which is a necessary future work. To assess cold vulnerability of residents in specific houses, local cold snaps, surrounding environment conditions, and occupant behaviors should be considered in the modeling and analysis.

We used a two-story residential prototype developed by the USDOE for its Building Energy Codes Program, designed to represent a typical single-family detached home. This approach ensures consistency, repro-

ducibility, and comparability with previous studies but does not capture the full diversity of housing types that may be more relevant to certain demographics. For instance, single-story homes typically have a higher envelope-to-floor area ratio, which can influence thermal performance. By using a standardized prototype rather than real building models, we enabled systematic comparisons across different vintages and climates. Such an approach would have been difficult in real buildings given their variability and lack of standardization. However, relying on prototype models limits the ability to directly validate results through field measurements. Given that these models are extensively used to assess energy savings across code cycles and have been rigorously tested for consistency, we considered this trade-off acceptable to support comparability and scenario-based analysis.

Additionally, this study did not cover the economic analysis considering the initial installation costs of the high-performance windows and monetizing the co-benefits of energy costs savings, improvements of human health, and avoided costs of property damages.

4.4. Future work

Future work can expand the modeling and analysis to houses in other cold climates (e.g., Climate zones 7 and 8) and to consider the variations of house characteristics (e.g., orientation, shading, window-wall-ratio) and occupant behavior (e.g., open and close windows, operate interior shades). Design and conducting an actual experiment to test a real house without power under extreme cold conditions to collect real world data for validating the simulation results is also an important future work to consider. High-performance window technologies such as thermochromic windows that enable automatic modulating of solar heat gains into indoor spaces (allowing more solar gains in winter while blocking it in summer) can be modeled and evaluated. As cold snaps can change in future, there is also a need to refresh the study using future climate and extreme weather data.

5. Conclusions

Although global overheating risk dominates current research efforts, local and regional cold vulnerability should not be underestimated. We examined the role of high-performance windows in enhancing the thermal resilience of buildings during extreme cold events—currently a leading cause of temperature-related deaths and a threat likely to become even deadlier in a future characterized by more extreme and variable climate conditions. We verified that the building stock is highly vulnerable in such a scenario—especially older leakier buildings with less insulation—if coupled with an overloaded and unstable power grid, leading to service interruption. Even buildings compliant with minimum requirements of the latest building energy codes are not able to sustain safe indoor thermal conditions over a few hours for residents, requiring a quick evacuation as temperature drops to freezing point within a day. The contribution of high-performance windows is to increase the duration of safe indoor thermal conditions so evacuation time can be extended from 30 min to 91 hours (i.e., nearly 4 days), depending on the intensity of the extreme event, building vintage, window technology, and occupant type (healthy or vulnerable). Thus, its effect is directly reflected in life-saving time, which is fundamental when snow and storms may slow or even prevent transportation and assistance.

Our findings show that upgrading the windows in older homes with high-performance windows can substantially reduce energy consumption for heating and cooling, offering both resilience benefits and long-term energy savings. Additionally, high-performance windows can reduce the risk of bursting frozen water pipes during winter, which is one of the most frequent causes of property damage in the United States. However, the initial costs and potential complications of window retrofitting should be carefully weighed against these benefits.

The findings from this study have important practical implications:

1. Incorporation of a standardized thermal resilience assessment into codes and regulations is urgently needed to allow identification of vulnerabilities and identify mitigation measures in building design and retrofitting.
2. Appropriate weather scenarios (e.g., datasets and/or methods for future extreme weather data curation) should be defined to comprehensively test resiliency, which could complement the current practice of using winter and summer design days, for example.
3. Advanced technologies, materials, and design practices are necessary to prepare buildings to respond to future extreme weather, and should be recommended or mandated by new building codes and standards. High-performance windows should be included in these recommendations, while government and utility incentives could help make them more affordable as they consolidate in the construction industry. Another relevant recommendation is to incentivize operable window products that freely allow occupant operation during hot days to leverage natural ventilation for passive cooling.
4. Vulnerability mapping, considering metrics such as the hours of safety, should be developed to speed up targeted assistance during extreme cold events, and budget allocation to prepare for evacuation efforts.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

Declaration of competing interest

All co-authors declare there is no conflict of interest in the reported work.

CRediT authorship contribution statement

Amanda F. Krelling: Writing – original draft, Visualization, Methodology, Formal analysis. **Yilin Jiang:** Writing – original draft, Methodology, Formal analysis, Data curation. **Kaiyu Sun:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Marc LaFrance:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Tianzhen Hong:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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Appendix A

Table A.1

Summary of all results for Chicago (climate zone 5A) across building vintages, window technologies, infiltration level, and number of power outage days.

Vintage	Window	Infiltration reduction [%]	Power outage days [#]	HOS (healthy) [h]	HOS (vulnerable) [h]	Water-pipe-danger hours [h]	EUI_c (electricity) [kWh/m^2]	EUI_h (natural gas) [kWh/m^2]
1975	Baseline	0	7	20.2	5.8	0	21.5	205.7
1975	Baseline	0	3	4	1.2	40.5	21.5	205.7
1975	Baseline	30	7	21.3	6.7	0	21	186.5
1975	Baseline	30	3	5.2	1.7	37.3	21	186.5
1975	R-10	0	7	23.5	16.8	0	18.2	151
1975	R-10	0	3	6.5	2.7	33.3	18.2	151
1975	R-10	30	3	8.2	3.3	12.7	17.7	131
1975	R-10	30	7	25.8	18.2	0	17.7	131
1975	R-10 high SHGC	0	7	24.3	18	0	21	142.9
1975	R-10 high SHGC	0	3	6.7	2.7	25	21	142.9
1975	R-10 high SHGC	30	7	27	19.2	0	20.5	123.1
1975	R-10 high SHGC	30	3	8.2	3.5	10.3	20.5	123.1
1975	Triple-pane	0	3	6	2.3	35.7	18.2	161.8
1975	Triple-pane	0	7	22.7	16.3	0	18.2	161.8
1975	Triple-pane	30	3	7.7	3	14.8	17.6	141.8
1975	Triple-pane	30	7	24.5	17.7	0	17.6	141.8
1975	Triple-pane high SHGC	0	3	6	2.5	31.3	20.9	154.7
1975	Triple-pane high SHGC	0	7	23.3	17.5	0	20.9	154.7
1975	Triple-pane high SHGC	30	3	7.7	3.2	12.5	20.4	134.7
1975	Triple-pane high SHGC	30	7	25.5	18.5	0	20.4	134.7
2009	Baseline	0	7	25.8	17.8	0	16.8	136.1
2009	Baseline	0	3	7.8	3.2	15	16.8	136.1
2009	Baseline	30	7	29	19.2	0	16.3	119.3
2009	Baseline	30	3	10.5	4.3	6	16.3	119.3
2009	R-10	0	3	9.5	4.2	9.7	16	114.1
2009	R-10	0	7	30	19.2	0	16	114.1
2009	R-10	30	3	14.2	5.7	0	15.6	96.9
2009	R-10	30	7	53.2	21.5	0	15.6	96.9
2009	R-10 high SHGC	0	7	31.7	20.7	0	18.7	106
2009	R-10 high SHGC	0	3	10.2	4.3	7.8	18.7	106
2009	R-10 high SHGC	30	3	16.5	5.7	0	18.3	89.1
2009	R-10 high SHGC	30	7	54.8	22.8	0	18.3	89.1
2009	Triple-pane	0	7	27.8	18.3	0	15.9	124.6
2009	Triple-pane	0	3	8.5	3.7	12.7	15.9	124.6
2009	Triple-pane	30	3	12.2	5.2	0	15.5	107.5
2009	Triple-pane	30	7	51.2	20.2	0	15.5	107.5
2009	Triple-pane high SHGC	0	7	29	19.5	0	18.5	117.4
2009	Triple-pane high SHGC	0	3	8.5	3.7	10.5	18.5	117.4
2009	Triple-pane high SHGC	30	7	52.8	21.5	0	18.2	100.5
2009	Triple-pane high SHGC	30	3	15.5	5.2	0	18.2	100.5
2021	Baseline	0	7	1009	24.7	0	13.3	83.2
2021	Baseline	0	3	18.2	7.5	0	13.3	83.2
2021	Baseline	30	3	21.2	10.8	0	13.1	76.1
2021	Baseline	30	7	1009	26.5	0	13.1	76.1
2021	R-10	0	3	21.5	11.2	0	12.5	66.2
2021	R-10	0	7	1009	29.2	0	12.5	66.2
2021	R-10	30	7	1009	51.3	0	12.3	59.1
2021	R-10	30	3	25.3	16.7	0	12.3	59.1
2021	R-10 high SHGC	0	3	22.7	16.3	0	15.3	59.1
2021	R-10 high SHGC	0	7	1009	31.5	0	15.3	59.1
2021	R-10 high SHGC	30	7	1009	54.3	0	15.2	52.2
2021	R-10 high SHGC	30	3	26.8	17.8	0	15.2	52.2
2021	Triple-pane	0	7	1009	26.2	0	12.4	76.4
2021	Triple-pane	0	3	19.8	8.5	0	12.4	76.4
2021	Triple-pane	30	7	1009	28.7	0	12.2	69.2
2021	Triple-pane	30	3	22.7	13.2	0	12.2	69.2
2021	Triple-pane high SHGC	0	7	1009	27.8	0	15.1	69.9
2021	Triple-pane high SHGC	0	3	20.7	8.5	0	15.1	69.9
2021	Triple-pane high SHGC	30	7	1009	30.5	0	15	62.9
2021	Triple-pane high SHGC	30	3	23.8	16.8	0	15	62.9

Table A.2

Summary of all results for Minneapolis (climate zone 6A) across building vintages, window technologies, infiltration level, and number of power outage days.

Vintage	Window	Infiltration reduction [%]	Power outage days [#]	HOS (healthy) [h]	HOS (vulnerable) [h]	Water-pipe-danger hours [h]	EUI_c (electricity) [kWh/m^2]	EUI_h (natural gas) [kWh/m^2]
1975	Baseline	0	7	7.5	2	23	20.5	243.1
1975	Baseline	0	3	2.2	0.3	16.3	20.5	243.1
1975	Baseline	30	7	8	2.7	15	20	220.7
1975	Baseline	30	3	3	0.8	11.5	20	220.7
1975	R-10	0	3	4.7	1.5	6.8	17.4	187.1
1975	R-10	0	7	9.3	4.3	3	17.4	187.1
1975	R-10	30	3	5.8	2	1.2	16.9	162.8
1975	R-10	30	7	19.7	5.5	0	16.9	162.8
1975	R-10 high SHGC	0	7	18.5	4.3	0.8	20.2	178.1
1975	R-10 high SHGC	0	3	4.8	1.7	4.7	20.2	178.1
1975	R-10 high SHGC	30	3	6	2.2	0	19.7	153.9
1975	R-10 high SHGC	30	7	20.7	5.7	0	19.7	153.9
1975	Triple-pane	0	3	4.2	1.3	8.8	17.4	199.8
1975	Triple-pane	0	7	9	3.7	5.3	17.4	199.8
1975	Triple-pane	30	3	5.3	1.8	4.2	16.9	175.6
1975	Triple-pane	30	7	18.3	4.7	0	16.9	175.6
1975	Triple-pane high SHGC	0	3	4.2	1.2	6.8	20.1	191.7
1975	Triple-pane high SHGC	0	7	9.2	3.7	4.3	20.1	191.7
1975	Triple-pane high SHGC	30	3	5.3	1.8	2.5	19.6	167.7
1975	Triple-pane high SHGC	30	7	19.3	4.7	0	19.6	167.7
2009	Baseline	0	3	5.2	1.3	2.3	16.1	170.3
2009	Baseline	0	7	18.8	5.3	0	16.1	170.3
2009	Baseline	30	3	6.7	2.2	0	15.6	150.7
2009	Baseline	30	7	21.3	6.8	0	15.6	150.7
2009	R-10	0	3	7.3	2.5	0	15.2	145.1
2009	R-10	0	7	22	7.3	0	15.2	145.1
2009	R-10	30	3	29.7	3.8	0	14.8	124.5
2009	R-10	30	7	26.2	8.3	0	14.8	124.5
2009	R-10 high SHGC	0	3	7.5	2.5	0	18	135.8
2009	R-10 high SHGC	0	7	23.3	7.3	0	18	135.8
2009	R-10 high SHGC	30	7	27.3	8.7	0	17.6	115.5
2009	R-10 high SHGC	30	3	30.8	3.8	0	17.6	115.5
2009	Triple-pane	0	7	20.5	6.7	0	15.2	157.2
2009	Triple-pane	0	3	6.3	1.8	0	15.2	157.2
2009	Triple-pane	30	7	23.5	7.7	0	14.8	137.1
2009	Triple-pane	30	3	27	3	0	14.8	137.1
2009	Triple-pane high SHGC	0	3	6.3	1.8	0	17.8	148.9
2009	Triple-pane high SHGC	0	7	21.3	6.7	0	17.8	148.9
2009	Triple-pane high SHGC	30	3	28	3	0	17.5	129
2009	Triple-pane high SHGC	30	7	24.7	7.7	0	17.5	129
2021	Baseline	0	3	42.2	5	0	12.9	105
2021	Baseline	0	7	29.7	17.3	0	12.9	105
2021	Baseline	30	3	45.2	6	0	12.7	96.7
2021	Baseline	30	7	48.3	19	0	12.7	96.7
2021	R-10	0	7	120	21.3	0	12.1	85.3
2021	R-10	0	3	48	19.5	0	12.1	85.3
2021	R-10	30	7	123.3	24	0	11.9	76.6
2021	R-10	30	3	51.7	23.8	0	11.9	76.6
2021	R-10 high SHGC	0	3	50.5	23	0	14.9	77
2021	R-10 high SHGC	0	7	121	23.2	0	14.9	77
2021	R-10 high SHGC	30	3	54	27.3	0	14.7	68.5
2021	R-10 high SHGC	30	7	124.7	25.8	0	14.7	68.5
2021	Triple-pane	0	3	43.8	6.2	0	12.1	97.2
2021	Triple-pane	0	7	48.7	18.8	0	12.1	97.2
2021	Triple-pane	30	3	47.7	7.3	0	11.9	88.7
2021	Triple-pane	30	7	53	20.8	0	11.9	88.7
2021	Triple-pane high SHGC	0	7	51	20.3	0	14.8	89.7
2021	Triple-pane high SHGC	0	3	47	6.2	0	14.8	89.7
2021	Triple-pane high SHGC	30	7	119.8	22.2	0	14.6	81.3
2021	Triple-pane high SHGC	30	3	49.7	7.3	0	14.6	81.3

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