Comparative Analysis of Building Envelope Performance across Income Levels for Enhancing Thermal Resilience during Heatwaves

[a]Suman Paneru
[a]Yuqing Hu
[b]Guangqing Chi
[a]Julian Wang*
[a]Department of Architectural Engineering, Penn State University, University Park, PA
[b]Department of Rural Sociology, Penn State University, University Park, PA
* Corresponding Author: julian.wang@psu.edu

https://doi.org/10.52202/077496-0030

Abstract

The increased occurrence of extreme heatwaves in communities can have disproportionate impacts on vulnerable low-income communities. The study of building envelopes and their role in reducing thermal vulnerability lacks a specific focus on low-income groups, which indicates that there is a research gap. This research explores the performance of the envelope in reducing thermal vulnerability across different community income levels. A Department of Energy (DOE) prototype building was selected and Atlanta was chosen as a case study to explore thermal resilience across three different income groups: low-income, middle-income, and high-income. The Energyplus simulation indicate that the peak cooling load is significantly higher for low-income groups compared to high-income groups (8.4 kW vs. 14.2 kW). Additionally, the energy usage during extreme heatwaves in low-income community groups compared to medium and high-income community groups is larger (3804.29 MJ vs. 3000.07 MJ). This suggests that with an improved and tailored building envelope the thermal vulnerability can be reduced.

Keywords: building envelope, thermal resilience, decarbonization, low-income communities

1.0 Introduction

The rising global temperatures and frequent extreme heatwaves highlight the critical role of building envelopes in mitigating the impact of climate change and improving resilience, particularly within vulnerable communities such as low-income ones (Flores-Larsen & Filippín, 2021). The increased frequency of these extreme events has demanded a resilience plan to mitigate climate change and extreme weather events (Sharifi & Yamagata, 2015). Climate-induced extreme events and weather variations will not only affect energy demand but also put extra strain on the resiliency of urban systems (Nik et al., 2021). As low-income communities often bear a disproportionate burden of heat stress, safeguarding them from heatwaves demands tailored solutions that address thermal resilience (Liu et al., 2023). Furthermore, acute or prolonged exposure to heat can have various adverse effects on human health and quality of life (Hatvani-Kovacs et al., 2016). In extreme cases, excessive exposure to heat can lead to mortality (Shindell et al., 2020). Although it is widely acknowledged that buildings in low-income communities exhibit less thermal resilience to heatwaves, putting occupants at a greater risk of health issues, there is a noticeable lack of quantitative analysis on how housing in these areas responds to heatwaves compared to those in middle- and high-income communities. During heatwaves or similar extreme weather stressors, building-envelope properties become the most crucial factor mediating the indoor environment and affecting passive habitability (Kesik et.al., 2019). In regions experiencing heatwaves, the between minimum use of the mechanical system with the high-performance envelope/enclosures can help to reduce thermal vulnerability. ***Accordingly, this study seeks to assess the thermal resilience of building envelopes within low-income communities during periods of heatwaves, in comparison to middle- and high-income communities***. Specifically, the study first

https://doi.org/10.52202/077496-0030

statistically identified the properties of the building envelope, including walls, roofs, windows, and infiltration aspects across different household income levels. Subsequently, we integrated these envelope properties into prototypical models as defined by the Department of Energy and conducted energy simulations under specific heatwave conditions. The analysis of energy use and peak energy demands allowed us to compare the resilience of these communities and discuss the potential vulnerabilities of low-income communities in the face of extreme heat.

2.0 Method

The methodology for this study consists of two parts: i) selection of envelope properties and ii) energy performance simulation as shown in Figure 1. For the selection of building envelope thermal properties, ResStock data for Atlanta, GA was used. We categorized the income brackets defined in this dataset into three levels: low (<$60K), middle ($60K-$150K), and high (>$150K), representing low, middle, and high-income community groups, respectively. Following this categorization, we computed the corresponding probabilities for various envelope components and properties. The envelope properties with the highest probabilities in each income cluster were considered. When the probabilities were similar, properties with lower thermally insulating levels were selected, assuming a worst-case scenario for each income cluster. Once the envelope properties for different community groups were established, energy simulations of the DOE prototypical buildings (single-family houses with a floor area of 4,754.19 square feet each) were carried out for each income group. A representative heatwave weather condition from July 23rd to July 29th, 2012, in Atlanta, GA, was employed in this specific simulation analysis. One-week energy use and peak demand are obtained through the simulations and then compared across different household income clusters.

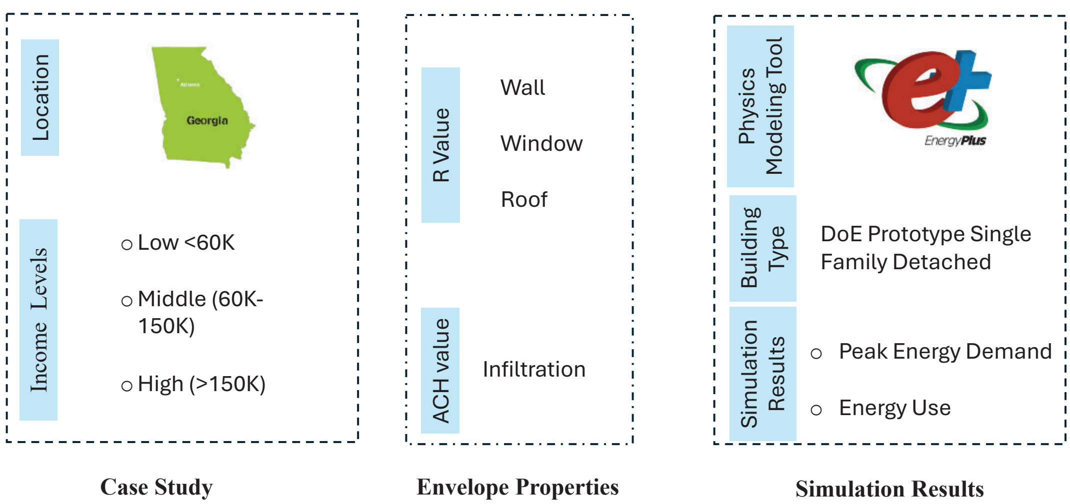


Fig. 1. Methodology used in this study

https://doi.org/10.52202/077496-0030

3.0 Results

This results section discusses the selection of building envelope properties across different communities and the simulated cooling load demand and energy use during the selected heatwave week.

3.1 Selection of Envelope Properties across Different Community Levels

The envelope properties with the highest probability within each cluster were selected as representative. Using the Restock dataset, a Dirichlet distribution was obtained for each income cluster (<$60K, $60-150K, >$150K) individually, with probability density frequencies of each envelope property depicted in Figs. 2-5. In particular, regarding the wall insulation conditions shown in Figure 2, for the low-income group (<$60K), uninsulated and R- 11 are both dominant wall insulation properties. As indicated above in the methodology section, the relatively lower thermal condition, uninsulated, was selected. For the middle-income group and the high-income group, the predominant R-value of the wall is R-11. As depicted in Figure 3, the Dirichlet distribution illustrates the window preferences across varying income levels. The following selections were identified based on the income levels: for incomes <$60K, single-clear windows with metal frames were chosen; for incomes between $60-150K, double-clear windows with metal frames were selected; and for incomes >$150K, double low-e windows with non-metal frames and m-gain were chosen. For roof, uninsulated (R-0) roofing thermal properties across all three household income levels, as depicted in Figure 4. Additionally, we analyzed the features of the whole home infiltration at the different income levels. The probability distribution in Figure 5 shows that the 15 ACH50 of infiltration dominates across all income clusters. This is also consistent with building codes and standards.

https://doi.org/10.52202/077496-0030

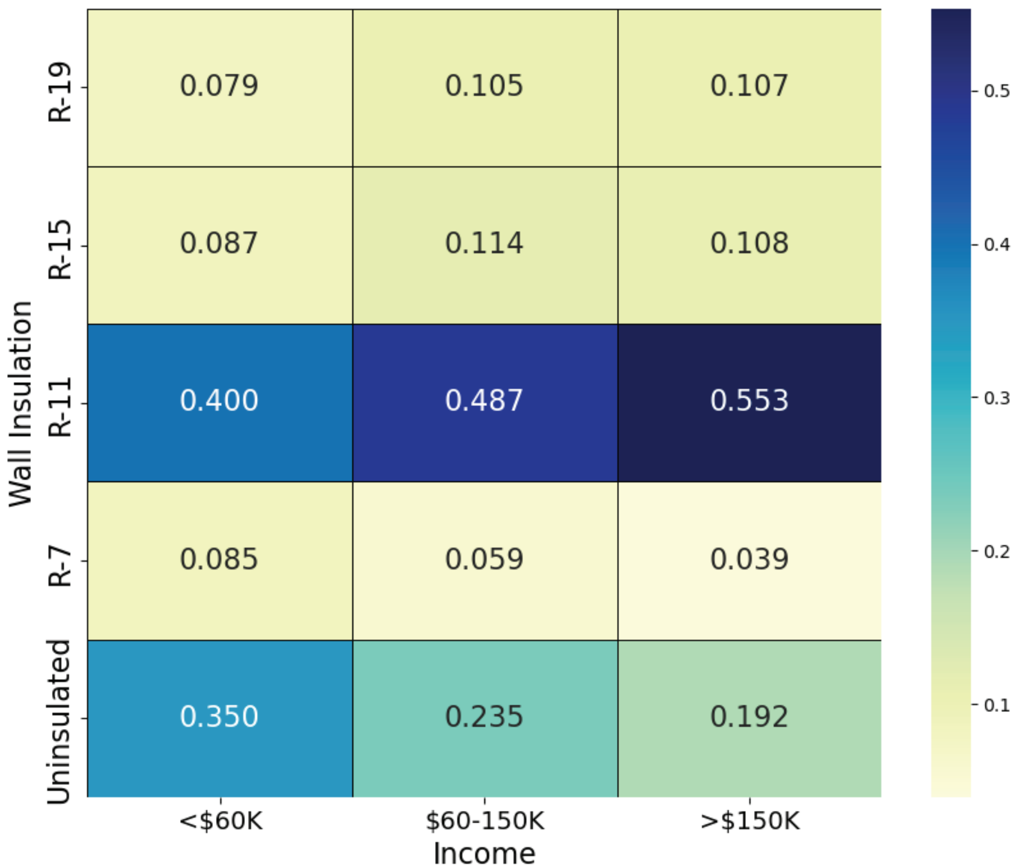


Fig. 2. Dirichlet Distribution of Insulation of wall for differing income levels

https://doi.org/10.52202/077496-0030

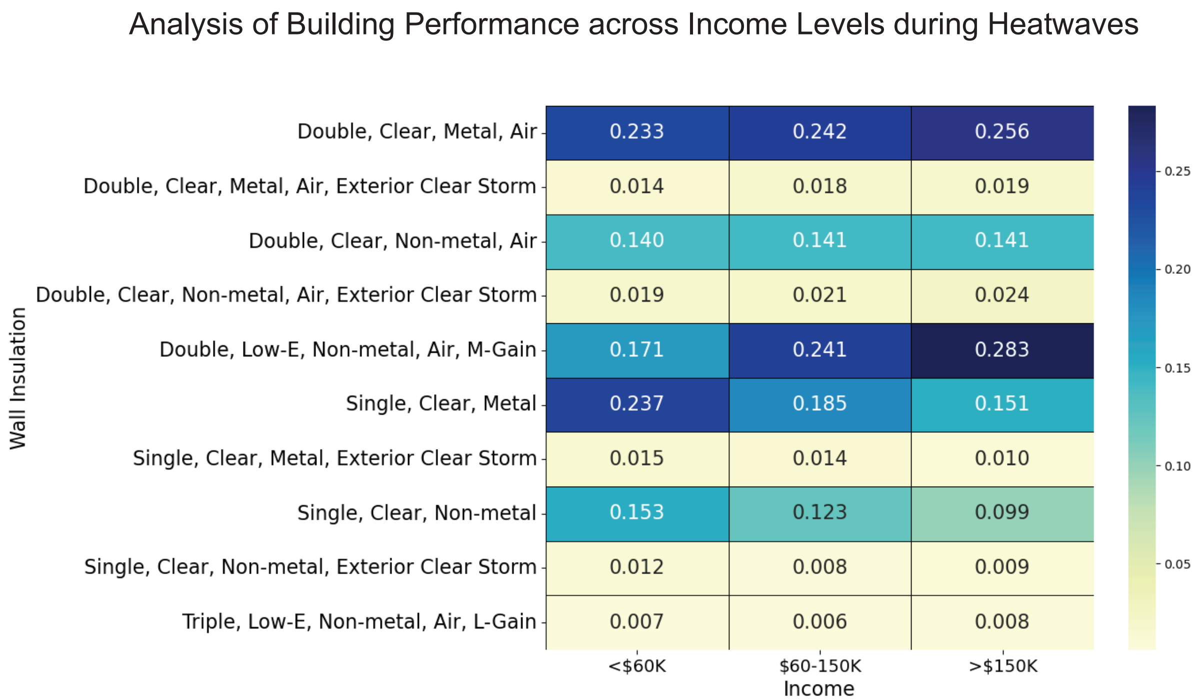
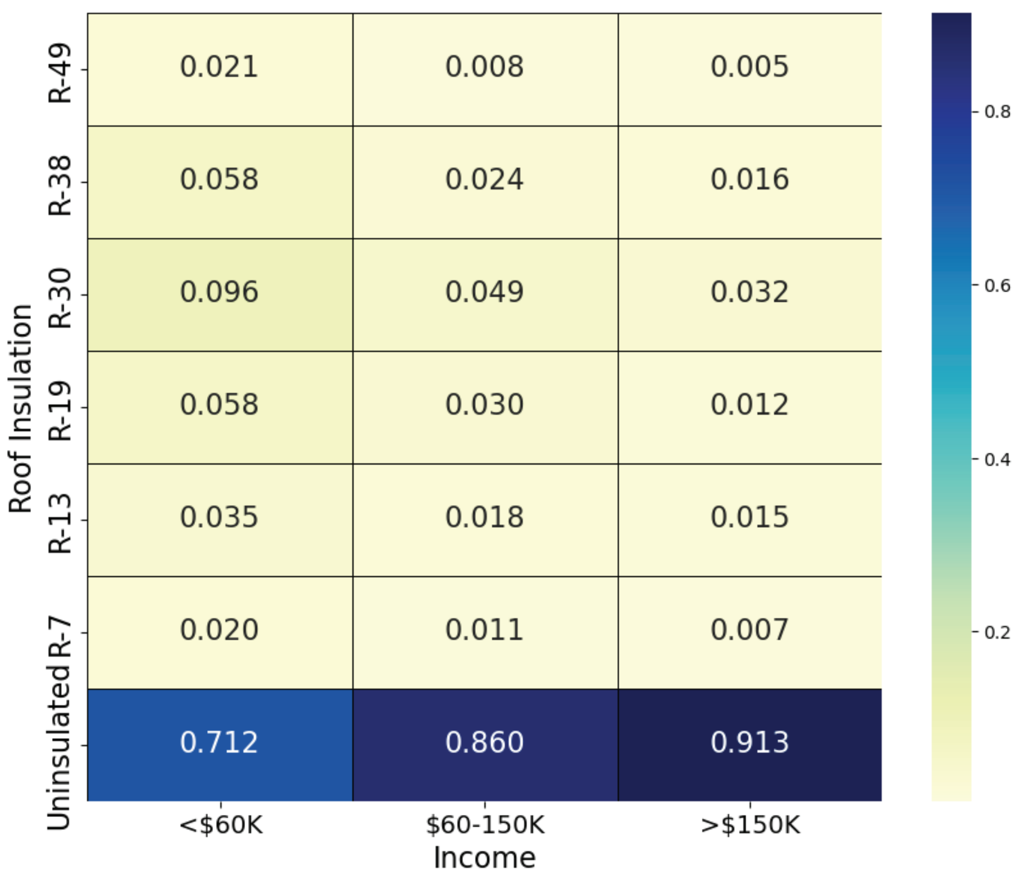


Fig. 3. Dirichlet Distribution of a window for differing income levels



https://doi.org/10.52202/077496-0030

Fig. 4. Dirichlet Distribution of roof insulation for differing income levels

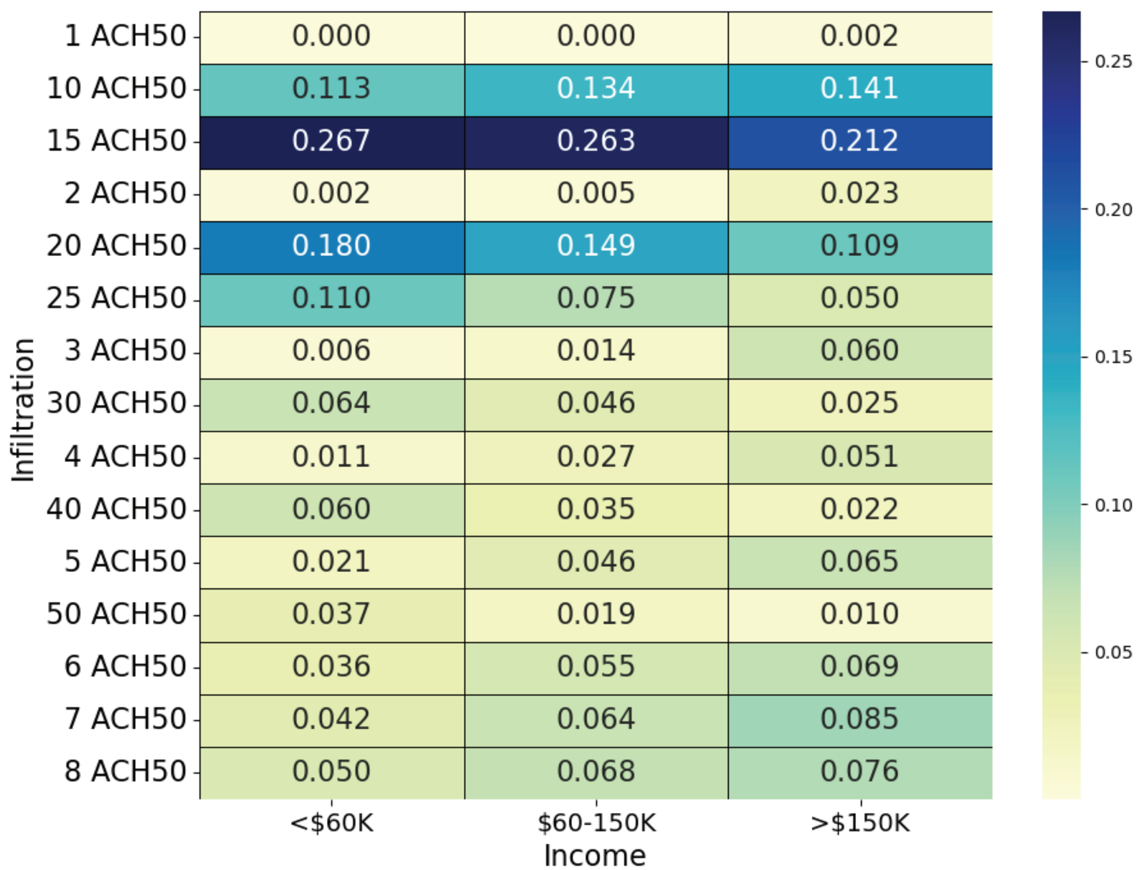


Fig. 5. Distribution of infiltration for differing income levels

Based on the above probability distributions across three different income-community levels, the findings are summarized in Table 1. The specific window properties for each window typology were determined based on the actual window product database and parametric relationship found in our prior studies (Wang, Caldas, Huo, et al., 2016). These data were then used to simulate the peak energy demand and energy use at the whole building level during heatwaves.

Table 1: Building Envelope Selection Based on Income

Income Level	**Low (<$60K)**	**Middle ($60-150K)**	**High (>$150K)**
Wall	Uninsulated	R-11	R-11
Window	Single-clear, metal frame U-factor=1.12	Double clear, metal frame U-factor=0.68	Double low-e, non-metal, m-gain U-factor=0.57 (e=0.1)

https://doi.org/10.52202/077496-0030

	SHGC=0.79 VT=0.76	SHGC=0.64 VT=0.69	SHGC=0.51 VT=0.64
Infiltration	15 ACH50	15 ACH50	15 ACH50
Roof	Uninsulated	Uninsulated	Uninsulated

Table 1 illustrates variations in envelope characteristics among low, medium, and high-income levels. These differences are evident in the R-values for walls and the U-values and solar heat gain coefficients (SHGC) for windows. For instance, there is a contrast between uninsulated and R-11 for the walls, between U values of 1.12 and 0.57, and between SHGC of 0.79 and 0.51 for windows. Relatively higher U-factors of building walls and windows in low-income community houses may not insulate the buildings well during extreme weather conditions, and the higher SHGC may further worsen the indoor heat gains from solar radiation. In brief, this reveals that the differences in income levels among communities influence the prioritization of specific envelope characteristics. Low-income communities may prioritize cost-effective options that still offer adequate thermal protection, while higher-income communities may opt for premium materials with superior insulation properties.

3.2 Heatwave Period-Specific Cooling Load Demand

The simulation was set up for a week from 07/23 to 07/29 for the year 2012. The envelope properties as depicted in Table 1 were used for simulation for three different communities: low-, middle-, and high-income groups. Understanding the peak cooling demand is crucial for sizing air conditioning systems appropriately. A higher peak demand necessitates a larger unit and it also puts more strain on the power grid. Thus, having insight into peak load demand in communities is vital for ensuring thermal resilience and reducing thermal vulnerability.

https://doi.org/10.52202/077496-0030

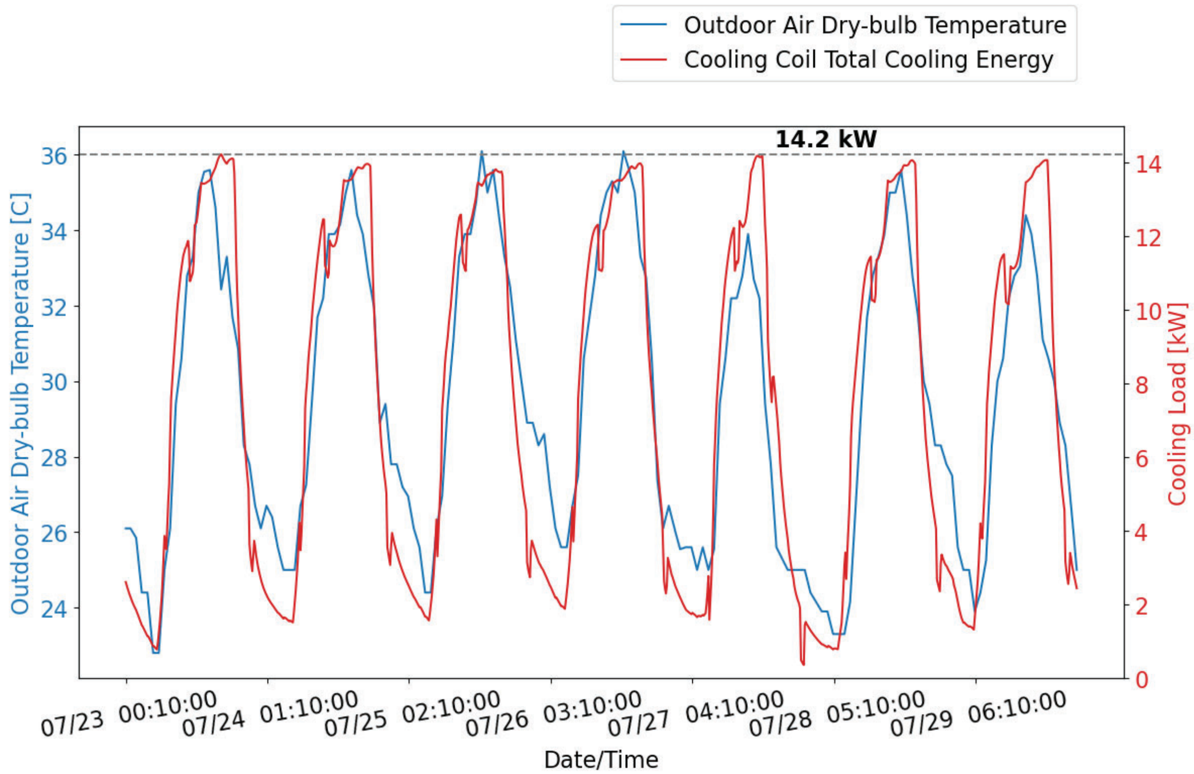


Fig. 6. Cooling load vs outdoor air-dry bulb temperature for low-income communities

https://doi.org/10.52202/077496-0030

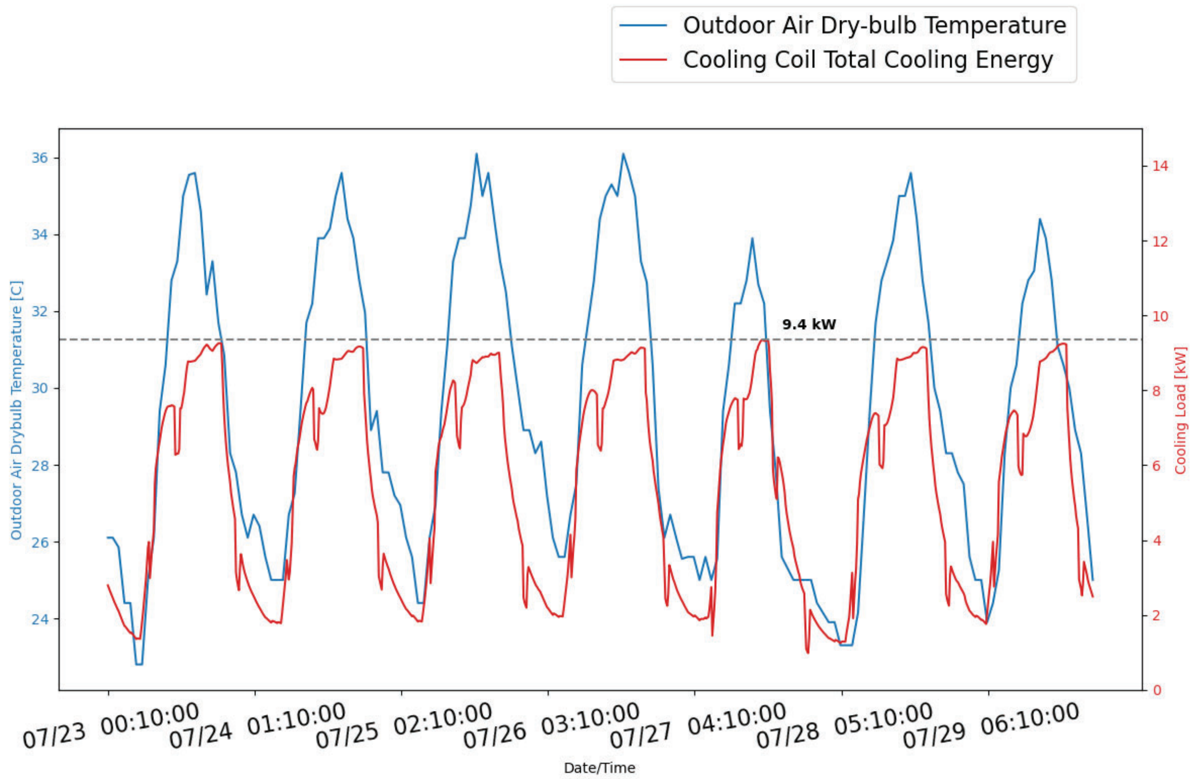


Fig. 7. Cooling load vs outdoor air-dry bulb temperature for middle-income communities

https://doi.org/10.52202/077496-0030

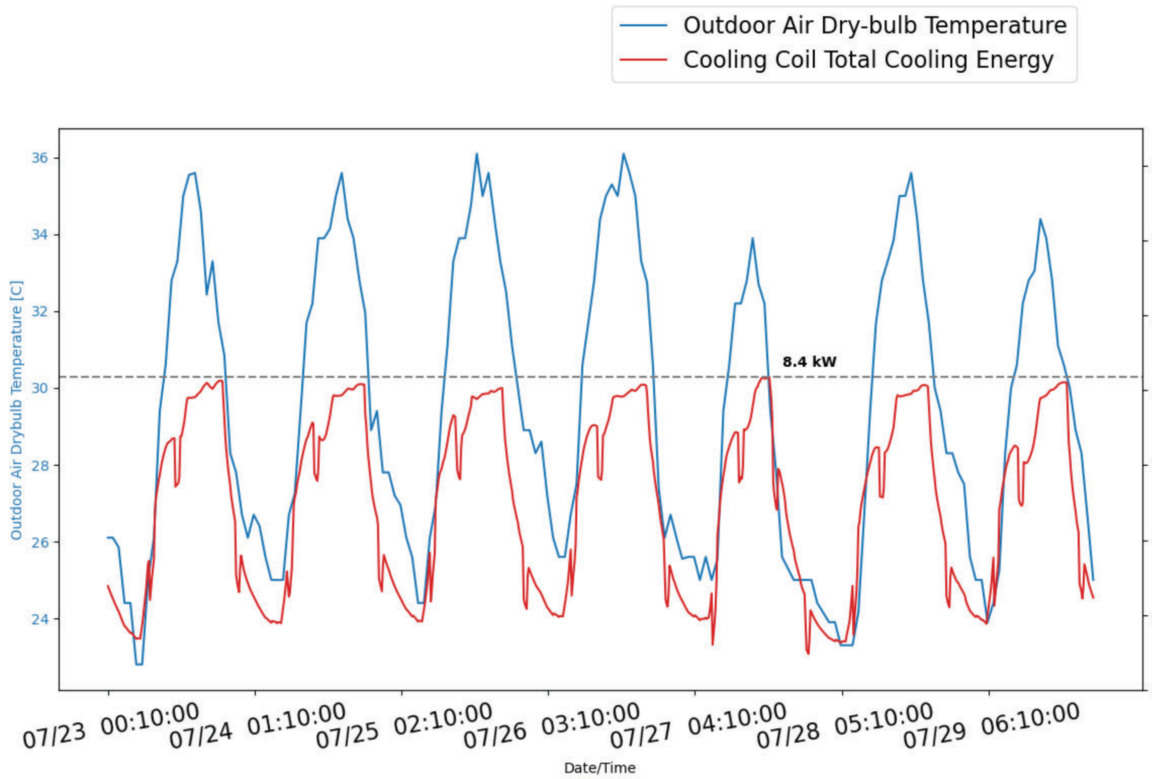


Fig. 8. Cooling load vs. outdoor air-dry bulb temperature for high-income communities

For the low-income community, the peak cooling load demand was 14.2 kW, as shown in Figure 6. As the temperature outside increased, the cooling load also increased subsequently. For the medium-income community, the peak cooling load demand was 9.4 kW, as shown in Figure 7. Though the pattern resembled the temperature profile, the overall cooling load demand was reduced significantly compared to the low-income groups. For the high-income community group, the peak cooling load demand was 8.4 kW, as shown in Figure 8. The highly insulated envelope helped to reduce the peak cooling demand significantly compared to the low-income groups; additionally, the peak demand was also lower than the medium-income community. The cooling load ratio between low and high-income groups is about 1.7.

During heatwaves, the cooling load is of utmost importance. The peak cooling load represents the maximum amount of cooling capacity required to maintain indoor comfort levels during these extreme conditions. It is evident from the simulations that the cooling load demand varies significantly across different income groups. Low-income communities typically experience higher cooling load demands due to factors such as inadequate insulation, lower-quality building materials, and limited access to energy-efficient cooling systems.

3.3 Heatwave Period-Specific Cooling Energy Use

https://doi.org/10.52202/077496-0030

The total cooling energy during the selected heatwave period in these three income community groups shown in Table 2. It presents that the energy consumption for the low-income groups is significantly higher than for the other two community groups. As residents increase their use of cooling systems to combat the heat, the demand for electricity rises, potentially straining the power grid and leading to higher energy consumption across the community.

Table 2: Energy use for various income groups

Community groups	**Total Energy Use (MJ)**
Low-income	3804.29
Medium-income	3286.84
High-income	3000.07

The comparison of cooling energy use during heatwave periods across the three income groups not only applies to those extreme conditions but also informs the understanding of energy use patterns under typical weather conditions throughout the year. Increased energy consumption can lead to higher utility costs, which could pose a financial burden for low-income people who are already struggling to make ends meet. This could potentially expose them to thermal vulnerability. If they opt not to condition their homes to maintain a certain indoor temperature, it could exacerbate existing adverse effects.

4.0 Conclusion

The study reveals a significant disparity in peak cooling load between low-income and high-income groups, with low-income households experiencing higher peak cooling demand (8.4 kW vs. 14.2 kW). Additionally, during the heatwaves, energy usage in low-income communities surpassed that of high-income groups (3,804.29 MJ vs. 3,000.07 MJ). These discrepancies exacerbate thermal vulnerability, especially for low-income households, due to costlier mechanical units and increased energy consumption, leading to higher utility expenses. Higher peak demands may exacerbate thermal vulnerability, especially for low-income groups. Effective mechanical systems and insulation significantly influence thermal resilience, with higher insulation levels correlating with reduced cooling energy demands. During heatwaves, cooling load demand peaks, particularly in low-income communities, which shows the importance of sufficient insulation in walls and windows. Ensuring equitable access to resources and solutions is essential for enhancing thermal comfort across communities. Enhancing the thermal characteristics of building envelopes through improved insulation and efficiency measures can mitigate these disparities. Prioritizing equitable access to resources and implementing targeted strategies is crucial for enhancing thermal comfort and resilience across all communities, irrespective of income levels.

There are limitations in our study. Firstly, we assumed that all income levels have the same building size, but in reality, this may not be the case. Future research will consider

https://doi.org/10.52202/077496-0030

varying building area sizes in thermal modeling. Secondly, we assumed that the representative DOE building prototype represented the households in Atlanta, GA.

Conflict of Interest

This research work is supported by the NSF Award # 2215421 CAS-Climate: An Integrated Framework to Investigate Thermal Resilience of Sustainable Buildings and Living Environments for Greater Preparedness to Extreme Temperature Events.

References

Flores-Larsen, S., & Filippín, C. (2021). Energy efficiency, thermal resilience, and health during extreme heat events in low-income housing in Argentina. *Energy and Buildings*, *231*, 110576. https://doi.org/10.1016/j.enbuild.2020.110576

Hatvani-Kovacs, G., Belusko, M., Skinner, N., Pockett, J., & Boland, J. (2016). Heat stress risk and resilience in the urban environment. *Sustainable Cities and Society*, *26*, 278–288. Scopus. https://doi.org/10.1016/j.scs.2016.06.019

Liu, L., Brossman, J., & Lou, Y. (2023). *ResStock communities LEAP Pilot residential housing analysis—detailed methodology* (NREL/TP--5500-88058, 2274781, MainId:88833; p. NREL/TP--5500-88058, 2274781, MainId:88833). https://doi.org/10.2172/2274781

Nik, V. M., Perera, A. T. D., & Chen, D. (2021). Towards climate resilient urban energy systems: A review. *National Science Review*, *8*(3), nwaa134. https://doi.org/10.1093/nsr/nwaa134

Sharifi, A., & Yamagata, Y. (2015). A conceptual framework for assessment of urban energy resilience. *Energy Procedia*, *75*, 2904–2909. https://doi.org/10.1016/j.egypro.2015.07.586

Shindell, D., Zhang, Y., Scott, M., Ru, M., Stark, K., & Ebi, K. L. (2020). The effects of heat exposure on human mortality throughout the United States. *GeoHealth*, *4*(4), e2019GH000234. https://doi.org/10.1029/2019GH000234

Thermal-Resilience-Guide-v1.0-May2019.pdf. (n.d.). Retrieved March 18, 2024, from https://pbs.daniels.utoronto.ca/faculty/kesik_t/PBS/Kesik-Resources/Thermal-Resilience-Guide-v1.0-May2019.pdf

 https://doi.org/10.52202/077496-0030

Wang, J., Caldas, L., Huo, L., & Song, Y. (2016). *Simulation-based optimization of window properties based on existing products*. Retrieved March 18, 2024, from https://publications.ibpsa.org/proceedings/bso/2016/papers/bso2016_1054.pdf