

# The Effects of Redlining on Residential Energy Efficiency and Resilience in Extreme Temperature Events

By

Haley Clapper

Advised by Dr. Brian McAdoo

In partnership with Eliza Hotchkiss, Dr. Philip White, Dr. Dana-Marie Thomas, Dr. Jordan Cox,  
and Jordan Burns

National Renewable Energy Laboratory (NREL)

*Masters project proposal submitted in partial fulfillment of the requirements for the Master of Environmental Management degree in The Nicholas School of the Environment of Duke University*

## Executive Summary

Residential energy efficiency is a component of individual and community resilience during extreme temperature events, especially extreme heat. Historic and lower-quality homes are often less energy efficient, requiring more time to heat up during extreme cold events or cool down during extreme heat events due to gaps in building envelopes. More intensive energy use to withstand these events may contribute to energy burden, the proportion of income spent on energy bills, which tends to affect people of lower socioeconomic status disproportionately. In the 1930s, the Homeowners' Loan Corporation developed mortgage lending maps of over 200 U.S. cities, grading neighborhoods based on the perceived lending risk associated with demographics (A = "Best"; B = "Still Desirable"; C = "Definitely Declining"; D = "Hazardous"). HOLC maps assigned neighborhoods mainly inhabited by white residents of higher socioeconomic status A or B and neighborhoods primarily inhabited by people of color, immigrants, and those of lower socioeconomic status C or D, which was labeled red on HOLC maps, hence the term "redlining." Over several decades, redlined neighborhoods received less investment, including energy efficiency upgrades, than non-redlined neighborhoods. While the Fair Housing Act of 1968 formally outlawed this practice, entrenched patterns of inequitable investment have left lasting effects on neighborhoods and homes.

This study explores how historical redlining and withholding of mortgage lending from redlined neighborhoods has left a legacy of inequities in housing quality and residential energy efficiency compared to non-redlined neighborhoods. This study focuses on Durham, North Carolina, because of its susceptibility to extreme heat, humidity, and occasional extreme cold and its history of redlining and residential segregation.

We used the National Renewable Energy Laboratory (NREL)'s ResStock tool to model the energy performance of Durham's housing stock. This physics-based tool generates statistically representative models of indoor energy performance in each location under desired scenarios. This study modeled homes under coincident three-day power outages and extreme heat or cold, or "summer" and "winter" outages. We modeled temperature change over time (SET Degree Hours, or SDH) to quantify the thermal resilience of homes. Higher SDH measurements indicated lower thermal comfort and reduced resilience, which are linked to poorer energy efficiency.

Additionally, we modeled five energy efficiency upgrade scenarios to identify potential opportunities for home retrofits, aiming to inform federal programs such as the Department of Energy (DOE) Weatherization Assistance Program (WAP) or the Department of Health & Human Services (DHHS) Low Income Home Energy Assistance Program (LIHEAP). Our modeled upgrade packages included adding varying levels of insulation and air sealing, as well as cooling and ventilation.

We then examined energy performance differences for specific building types that are notably more or less prevalent in redlined and non-redlined neighborhoods in Durham. Using residential structure data from the U.S. Army Corps of Engineers (USACE) and digitized HOLC maps from the University of Richmond's Digital Scholarship Lab, we first categorized homes by

redlining grade (A, B, C, or D). Then, we used a clustering method to identify unique combinations (“home types”) of building characteristics, including frame, occupancy, foundation, and vintage. Home groupings were then selected based on notable differences in prevalence between redlined and non-redlined areas and compared to the ResStock outputs to gauge differences in performance and thermal resilience with and without efficiency upgrades.

We identified several home types that were notably more prevalent in redlined areas for summer and winter outages. Most, but not all, of these home types exhibited higher SDH measurements on average compared to home types that were more prevalent in non-redlined areas and compared to all homes in the modeled Durham housing stock. These results indicate a potential link between discriminatory zoning and construction practices and lesser residential energy efficiency.

Adding energy efficiency upgrades reduced SDH measurements for all home types for summer and winter outages compared to the outage-only control with no upgrades. The most robust Advanced Envelope and Universal Cooling package resulted in the most significant SDH reductions. However, our results did not provide sufficient evidence to suggest that certain home types experience more significant SDH reductions than others with the addition of upgrades. These model results suggest that there may be plentiful upgrade opportunities in the Durham housing stock, and home types more prevalent in historically redlined areas could be prioritized as having the greatest need. However, additional studies are needed to elucidate this pattern further.

This study provides insight into potential relationships between historical redlining and gaps in the building envelopes of the current housing stock. Our results indicate that people in primarily redlined home types may experience less thermal comfort and resilience than those in primarily non-redlined homes. Layered with other consequences of neighborhood disinvestment, such as urban heat island effects, inequities in residential energy efficiency may threaten human health, energy affordability, and overall resilience during extreme temperature events.

### *Key Findings*

1. Redlined Areas and Home Types
  - a. Several home types were notably more prevalent in historically redlined areas, potentially indicating a link between discriminatory zoning and construction practices.
  - b. Most home types prevalent in redlined areas exhibited higher average SET Degree Hour (SDH) measurements compared to those in non-redlined areas and the overall Durham housing stock, indicating reduced thermal comfort and resilience for occupants.
  
2. Effectiveness of Energy Efficiency Upgrades

- a. Energy efficiency upgrades significantly reduced SDH measurements for all home types during summer and winter outages.
  - b. The most effective upgrades, notably the Advanced Envelope package paired with Universal Cooling, resulted in the most significant reductions in SDH measurements.
3. Implications for Prioritizing Upgrades
- a. The results suggest plentiful upgrade opportunities in the Durham housing stock, including home types in historically redlined areas.
  - b. Additional studies are needed to identify clear differences in the benefits conferred by different house types after adding energy efficiency upgrades and to inform retrofit programs on potential investment prioritization.

Table of Contents

**Executive Summary** ..... 1

**Introduction** ..... 5

*Extreme Temperature, Health, and Energy Burden* ..... 5

*Redlining, Urban Heat, and Energy Inequity*..... 7

*Research Gaps*..... 10

**Methodology Overview** ..... 10

*ResStock Tool Description*..... 10

*Data Sources*..... 13

*Spatial Mapping and Home Type Clustering* ..... 13

*Thermal Resilience Analysis*..... 14

**Results and Discussion** ..... 15

*Housing Stock Characterization*..... 15

*Home Type Prevalence* ..... 16

*Summer Outage Results*..... 18

        Baseline Thermal Resilience..... 18

*Winter Outage Results* ..... 19

        Baseline Thermal Resilience..... 19

*Energy Efficiency Upgrade Modeling* ..... 22

**Challenges and Limitations** ..... 28

**Conclusions, Applications, and Future Research**..... 28

**Acknowledgments**..... 29

**References** ..... 30

## Introduction

The energy efficiency of buildings is a potential component of individual and community resilience during extreme temperature events, especially extreme heat. Historic and lower-quality homes are often less energy efficient, taking longer to heat up during extreme cold or cool down during extreme heat due to gaps in building envelopes. More intensive energy use to withstand these events could create a financial burden for residents (i.e., energy burden), especially those disproportionately impacted by extreme temperatures. The Home Owners' Loan Corporation (HOLC) was a government-sponsored organization established by the New Deal to refinance home mortgages and invigorate the housing market after the Great Depression. In the 1930s, HOLC developed residential security maps of over 200 U.S. cities to appraise neighborhoods based on mortgage lending risk. This perceived risk was assessed using neighborhood demographic data, including the race, ethnicity, and socioeconomic status of residents (Mitchell, 2018). Neighborhoods predominantly occupied by low-income and non-white residents were considered “hazardous” or too risky for lending purposes. As a result, redlined neighborhoods subjected to this practice have experienced decades of disinvestment perpetrated by city planners and policymakers, loan officers, appraisers, and real estate developers throughout the urban planning process (Mitchell, 2018).

Today, most historically redlined neighborhoods experience diminished rates of home ownership, lower home values, higher vacancy rates, and disproportionate rent burden compared to non-redlined areas (Aaronson et al., 2021). Further, approximately 74% of D-rated neighborhoods are low-to-moderate income (LMI), and 64% are predominantly occupied by people of color today, indicating similar neighborhood demographic patterns nearly 60 years after redlining was outlawed (Mitchell, 2018).

The systematic lack of investment in redlined neighborhoods may result in less vegetation (i.e., trees, parks, and other green spaces), replaced by dark pavement and structures, which can raise outdoor temperatures compared to shadier areas with more green spaces and less dark surfaces, known as the Urban Heat Island (UHI) effect (Manley, 1958; Chakraborty et al., 2022). Additionally, people of color and those of lower socioeconomic status are more likely to live in lower-quality and less energy-efficient housing (Harrison & Popke, 2011).

Disproportionate exposure to heat, combined with poorer housing quality on average, could negatively impact the well-being of residents in historically redlined areas. If homes in redlined areas tend to be less energy efficient compared to those in non-redlined areas, residents of the former could be disproportionately less protected during extreme temperature events. To investigate this, our study aims to characterize the effects of historical redlining on present-day residential energy efficiency and extreme temperature resilience.

### *Extreme Temperature, Health, and Energy Burden*

The effects of anthropogenic climate change have altered weather patterns, including extreme temperature events like heat waves and cold snaps throughout the U.S. (EPA, 2023a). In the last 60 years, the average number of heat waves per year has tripled, the average heatwave

duration has increased by a day, and the average heat wave season has lengthened by 49 days with hotter average temperatures (EPA, 2023b). With Arctic warming and the southward expansion of the polar vortex, cold weather has become more erratic, delivering cold snaps and deadly winter storms to areas in the South, including North Carolina, which lack appropriate adaptations (Cohen et al., 2021). As climate change progresses in the coming decades, temperature extremes will pose significant environmental, health, and financial burdens for the U.S. and global populations. Further, extreme temperature events may have a disproportionate impact on historically underserved groups, including people of color and those with lower incomes.

In the U.S., heat event days are responsible for an average of 235,000 emergency department visits, 56,000 hospitalizations for heat-related illnesses, 658 heat-related deaths, and \$1 billion in healthcare costs per summer (Woolf et al., 2023; CDC, n.d.). Extreme cold-related illness and death are less reported than that of heat, yet a study of weather-related mortalities from 2006-2010 found that an average of 1,330 people died of cold exposure each year in the U.S. (Berko et al., 2014). Further, cold-related mortality rates in winter months have increased on average since 1979. However, it is important to note that reported cold-related deaths include deaths directly from cold exposure, pre-existing illnesses that can be exacerbated by cold exposure, such as cardiovascular and respiratory illnesses, and can be associated with seasonal increases in rates of communicable diseases, like influenza (Gasparri et al., 2015; EPA, 2021).

Morbidity and mortality associated with extreme heat and cold vary across races. A national study from 1999 to 2017 on excessive heat-related mortality found that American Indian and Alaskan Native populations experience the highest mortality rates, followed by Blacks, whites, Latinos, Asians, and Pacific Islanders, controlling for age (Adams et al., 2021). Several vulnerability factors contribute to these health inequities: neighborhood characteristics like social cohesion or isolation and access to public spaces, housing, and infrastructure characteristics that may exacerbate UHI effects or determine availability of cooling services, individual behaviors like energy (i.e., cooling) or medication use, and comorbidities with physical and mental illnesses (Gronlund, 2014).

In addition to adverse health effects, extreme heat and cold occur in locations with infrastructure unaccustomed to and, in some cases, ill-equipped to handle such events. For example, a record heat wave in the Pacific Northwest in 2021 reached temperatures 20-35°F above average (Jones, 2021). In areas with some of the lowest usage of air-conditioning in the U.S. and a lack of other cooling infrastructure (American Housing Survey 2020), this event contributed to at least 914 excess deaths due to heat-related illnesses (Popovich & Choi-Schagrin, 2021) and \$8.9 billion in damages (NOAA), including buckling of roads and sidewalks and deterioration of public transportation (Graff, 2021; Lachacz, 2021; Thompson, 2021). Similarly, Winter Storm Uri in 2021 illustrated how Texas's power grid was unprepared for such extreme cold and a massive spike in demand for indoor heating, resulting in a loss of power for 4.8 million people across the state (DOE).

The effects of extreme weather pose threats to grid reliability across the board. According to the U.S. Energy Information Administration (EIA) annual report, “the average electricity customer experienced seven hours and 20 minutes without power in 2021.” Five of these hours were attributed to extreme weather events, including hurricanes, wildfires, and snowstorms (EIA, 2021). Indoor heating and cooling account for the majority (51% in 2015) of household energy consumption and are residents’ best at-home defense against the effects of extreme temperatures (EIA, 2020). However, the increasing frequency, duration, and intensity of extreme temperature events, energy consumption spikes, and fuel costs have led to increased energy bills for millions across America.

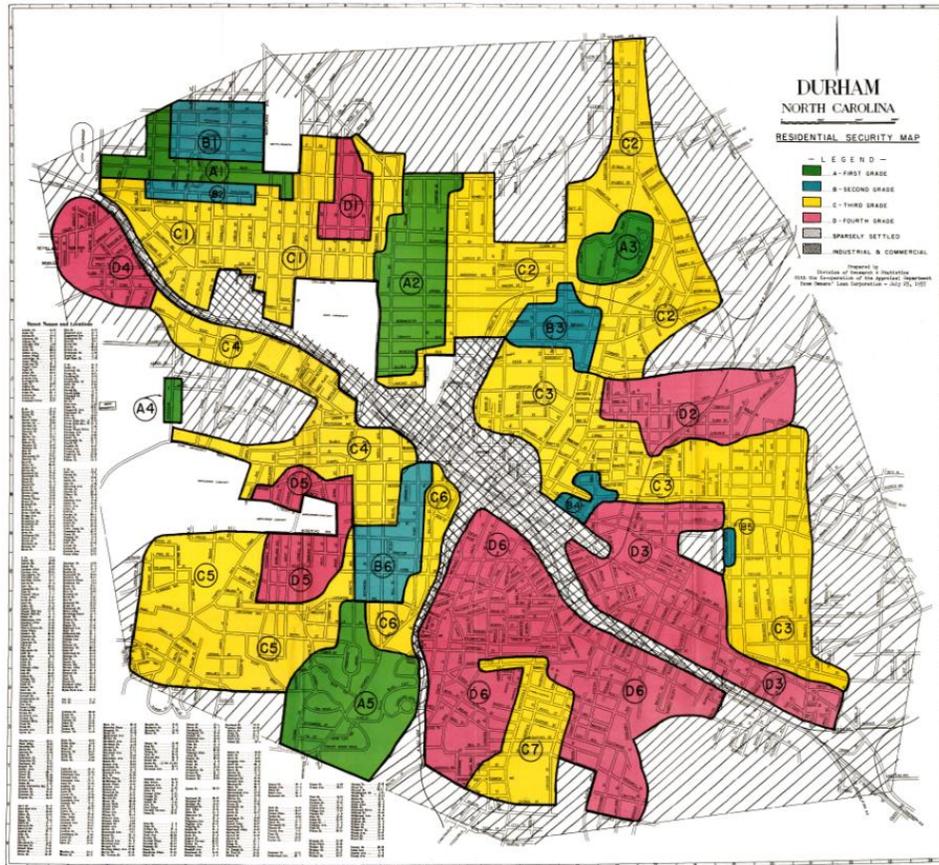
Rising energy costs have left millions in a “heat or eat” dilemma, in which individuals must prioritize other necessities over energy use, and these costs affect lower-income groups disproportionately (Hernandez, 2016). Energy burden, the percentage of gross household income spent on energy costs, is three times higher for low-income households than for higher-income households” (DOE LEAD Tool). Moreover, people of color also experience disproportionately high energy burdens: African American and Latino households experience a 64% and 24% greater median energy burden, respectively, compared to white households of similar socioeconomic backgrounds (Drehobl & Ross, 2016). To reduce energy bills, some households turn off air conditioning systems entirely or delay use until later in the season, and these behaviors vary across race and income levels (Cong et al., 2022). One study found that people of lower socioeconomic status tend to delay the use of cooling services until later in the summer compared to their wealthier counterparts.

### *Redlining, Urban Heat, and Energy Inequity*

Disparities in housing quality across race, ethnicity, and income are crucial to understanding energy burden and health inequity during extreme temperature events. Patterns of housing inequality in cities are partially rooted in discriminatory urban planning, namely the historical redlining of neighborhoods. For several decades, appraisers and real estate developers used HOLC’s residential security maps (Figure 1) to assess mortgage lending risk by neighborhood, preceding the mass suburbanization of the 1950s and “white flight” away from city centers. HOLC created color-coded risk grades using neighborhood demographics and labeled neighborhoods as “Best,” indicating all-white and upper-middle-class residents; “Still Desirable,” indicating nearly or all-white and middle-class residents; “Definitely Declining,” indicating working-class residents, typically first- or second-generation European immigrants, and “Hazardous,” indicating areas primarily occupied by Jewish, Asian, Hispanic, and Black residents (Mitchell, 2018). By establishing HOLC, the federal government mandated redlining in the urban planning process until it was formally outlawed in the Fair Housing Act of 1968—however, decades of disinvestment away from redlined neighborhoods led to lasting consequences.

Today, residential segregation across race, ethnicity, and income persists in most historically redlined cities, as do associated systemic inequities (Figure 2). In Figure 1, green

areas indicate Grade A or “Best,” blue indicates Grade B or “Still Desirable,” yellow indicates Grade C or “Declining,” and red indicates Grade D or “Hazardous.”



*Figure 1. HOLC residential security Map of Durham, NC  
Digitized and sourced from the University of Richmond’s Mapping Inequality project.*

Redlined areas tend to fall in more densely populated city centers with less vegetation, which can contribute to UHI effects compared to those farther from the city center and suburban areas, which were typically not redlined. A study of 481 U.S. urban areas exceeding populations of 50,000 found that people of lower socioeconomic status are disproportionately burdened by heat stress in 94% of urban populations, and heat stress inequities are strongly tied to residential segregation (Chakraborty et al., 2022). Further, urban heat inequity is tied to disproportionate rates of heat-related illness. A study of 11 Texas cities found that historically redlined areas exhibit higher rates of heat-related outpatient visits and higher inpatient admission rates compared to non-redlined areas (Li et al., 2022).

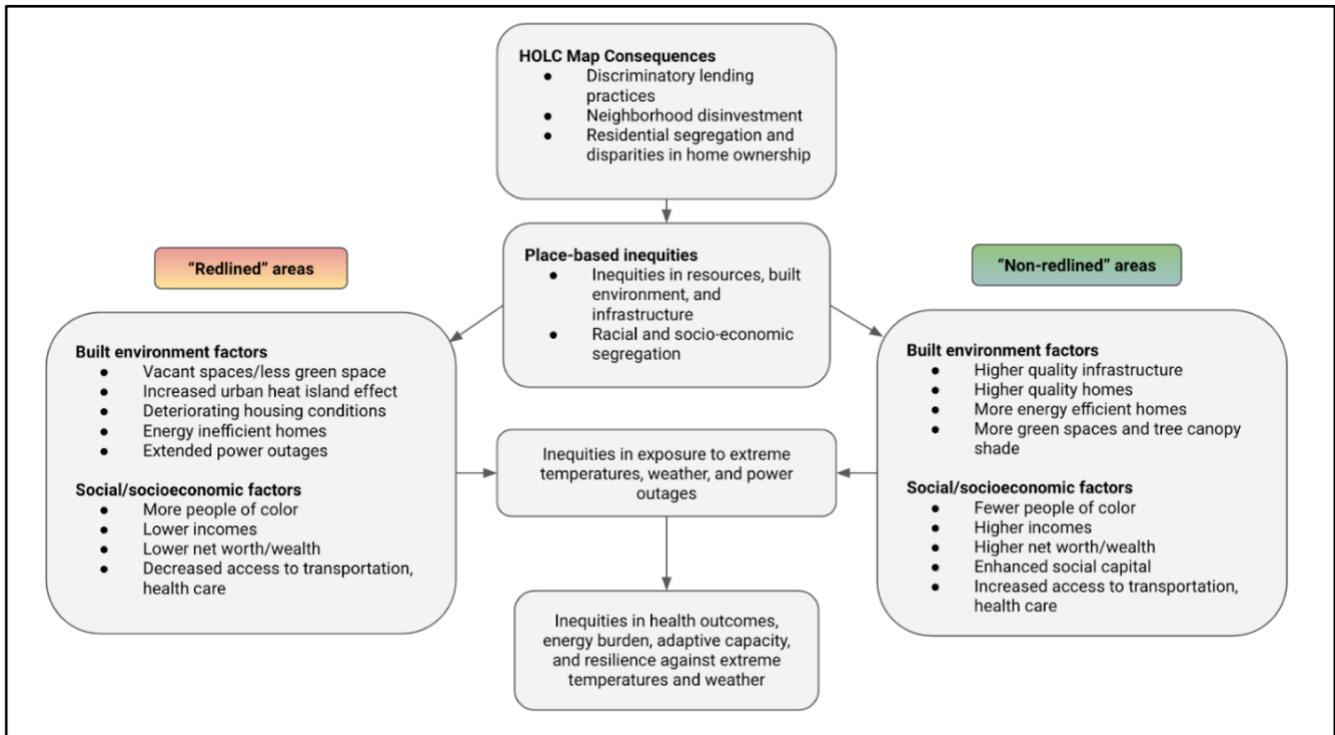


Figure 2. Diagram illustrating the downstream consequences of redlining associated with HOLC Residential Security Maps, adapted from Lee et al., 2022.

Additionally, disparities in neighborhood investment are often reflected in housing quality. Compared to wealthier whites, people of color and lower socioeconomic status are more likely to reside in homes that are older, decaying, under-insulated, and constructed using lower quality materials, that are more susceptible to leaks, drafts, and HVAC system failures (Harrison & Popke, 2011). Poor housing quality may be associated with disparities in energy efficiency, as shown in several studies that modeled residential energy use intensity (EUI, energy/housing unit/year). One study found that areas with larger non-white populations and low socioeconomic status had higher EUI compared to whiter, higher-income areas, directly attributable to less energy-efficient housing, not higher energy consumption (Bednar et al., 2017). Another found EUI and income to be inversely related, and this relationship is stronger among Black households, specifically female Black households, compared to white households (Adua et al., 2022). Overall, less energy-efficient homes require more intensive energy use to heat up or cool down spaces, creating a greater burden for these residents compared to those in more energy-efficient homes, which are often newer and located in more affluent areas.

To mitigate the effects of urban heat and reduce the energy burden in homes, residents can seek energy bill assistance from state utility regulators and support from federal programs like the Department of Energy (DOE) Weatherization Assistance Program (WAP) and the Department of Health & Human Services (DHHS) Low-Income Home Energy Assistance Program (LIHEAP). These programs also facilitate retrofits to enhance building envelopes, an

essential strategy for bolstering energy efficiency and decarbonizing buildings. However, energy efficiency upgrades like insulation, HVAC replacements, electrification, smart thermostats and appliances, and overall building repair are needed to reduce energy burden significantly, and these strategies are currently underutilized in low-income areas and communities of color (Drehobl & Ross, 2016). While several states have set forth energy efficiency standards and updated building codes, these standards are not applied equally in practice. Previous studies have shown that access to energy efficiency technology varies by race and ethnicity and across income gradients (Lewis et al., 2019; Reames, 2016).

### *Research Gaps*

While there is a demonstrated need for neighborhood-wide investment in underserved communities, namely for energy efficiency upgrades, there is a critical gap in understanding the effects of historical redlining on residential energy efficiency disparities. Further investigation is needed to understand how the legacy of redlining has affected indoor residential building performance during times of increased energy demand, such as extreme weather events.

In this study, we hypothesize that historically redlined areas experience a greater need for energy efficiency upgrades compared to non-redlined areas to withstand, absorb, and adapt to the effects of extreme temperature events, including heat waves and cold snaps. To investigate this, we will compare energy performance in different types of residential buildings with varying prevalence in redlined and non-redlined areas in Durham, North Carolina. Durham was selected as a case study because of its susceptibility to extreme heat, humidity, and occasional extreme cold, as well as its history of redlining and residential segregation. Our primary objective is to model scenarios of potential differences in residential energy performance between redlined and non-redlined areas during extreme temperature events. Subsequently, we aim to use this information to identify the need for energy efficiency upgrades, communicate findings to stakeholders, and develop actionable solutions. Overall, this research will provide insights into the potential relationships between historical redlining, energy efficiency inequity, and implications for individual and community resilience against extreme temperature events.

## **Methodology Overview**

### *ResStock Tool Description*

To model residential energy performance during coincident power outages and extreme temperature events, we used the National Renewable Energy Laboratory (NREL)'s ResStock™ tool. ResStock uses a physics-based simulation modeling tool, EnergyPlus, to calculate the energy use of the U.S. residential building stock as it was in 2018. ResStock combines data from the Energy Information Administration (EIA)'s Residential Energy Consumption Survey (RECS) and the American Community Survey (ACS) and weather and power outage data to generate statistically representative models of the building stock for regions and environmental conditions of interest. These models are representative of the actual housing stock, averaged to the Public Use Microdata Area (PUMA) granularity. PUMAs vary in area, but each contains

several census tracts and has a minimum population of 100,000. For example, Durham, NC, has a population of approximately 285,527 across two PUMAs. At the U.S. national scale, ResStock datasets typically use 550,000 samples to represent 133,172,057 dwelling units (approximately 1:242).

In addition to baseline energy use, ResStock can model energy efficiency upgrades, such as the addition of insulation, cooling services, heat pumps, sealing, electrification, and more. Using these additional features, we can analyze how envelope improvements could impact home energy performance under extreme temperatures in redlined areas compared to those historically graded “A” or “B.”

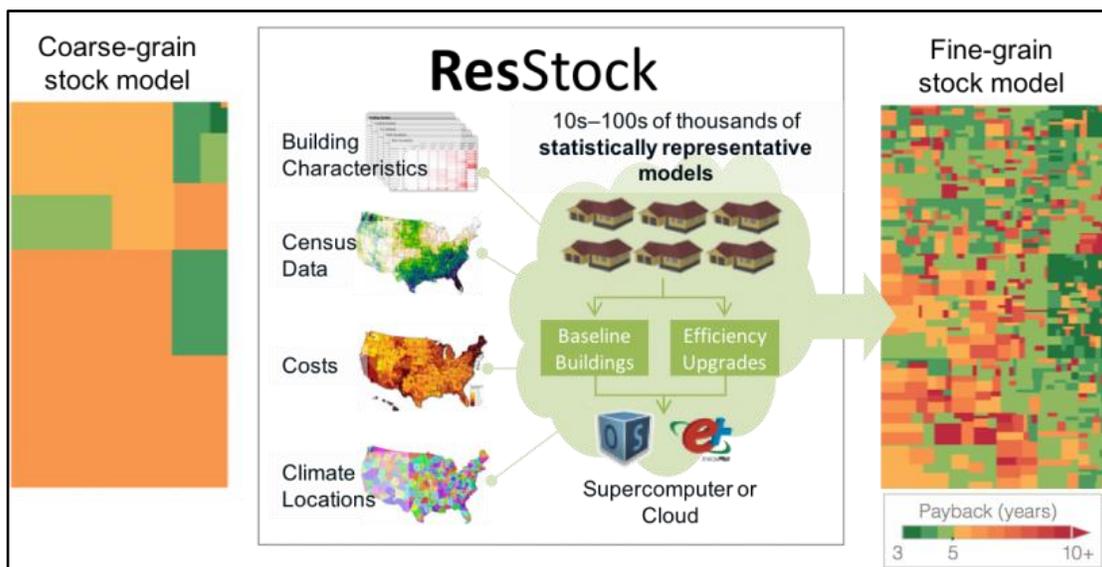


Figure 3. Visual representation of ResStock. Source: NREL

Figure 3 shows a visual representation of ResStock, including “payback period heat maps” for modeled insulation upgrades in parts of Washington’s and Oregon’s housing stock. The most cost-effective upgrade opportunities are shown in green. Overall, this illustration shows ResStock’s higher-resolution capabilities compared to traditional, lower-resolution methodologies that may not capture all upgrade opportunities.

To understand the performance of homes during extreme temperature events, we used ResStock to model home characteristics under combined extreme temperatures that coincide with power outages in Durham. We input outage length in hours during the summer and winter to include hot and cold weather, each outage lasting at least two days. We chose to model longer-than-average outages to understand the long-term consequences of an outage on the thermal behavior within the home. Additionally, we input weather data from the National Solar Radiation Database (NSRDB) for the period coinciding with each outage, summarized in Table 1. The NSRDB uses NREL’s Physical Solar Model (PSM) to generate temporal and spatial data for regional solar radiation climates (Sengupta et al., 2018). Data for the power outages was taken using the Environment for Analysis of Geo-Located Energy Information (EAGLE-I) dataset

(Tansakul, 2023). Long (several-day) outages were discovered using the SciPy Find Peaks algorithm and visual inspection of the data.

*Table 1. Power outage occurrence and length used for ResStock modeling.*

Location	Outage Date(s)	Outage Length
Durham, NC	Summer: October 10-14, 2022	72.5 hours
	Winter February 26-27, 2015	40.5 hours

A central focus of the model outputs is the Standard Effective Temperature (SET). Gagge et al. developed SET as a thermal comfort metric for passive survivability, and it can be used as a proxy for thermal resilience in the event of an extended power outage or loss of heating fuel. SET describes the thermal conditions of a home more comprehensively than dry-bulb air temperature alone. It is “the temperature of a hypothetical environment with 50 percent relative humidity, an air velocity below 0.1 meters per second, and a two-node method to represent physiological factors of hypothetical occupants, including activity and clothing levels” (Overbey, 2016).

The U.S. Green Buildings Council defines “livable” or comfortable temperatures as SET degrees between 54°F and 86°F. Our ResStock outputs provide SET Degree-Hours (SDHs), or the magnitude and duration outside of the livable range (below 54°F during a winter outage and above 86°F during a summer outage) multiplied by the outage length in hours. Overall, SDHs measure how long and to what extent a home is outside the livable SET range in the event of coincident power outages and extreme temperatures, thus the level of exposure occupants experience if inside. The greater the SDHs, the less thermal comfort occupants experience, and the more hazardous the thermal conditions in the home. This study focused on the SDHs over the entire outage (Quantity of Interest 1, QOI1) and the first 24 hours of the outage (QOI2).

To investigate the potential benefits of energy efficiency retrofits, we simulated building envelopes during a power outage with the addition of three packages of energy efficiency upgrades, outlined in Table 2. QOI1 and QOI2 were each modeled under six scenarios: Measure 1, Measure 2, Measure 3, Measure 1 + 3, Measure 2 + 3, and no upgrades as a control model.

Table 2. Energy efficiency upgrade packages are modeled in the residential building stock using ResStock. Adapted from ResStock technical documentation.

Upgrade Package	Summary
<b>Measure 1:</b> Light Touch Envelope	<ul style="list-style-type: none"> <li>• Attic floor insulation up to International Energy Conservation Code (IECC) - Residential 2021 levels for dwelling units with vented attics and lower-performing insulation</li> <li>• General air sealing: 30% total reduction in ACH50 for dwelling units with greater than 10 ACH50</li> </ul>
<b>Measure 2:</b> Advanced Envelope	<ul style="list-style-type: none"> <li>• Everything in Measure 1 except for general air sealing</li> <li>• 1” exterior extruded polystyrene (XPS) insulation (R-5/in) for wall insulation of less than R-19</li> <li>• ENERGY STAR windows (v7)</li> <li>• Insulate finished attics and cathedral ceilings to R-30</li> <li>• Air seal to IECC 2021 requirements with energy recovery ventilator (ERV) added</li> </ul>
<b>Measure 3:</b> Universal Cooling	<ul style="list-style-type: none"> <li>• Add energy efficiency ratio (EER) 12.0 room air conditioning (AC) units for dwelling units without cooling and with HVAC based on the floor area of the building</li> <li>• Add seasonal energy efficiency ratio (SEER) 14 and 15 AC units for dwelling units without cooling and with HVAC ducts and add 100% partial space conditioning in northern and southern states respectively.</li> </ul>

#### Data Sources

The original HOLC Residential Security Maps were digitized in the *Mapping Inequality* project from the University of Richmond’s Digital Scholarship Lab and are publicly available as spatial polygon Geographical Information System (GIS) files. Each city’s neighborhoods are categorized by grade: A, B, C, and D. We collected redlining GIS polygons for Durham. Structure data, also spatially correlated in GIS, were collected from the U.S. Army Corps of Engineers (USACE) National Structure Inventory (NSI), which includes point data of residential, commercial, industrial, and public buildings across the U.S. We collected data for Durham County and filtered for residential structures only.

#### Spatial Mapping and Home Type Clustering

Spatial GIS mapping was required to identify the number and type of present-day residential structures within each area graded (“redlined”) in the original HOLC maps. The point

location, construction type, year built, and occupancy type of residential structures were collected from the NSI and combined with HOLC polygons to categorize each present-day building according to its HOLC grade. This spatial join allowed for the identification of differences in the prevalence of combinations of building characteristics (Table 3). For this study, homes graded “A” or “B” were considered non-redlined, while homes graded “C” or “D” were considered redlined.

An R script was developed to cluster residential buildings based on the characteristics described in Table 3 and calculate the prevalence of different characteristics based on location. Building characteristics with a more than 10% difference in prevalence between redlined and non-redlined areas were identified for deeper examination in the ResStock temperature results. For Durham, NC, nine unique combinations of home age, construction material, and occupancy type (“home types”) were identified as being notably more or less common in redlined and non-redlined areas (see results). Codes for home types were developed according to the combinations of characteristics and the standard structure codes developed by FEMA. For example, a single-family, wood frame, one-story home with a basement, built in the 1940s, is coded as “wood40res1-1swb.”

*Table 3. Building characteristics chosen for examination in both National Structure Inventory and ResStock data.*

<b>Occupancy Characteristics</b>	<b>Construction Characteristics</b>	<b>Age Characteristics</b>
Single Family, Multi-Family, Manufactured Home, Hotel, Dormitory	Wood, Masonry/Brick, Steel, or Manufactured	1930s, 1940s, 1950s, 1960s, 1970s, 1980s, 1990s, 2000s
	Number of Stories	
	Number of Units (Multi-Family)	
	Inclusion of Basement	

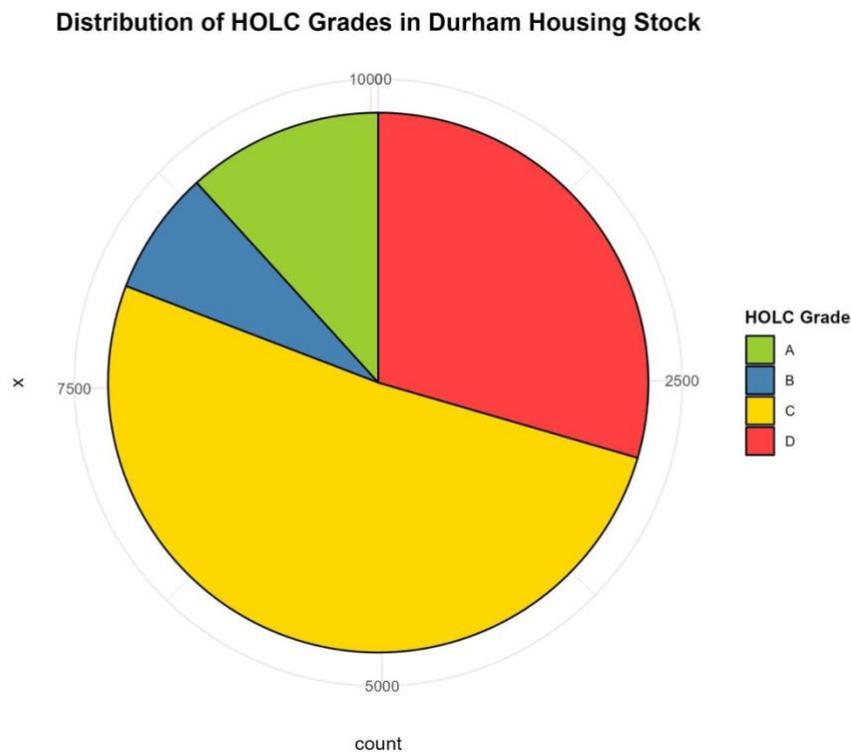
*Thermal Resilience Analysis*

Once housing types with large differences in prevalence between redlined and non-redlined areas were identified, we examined and compared their thermal resilience using ResStock temperature results, including SDHs during outage events with and without efficiency upgrade packages. Data exploration and visualization were used to investigate differences in thermal resilience by home type and identify potential trends. Due to the lack of randomness in the housing stock, traditional sampling and statistical tests were deemed less effective methods for this study. This is discussed further in the “Challenges and Limitations” section.

## Results and Discussion

### *Housing Stock Characterization*

The NSI dataset for Durham County contained 96,755 residential structures, 10,043 of which are within the bounds of the original HOLC map when superimposed in GIS. This indicates that approximately 89.6% of Durham County’s present-day housing stock falls outside of HOLC-defined boundaries because of the communities outside of the City of Durham and the city’s expansion since the map’s creation in the 1930s. Figure 4 shows that most homes within HOLC boundaries were graded “C” or “Declining” (n = 5,154; 51.3%), followed by “D” or “Hazardous” (n = 2,962; 29.5%). Thus, approximately 80.8% of Durham’s homes within the HOLC boundaries are in historically redlined neighborhoods.



*Figure 4. Pie chart illustrating the distribution of HOLC grades in the Durham housing stock bounded by the original HOLC map.*

Most homes in Durham’s HOLC boundaries have a wood frame (n = 8,582; 85.5%), followed by masonry (n = 1,281; 12.8%) (Figure 5a). Additionally, most of the housing within HOLC boundaries was constructed in the 1940s (n = 3,245; 32.3%), 1950s (n = 2,926; 29.1%), and 1960s (n = 2,303; 22.9%), which were also the decades in which redlining was legally enforced (Figure 5b). Lastly, most homes are single-family occupancy, particularly one-story with no basement (n = 3,778; 37.6%), two-story with no basement (n = 2,357; 23.5%), and two-

story with basement (n = 1,001; 10%). A significant portion of the housing stock is also comprised of multi-family, two-unit homes (n = 1,498; 14.9%) (Figure 5c).

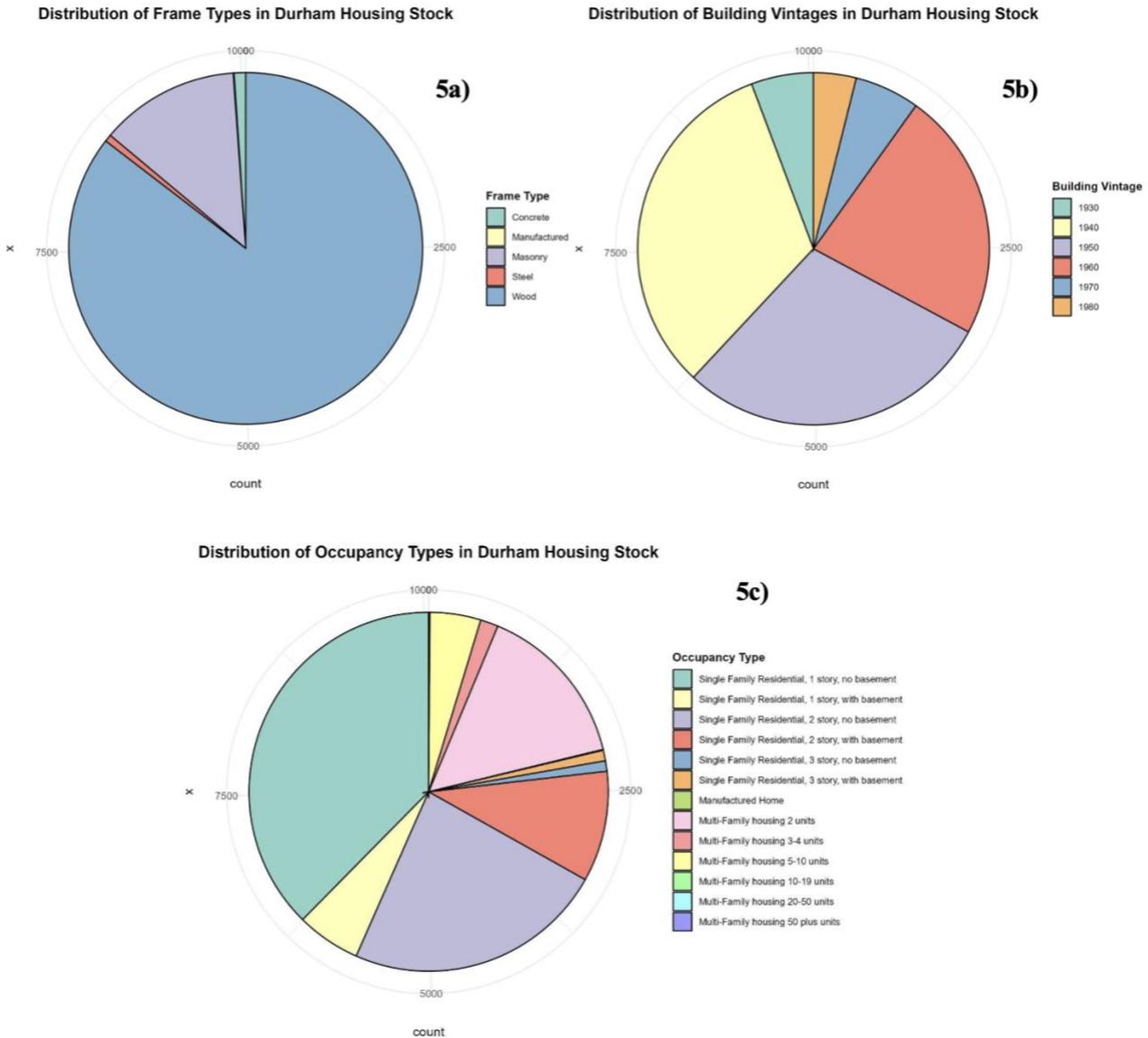


Figure 5. Pie charts illustrating the distributions of building characteristics in the housing stock within Durham’s HOLC boundaries. a) Distribution of frame types. b) Distribution of building vintages. c) Distribution of occupancy types.

### Home Type Prevalence

Our analysis of home type prevalence revealed five home types that were notably more prevalent in redlined areas and four home types that were notably more prevalent in non-redlined areas (Table 4), which could indicate differences in housing investment and construction. While

both single-family and multi-family construction is prevalent in redlined areas, the multi-family home types selected were only prevalent in redlined areas, aligning with the fact that multi-family zoning is more prevalent in redlined areas in general, as it requires less mortgage investment and people of lower socioeconomic status more frequently reside in multi-family buildings compared to those of higher socioeconomic status (Lee et al., 2022).

Not surprisingly, our results also show that single-family homes are more prevalent in non-redlined areas. Further, two-story single-family homes tend to have the highest rates of prevalence in non-redlined areas (Table 4). These disparities may be partially because multi-level single-family homes tend to be of higher value and require more mortgage investment compared to single-story housing.

*Table 4. Comparison of Prevalence of Home Groupings Among Redlined and Non-Redlined Areas in Durham, NC for the Summer Outage Scenario. Percentages depicted in red text indicate higher prevalence in redlined areas compared to non-redlined.*

<b>Home Grouping</b>	<b>% Homes in Redlined Areas</b>	<b>% Homes in Non-Redlined Areas</b>	<b>% Difference</b>
Single-Family 1-Story, Wood Frame, No Basement, 1940s <i>“wood40res1-lsnb”</i>	44.4	26.4	18
Single-Family 2-Story, Wood Frame, with Basement, 1940s <i>“wood40res1-2swb”</i>	5.1	25.7	-20.6
Multi-Family 2-Unit, Wood Frame, 1940s <i>“wood40res3a”</i>	14.0	3	11
Single-Family 1-Story, Wood Frame, No Basement, 1950s <i>“wood50res1-lsnb”</i>	44.6	20.9	23.7
Single-Family, 2-Story, Wood Frame with Basement, 1950s	8.4	33.7	-25.3

“wood50res1-2swb”			
Single-Family, 1-Story, Wood Frame, No Basement, 1960s	44.4	24.0	20.4
“wood60res1-1snb”			
Single-Family, 1-Story, Wood Frame with Basement, 1960s	5.1	13.5	-8.4
“wood60res1-1swb”			
Single-Family, 2-Story, Wood Frame with Basement, 1960s	7.2	22.1	-14.9
“wood60res1-2swb”			
Multi-Family 2-Unit, Wood Frame, 1960s	15.3	1.9	13.4
“wood60res3a”			

### *Summer Outage Results*

#### Baseline Thermal Resilience

Our thermal resilience analysis of homes modeled during the summer power outage without simulated energy efficiency upgrades revealed some variability. For both the first 24 hours of the outage and the total duration of the outage, two out of the five home types more prevalent in redlined areas, wood frame, multi-family, two-unit homes built in the 1940s and 60s (wood40res3a, wood60res3a), exhibited notably higher SDHs on average, both with higher median SDHs compared to home types more prevalent in non-redlined areas and the entire Durham housing stock (“ALL”) (Figure 6). Both home types are wood frame, multi-family, two-unit homes of moderate age. Single-family, one-story homes without basements built in the 1950s and 60s (wood50res1-1snb and wood60res1-1snb), also more prevalent in redlined areas, had elevated SDHs compared to most home types more prevalent in non-redlined areas and the whole housing stock (Figure 6).

In both scenarios, one home type more prevalent in redlined areas, wood frame one-story single-family homes without basements built in the 1940s (wood40res1-1snb), performed better with lower SDHs on average than most other home types, redlined and non-redlined. While this does not align with the other typically redlined home types, it is worth noting that this home type

is one of the most common in the housing stock within Durham's HOLC boundaries (Figure 2). Thus, its energy performance could vary significantly by neighborhood.

### *Winter Outage Results*

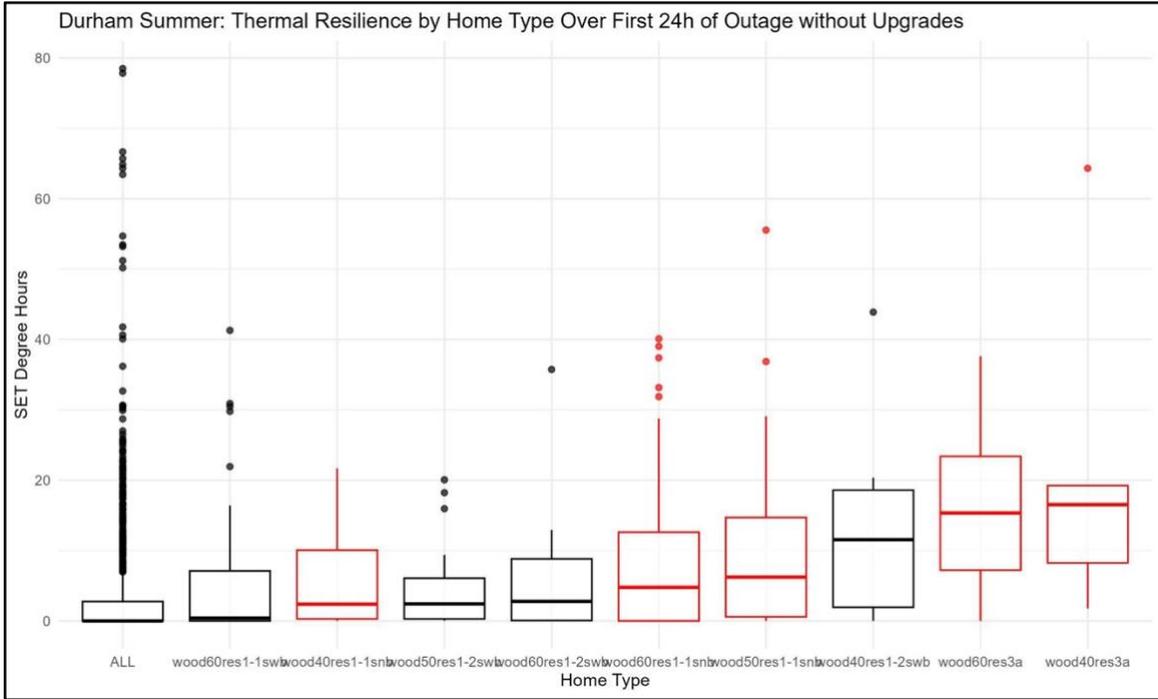
#### Baseline Thermal Resilience

The thermal resilience analysis of homes modeled under the winter power outage scenario revealed similar results to those in the summer outage scenario. For the first 24 hours of the winter outage, two of the five home types, wood frame single-family one-story homes built in the 1950s without basements (wood50res1-1snb), and wood frame multi-family two-unit homes built in the 1940s (wood40res3a), both more prevalent in redlined areas, had the second highest and highest SDHs on average, respectively. The remaining three home types that were more prevalent in redlined areas exhibited SDHs comparable to home types that were more prevalent in non-redlined areas, falling within the middle of the range. However, wood frame single-family one-story homes without basements built in the 1940s (wood40res1-1snb) had the most elevated SDHs of the three and was notably high among all home types. Overall, all five types more prevalent in redlined areas had elevated SDHs compared to the whole housing stock (Figure 7a).

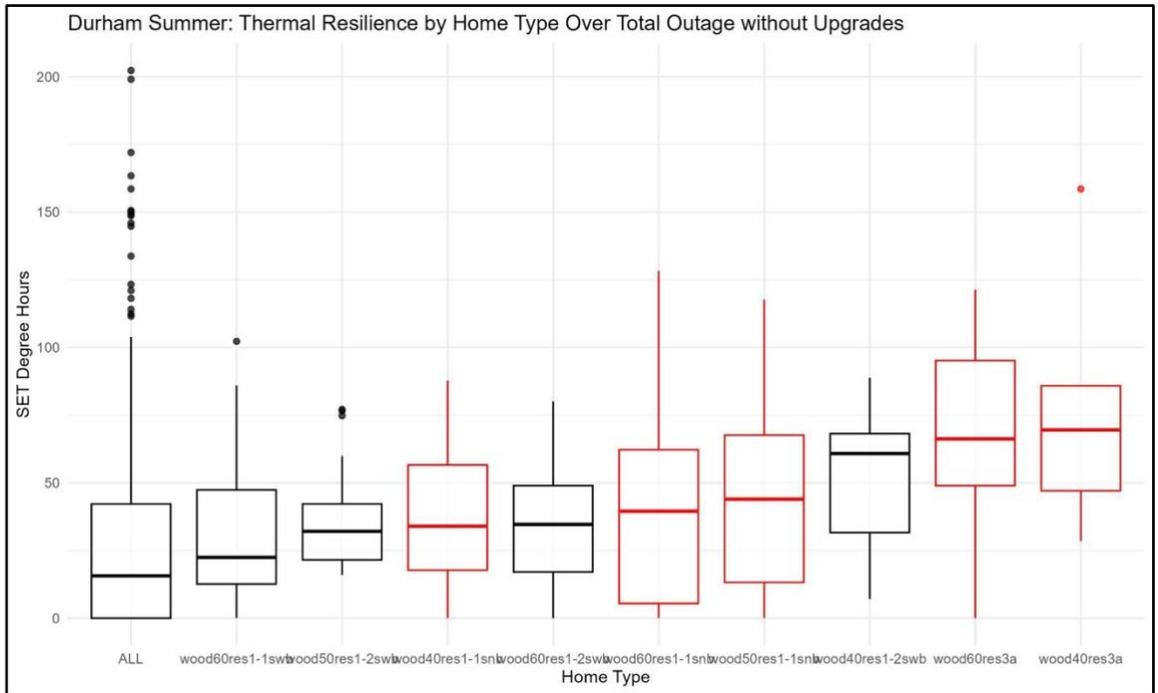
For the total duration of the winter outage, we observed a more consistent pattern. Four of the five home types most prevalent in redlined areas had the highest SDHs compared to home types that were more prevalent in non-redlined areas and the whole housing stock. Wood frame multi-family two-unit homes built in the 1960s (wood60res3a) had a notably lower SDH distribution than expected compared to the patterns observed in the summer outage. For the summer outage, this home type consistently had one of the highest overall distributions of SDHs (Figure 7b). In contrast, it had one of the lowest for the total duration of the winter outage. While this could be indicative of this type's performance in hot vs. cold weather, it is important to note, however, the difference in scales between the two outages, which may have resulted from different weather inputs in ResStock between summer and winter.

*Thermal Resilience Results (Summer Outage, No Upgrades)*

6a)



6b)

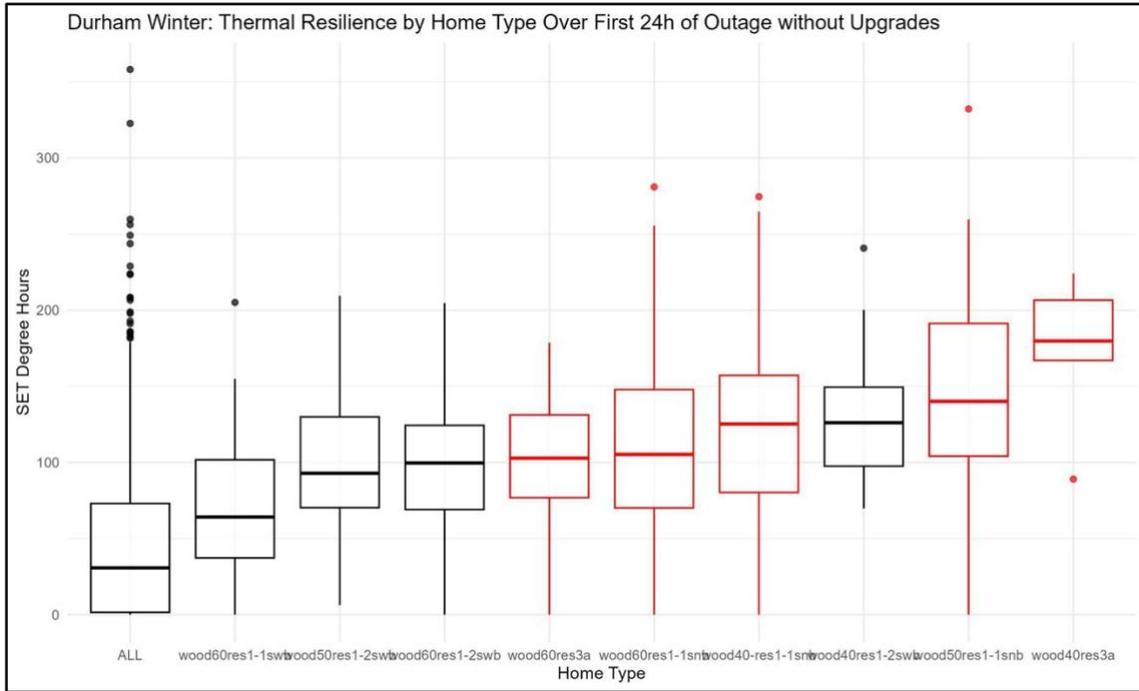


*Figure 6. Summer outage boxplots depicting the distributions of SET Degree Hour measurements for home types with notable prevalence differences between redlined and non-*

redlined areas. a) Results for the first 24 hours of the outage without energy efficiency upgrades. b) Results for the total course of the outage without energy efficiency upgrades. Boxplots in red indicate home types are more prevalent in redlined neighborhoods than in non-redlined neighborhoods in black.

**Thermal Resilience Results (Winter Outage, No Upgrades)**

**7a)**



7b)

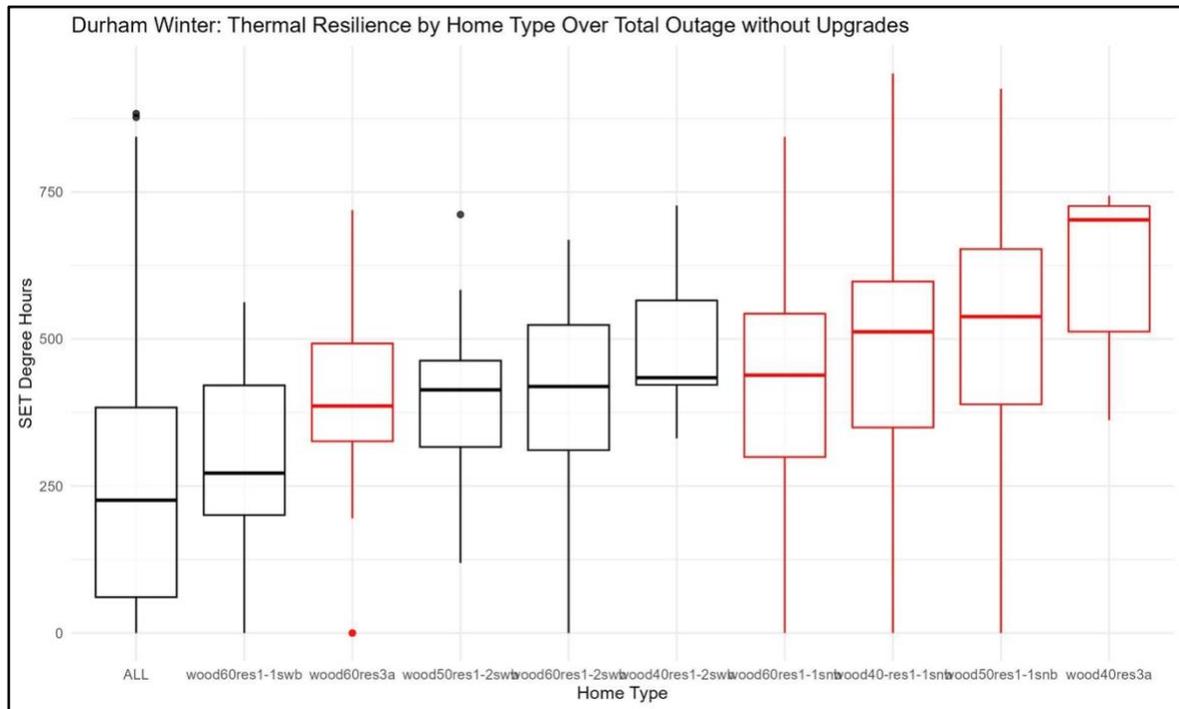


Figure 7. Winter outage boxplots depicting the distributions of SET Degree Hour measurements for home types with notable prevalence differences between redlined and non-redlined areas. a) Results for the first 24 hours of the summer power outage scenario without energy efficiency upgrades. b) Results for the total outage without energy efficiency upgrades. Boxplots in red indicate home types are more prevalent in redlined neighborhoods than in non-redlined neighborhoods.

### Energy Efficiency Upgrade Modeling

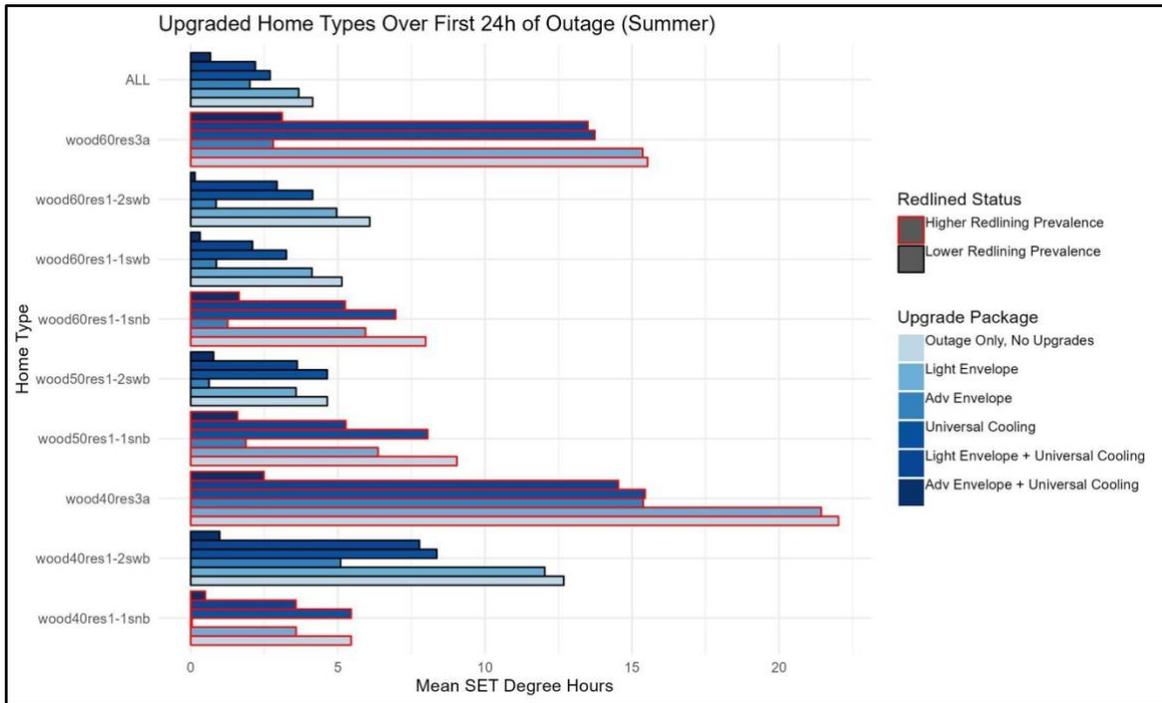
Our modeling of energy efficiency upgrades found that, compared to no upgrades, all upgrade packages decreased the average SDHs for each home grouping across the first 24 hours and the entirety of each summer and winter outage (Figures 8 & 9). This was especially notable for the Advanced Envelope with Universal Cooling package, the most robust package upgrades simulated. Tables 5-8 show the percentage differences in mean SDH measurements by home type for each outage and QOI between a no-upgrade scenario and the Advanced Envelope and Universal Cooling upgrade scenario. While we observe significantly reduced SDHs in home types more prevalent in redlined areas than non-redlined, there is no clear trend indicating that the former experiences significantly greater percentage SDH reductions than the latter.

These results indicate that, while home groupings disproportionately prevalent among redlined areas perform less efficiently on average, the addition of energy efficiency upgrades shows significant promise for bolstering the thermal resilience of these homes. However, these results do not provide a clear indication that home types that are more prevalent in redlined areas

experience more significant benefits of upgrades than those of homes that are more prevalent in non-redlined areas. Additional research is needed to understand the complex interactions of home types and demographics before directing investment in efficiency retrofits to certain home types, especially as city and neighborhood demographics change over time.

***Thermal Resilience Results with Energy Efficiency Upgrades***

**8a)**



8b)

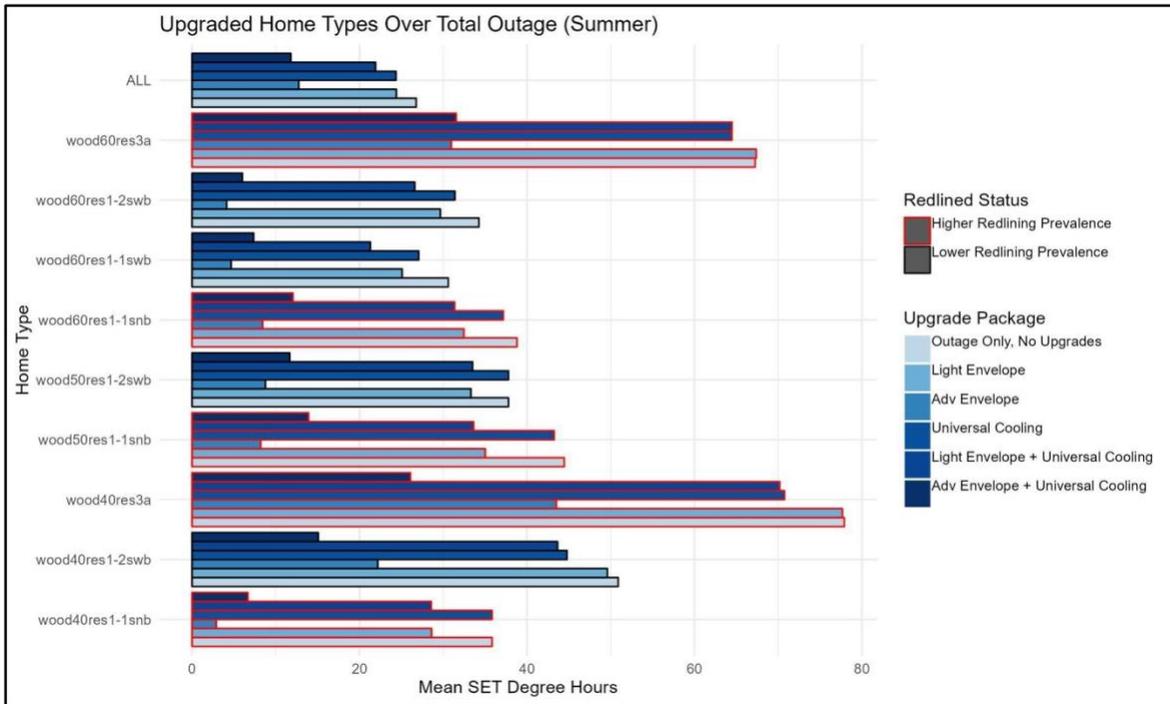
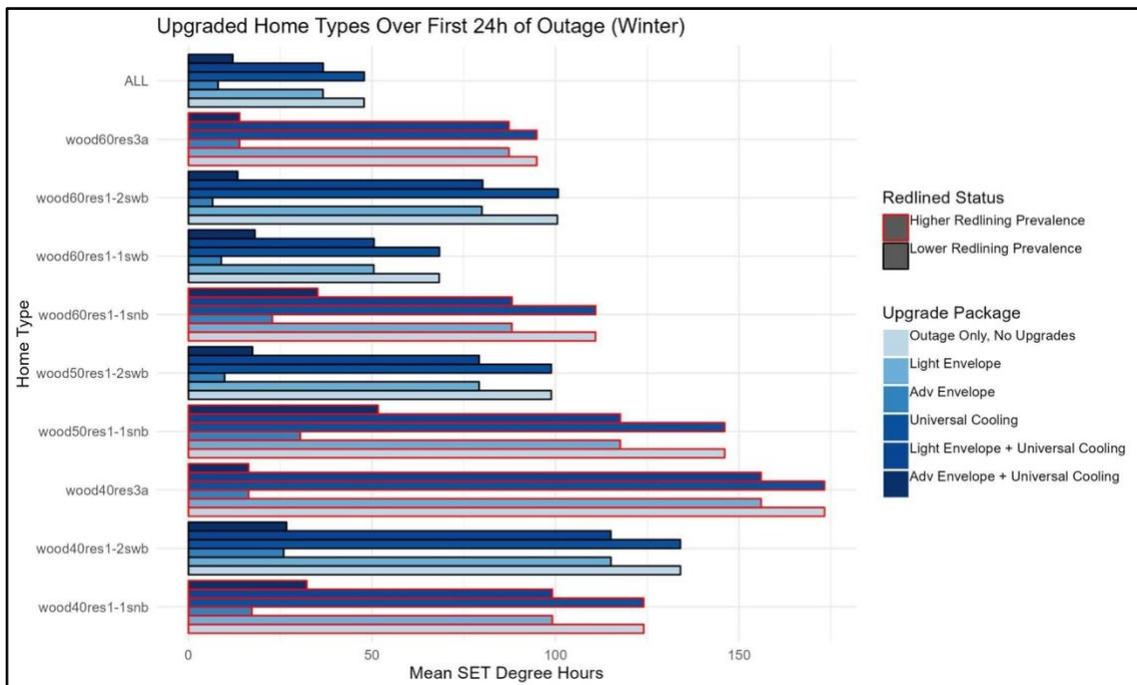


Figure 8. Summer outage plot showing changes in mean SET Degree Hours with the addition of energy efficiency upgrade packages, by home type. a) Results for the first 24 hours of the outage. b) Results for the total outage. Bars outlined in red represent results for home types more prevalent in redlined neighborhoods compared to non-redlined neighborhoods.

9a)



9b)

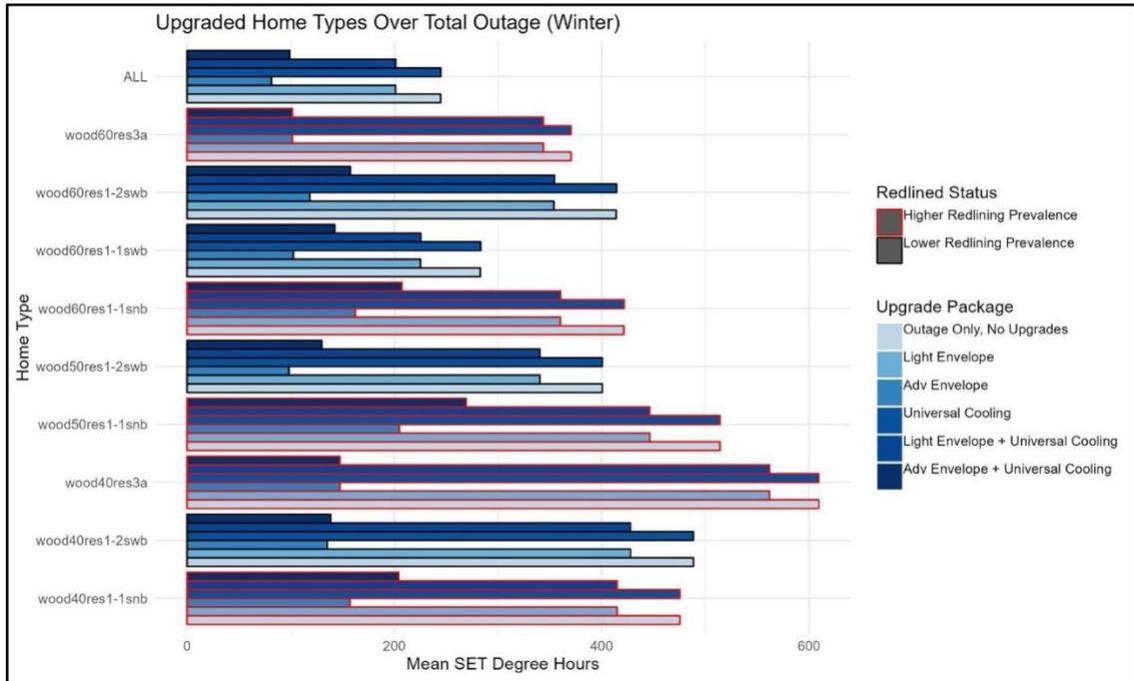


Figure 9. Winter outage plot showing changes in mean SET Degree Hours with the addition of energy efficiency upgrade packages by home type. a) Results for the first 24 hours of the outage. b) Results for the total outage. Bars outlined in red represent results for home types more prevalent in redlined neighborhoods compared to non-redlined neighborhoods.

Table 5. Percentage differences in mean SET Degree-Hour measurements between a no-upgrade scenario and an Advanced Envelope + Universal Cooling upgrade scenario. Results for the first 24 hours of the summer outage. Home types in red are more prevalent in redlined areas than in non-redlined areas.

Mean SDH Differences Between No Upgrades and Advanced Envelope + Universal Cooling by Home Type (Summer, First 24h)				
Home Type	Mean SET Degree-Hours		Percentage Difference	
	Mean SDH (No Upgrades)	Mean SDH (Adv. Envelope + UC)	Percentage Difference (%)	
ALL	4.15	0.67	-83.89	
wood40res1-1snb	5.45	0.49	-90.96	
wood40res1-2swb	12.68	0.98	-92.24	
wood40res3a	22.02	2.49	-88.70	
wood50res1-1snb	9.04	1.59	-82.42	
wood50res1-2swb	4.64	0.78	-83.27	
wood60res1-1snb	7.98	1.64	-79.44	
wood60res1-1swb	5.14	0.32	-93.80	
wood60res1-2swb	6.08	0.14	-97.65	
wood60res3a	15.53	3.11	-79.99	

Table 6. Percentage differences in mean SET Degree-Hour measurements between a no-upgrade scenario and an Advanced Envelope + Universal Cooling upgrade scenario. Results for the total duration of the summer outage. Home types in red are more prevalent in redlined areas than in non-redlined areas.

Mean SDH Differences Between No Upgrades and Advanced Envelope + Universal Cooling by Home Type (Summer, Total Outage)				
Home Type	Mean SET Degree-Hours		Percentage Difference	
	Mean SDH (No Upgrades)	Mean SDH (Adv. Envelope + UC)	Percentage Difference (%)	
ALL	26.76	11.80	-55.90	
wood40res1-1snb	35.83	6.67	-81.40	
wood40res1-2swb	50.89	15.07	-70.38	
wood40res3a	77.89	26.08	-66.52	
wood50res1-1snb	44.44	13.92	-68.68	
wood50res1-2swb	37.79	11.67	-69.12	
wood60res1-1snb	38.80	12.05	-68.93	
wood60res1-1swb	30.60	7.35	-75.97	
wood60res1-2swb	34.27	6.01	-82.47	
wood60res3a	67.25	31.54	-53.10	

Table 7. Percentage differences in mean SET Degree-Hour measurements between a no-upgrade scenario and an Advanced Envelope + Universal Cooling upgrade scenario. Results for the first 24 hours of the winter outage. Home types in red are more prevalent in redlined areas than in non-redlined areas.

Mean SDH Differences Between No Upgrades and Advanced Envelope + Universal Cooling by Home Type (Winter, First 24h)			
Home Type	Mean SET Degree-Hours		Percentage Difference
	Mean SDH (No Upgrades)	Mean SDH (Adv. Envelope + UC)	Percentage Difference (%)
ALL	47.84	12.08	-74.75
wood40res1-1snb	124.03	32.23	-74.01
wood40res1-2swb	134.04	26.74	-80.05
wood40res3a	173.29	16.39	-90.54
wood50res1-1snb	146.10	51.66	-64.64
wood50res1-2swb	98.85	17.47	-82.33
wood60res1-1snb	110.89	35.22	-68.24
wood60res1-1swb	68.30	18.12	-73.47
wood60res1-2swb	100.50	13.43	-86.64
wood60res3a	94.89	13.92	-85.33

Table 8. Percentage differences in mean SET Degree-Hour measurements between a no-upgrade scenario and an Advanced Envelope + Universal Cooling upgrade scenario. Results for the total duration of the winter outage. Home types in red are more prevalent in redlined areas than in non-redlined areas.

Mean SDH Differences Between No Upgrades and Advanced Envelope + Universal Cooling by Home Type (Winter, Total Outage)			
Home Type	Mean SET Degree-Hours		Percentage Difference
	Mean SDH (No Upgrades)	Mean SDH (Adv. Envelope + UC)	Percentage Difference (%)
ALL	244.60	99.06	-59.50
wood40res1-1snb	475.45	204.25	-57.04
wood40res1-2swb	488.57	138.51	-71.65
wood40res3a	609.38	147.39	-75.81
wood50res1-1snb	514.09	269.31	-47.61
wood50res1-2swb	400.61	130.01	-67.55
wood60res1-1snb	421.35	207.25	-50.81
wood60res1-1swb	282.88	142.47	-49.63
wood60res1-2swb	413.93	157.61	-61.92
wood60res3a	370.35	101.59	-72.57

## **Challenges and Limitations**

While this study provides valuable insight into housing stock performance disparities between redlined and non-redlined areas, we experienced some challenges and found some limitations in the methodologies used. First, data availability and granularity proved to be challenging. As mentioned, the survey data on demographics, building characteristics, energy use, and performance used to inform modeling in ResStock were collected at the PUMA level, a lower level of granularity compared to the Census tract or block. Ideally, to fully understand housing stock performance, it would be most beneficial to use data collected from individual homes. These data, however, were unavailable for this project. Further, as also previously stated, ResStock results are statistical representations, not actual performance measurements, of the housing stock in each location. While modeling the housing stock is beneficial for this study, there may be inherent discrepancies between models and “real” homes.

Additionally, because zoning and housing policies are intentional decisions, there is little to no randomness within the housing stock and where certain home types are distributed in each city. Thus, traditional statistical tests may not be appropriate for assessing significance, presenting a challenge for validating prevalence differences. Lastly, in the decades since HOLC maps were drawn and redlining was formally practiced, cities have undergone significant expansion and changes to building and neighborhood characteristics, mainly due to processes like gentrification. When modeling homes using recently collected data, it is possible that housing stock changes over time are not fully captured. However, we and other researchers find that redlining has created entrenched patterns of investment disparities, translating into housing quality and energy efficiency disparities, that largely transcend the effects of neighborhood and building changes over time.

## **Conclusions, Applications, and Future Research**

Our results indicate that some home types that are more prevalent in redlined areas perform less efficiently than those in non-redlined areas on average when modeled under coincident extreme temperature and power outage scenarios. However, not all primarily redlined home types performed worse than primarily non-redlined homes. These results provide insight into potential relationships between residential energy efficiency and residents’ resilience in the face of extreme temperature events, but further study is needed to understand these relationships comprehensively. While this study included results for Durham, NC only, we will expand our analyses to Tampa, FL, Chicago, IL, and Seattle, WA, to investigate relationships between redlining and residential energy efficiency across different climate zones, social and physical vulnerabilities, and housing stocks.

Additionally, our simulation of energy efficiency upgrades indicated that notable improvements to building envelopes could be made, bolstering the resilience of homes and their

residents, including homes primarily situated in redlined neighborhoods. However, the upgrade results did not provide sufficient evidence that home types that are more prevalent in redlined areas confer more significant benefits from upgrades than home types that are more prevalent in non-redlined areas. While we can confidently conclude that primarily redlined home types benefit significantly from upgrades, we cannot confidently distinguish between primarily redlined and non-redlined home types to prioritize retrofits for specific home types. Additional studies, including other locations, climate zones, and upgrades, can help clarify the results of this study and potentially aid in understanding if there are significant differences in the benefits of upgrading homes. Once potential differences are identified, such studies could help inform policies and programs providing home retrofit and weatherization assistance.

The disparities in residential thermal resilience observed in this study may be linked to adverse downstream effects on residents of redlined neighborhoods, indicating a broader systemic issue of resilience inequity, which requires additional study. With a hindered ability to withstand and adapt to extreme temperature events due to gaps in building envelopes, residents of historically redlined neighborhoods may be disproportionately exposed to extreme temperatures. When layered with other patterns of inequity, such as health indicators or energy burden, residential energy efficiency disparities could have a cumulative effect on overall resilience.

Overall, this study identified potential inequities underlying residential energy efficiency associated with redlining and spatial differences in prevalence home construction characteristics. These inequities can threaten human health, energy affordability, and overall resilience during extreme temperature events. Paired with additional studies, this research can help inform policies and practices to equitably build resilience for communities most affected by the effects of extreme temperatures.

## **Acknowledgments**

This work was funded by the U.S. Department of Energy's Building Technologies Office. The authors are appreciative of the support of Jeremy Williams, Michael Reiner, and Christopher Perry at DOE for this research.

I want to thank my advisor, Dr. Brian McAdoo, for his guidance and mentorship throughout this project and Dr. Betsy Albright for her support. I would also like to thank my NREL team, including Eliza Hotchkiss, Dr. Philip White, Jordan Burns, Dr. Dana-Marie Thomas, and Dr. Jordan Cox, for their contributions and support. Lastly, I would like to thank my family, friends, and classmates for their encouragement and support during my time at Duke.

## References

1. Aaronson, D., Hartley, D., & Mazumder, B. (2021). The Effects of the 1930s HOLC “Redlining” Maps. *American Economic Journal: Economic Policy*, 13(4), 355–392. <https://doi.org/10.1257/pol.20190414>
2. Adams R.M., Evans C.M., Mathews M.C., Wolkin A., Peek L. (2021). Mortality From Forces of Nature Among Older Adults by Race/Ethnicity and Gender. *J Appl Gerontol*, 40(11):1517-1526. doi: 10.1177/0733464820954676.
3. Adua, L., De Lange, R., & Aboyom, A. I. (2022). Differentiated disadvantage: Class, race, gender, and residential energy efficiency inequality in the United States. *Energy Efficiency*, 15(7), 49. <https://doi.org/10.1007/s12053-022-10056-7>
4. American Housing Survey: Heating, Air Conditioning, and Appliances. Last updated June 6, 2020.
5. Bednar, D. J., Reames, T. G., & Keoleian, G. A. (2017). The intersection of energy and justice: Modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy and Buildings*, 143, 25–34. <https://doi.org/10.1016/j.enbuild.2017.03.028>
6. Berko, J. (2014). *Deaths Attributed to Heat, Cold, and Other Weather Events in the United States, 2006–2010*. 76.
7. "Billion-Dollar Weather and Climate Disasters: Events". NOAA. February 2022.
8. Centers for Disease Control and Prevention (CDC). (n.d.). *Picture of America Report: Heat-Related Illness*. Accessed August 15, 2023. [https://www.cdc.gov/pictureofamerica/pdfs/picture\\_of\\_america\\_heat-related\\_illness.pdf](https://www.cdc.gov/pictureofamerica/pdfs/picture_of_america_heat-related_illness.pdf)
9. Chakraborty, T., Newman, A. J., Qian, Y., Hsu, A., & Sheriff, G. (2023). Residential segregation and outdoor urban moist heat stress disparities in the United States. *One Earth*, 6(6), 738–750. <https://doi.org/10.1016/j.oneear.2023.05.016>
10. Cohen, J., Agel, L., Barlow, M., Garfinkel, C. I., & White, I. (2021). Linking Arctic variability and change with extreme winter weather in the United States. *Science*, 373(6559), 1116–1121. <https://doi.org/10.1126/science.abi9167>
11. Cong, S., Nock, D., Qiu, Y. L., & Xing, B. (2022). Unveiling hidden energy poverty using the energy equity gap. *Nature Communications*, 13(1), 2456. <https://doi.org/10.1038/s41467-022-30146-5>
12. Davis R.E., Markle E.S., Windoloski S., Houck M.E., Enfield K.B., Kang H., et al. (2020). A comparison of the effect of weather and climate on emergency department visitation in Roanoke and Charlottesville, Virginia. *Environ Res*, 191:110065.
13. Drehobl, A., & Ross, L. (2016). *Lifting the High Energy Burden in America’s Largest Cities: How Energy Efficiency Can Improve Low Income and Underserved Communities*. American Council for an Energy-Efficient Economy.
14. Energy Information Administration (EIA). *Electric Power Annual 2021*. (n.d.).

15. Falconer, R., Freedman, A. (2023, June 19). *Heat Wave Fuels Deadly Storms and Power Outages Across Southern U.S.* Axios. <https://www.axios.com/2023/06/18/heat-wave-storms-power-outages-southern-us-texas>
16. Gagge, A. P. (1973). Standard Effective Temperature - A Single Temperature Index of Temperature Sensation and Thermal Discomfort *Proc. of The CIB Commission W 45 (Humen Requirements) Symposium, Thermal Comfort and Moderate Heat Stress, Building Research Sta.* 229-250 <https://cir.nii.ac.jp/crid/1573668924242133120>.
17. Gasparrini, A., et al. (2015). Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet* 386(9991):369–375.
18. Graff, A. (2021, June 28). It's so hot in the Pacific Northwest that roads are buckling. *San Francisco Chronicle*.
19. Gronlund, C.J. (2014). Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review. *Curr Epidemiol Rep*, 1(3):165-173. doi: 10.1007/s40471-014-0014-4.
20. Harrison, C., & Popke, J. (2011). “Because You Got to Have Heat”: The Networked Assemblage of Energy Poverty in Eastern North Carolina. *Annals of the Association of American Geographers*, 101(4), 949–961. <https://doi.org/10.1080/00045608.2011.569659>
21. Hernández, D. (2016). Understanding ‘energy insecurity’ and why it matters to health. *Social Science & Medicine*, 167, 1–10. <https://doi.org/10.1016/j.socscimed.2016.08.029>
22. “Home Owners Loan Corporation (HOLC) | Encyclopedia.Com.” Accessed April 26, 2024. <https://www.encyclopedia.com/economics/encyclopedias-almanacs-transcripts-and-maps/home-owners-loan-corporation-holc>.
23. Jones, D. (June 26, 2021). "Record Heat Wave Set To Scorch Pacific Northwest To Southern California". *NPR.org*.
24. Lachacz, A. (2021, July 15). Toll of the heat wave: wildfires, 911 calls, and sidewalks buckling. *CTV News Edmonton*.
25. Lee, E. K., Donley, G., Ciesielski, T. H., Gill, I., Yamoah, O., Roche, A., Martinez, R., & Freedman, D. A. (2022). Health outcomes in redlined versus non-redlined neighborhoods: A systematic review and meta-analysis. *Social Science & Medicine*, 294, 114696. <https://doi.org/10.1016/j.socscimed.2021.114696>
26. Lewis, J., Hernández, D., Geronimus, A.T. (2019). Energy efficiency as energy justice: Addressing racial inequities through investments in people and places. *Energy Efficiency*, 13, 419–432.
27. Li, D., Newman, G. D., Wilson, B., Zhang, Y., & Brown, R. D. (2022). Modeling the relationships between historical redlining, urban heat, and heat-related emergency department visits: An examination of 11 Texas cities. *Environment and Planning B: Urban Analytics and City Science*, 49(3), 933–952. <https://doi.org/10.1177/23998083211039854>

28. Low Income Home Energy Assistance Program (LIHEAP).  
<https://www.liheap.org/about>. Accessed August 14, 2023.
29. Manley, G., (1958). On the frequency of snowfall in metropolitan England. Q. J. R. Meteorol. Soc. 84, 70–72. <http://dx.doi.org/10.1002/qj.49708435910>.
30. Mitchell, B. (2018). *HOLC “Redlining” Maps: The Persistent Structure of Segregation and Economic Inequality*. National Community Reinvestment Coalition.  
<https://ncrc.org/holc/>
31. NERC. (May 2023) 2023 Summer Reliability Assessment. Accessed from  
[https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC\\_SRA\\_2023.pdf](https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf)
32. Overbey, D. Standard Effective Temperature (SET) and Thermal Comfort | 2016-01-18 | Building Enclosure. <https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/85635-standard-effective-temperature-set-and-thermal-comfort>. Accessed 8 Mar. 2024.
33. Popovich, N., Choi-Schagrin, W. (2021, August 11). Hidden Toll of the Northwest Heat Wave: Hundreds of Extra Deaths. *The New York Times*. ISSN 0362-4331.
34. Present, E., White, P., Harris, C., Adhikari, R., Lou, Y., Liu, L., Fontanini, A., Moreno, C., Robertson, J., Maguire, J. (2024). ResStock Dataset 2024.1 Documentation. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-88109.  
<https://www.nrel.gov/docs/fy24osti/88109.pdf>.
35. Reames, T. G. (2016). Targeting energy justice: Exploring spatial, racial/ethnic and socioeconomic disparities in urban residential heating energy efficiency. *Energy Policy*, pp. 97, 549–558.
36. Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., Shelby, J., (2018). The National Solar Radiation Data Base (NSRDB). *Renew. Sustain. Energy Rev.* 89, 51–60. <https://doi.org/10.1016/j.rser.2018.03.003>
37. Tansakul, V., Myers, A., Tennille, S., Denman, M., Hamaker, A., Huihui, J., Medlen, K., Allen, K., Redmon, D., Chinthavali, S., Coletti, M., Grant, J., Lee, M., Maguire, D., Newby, S., Stahl, C., Bhaduri, B., & Sanyal, J. (2023). *EAGLE-I Power Outage Data 2014 - 2022*. United States: N. p. doi:10.13139/ORNLNCCS/1975202.
38. Thompson, F. (2021, June 28). Excessive heat impacts travel, services across the region. *Q13 Fox*.
39. U.S. Department of Energy (DOE) Low-Income Energy Affordability Data (LEAD) Tool. <https://www.energy.gov/scep/slsc/low-income-community-energy-solutions#:~:text=Energy%20burden%20is%20defined%20as,which%20is%20estimated%20at%203%25>.
40. U.S. Department of Energy (DOE). (2021, February 21). Situation Report: Extreme Cold & Winter Weather. [https://www.energy.gov/sites/prod/files/2021/02/f83/TLP-WHITE\\_DOE%20Situation%20Update\\_Cold%20%20Winter%20Weather\\_%236.pdf](https://www.energy.gov/sites/prod/files/2021/02/f83/TLP-WHITE_DOE%20Situation%20Update_Cold%20%20Winter%20Weather_%236.pdf). Accessed August 18, 2023.

42. U.S. Department of Energy (DOE). Weatherization Assistance Program (WAP). <https://www.energy.gov/scep/wap/weatherization-assistance-program>. Accessed August 14, 2023.
43. U.S. Energy Information Administration, *Residential Energy Consumption Survey 2015*.
44. U.S. Environmental Protection Agency (EPA) (2023a). *Climate Change Indicators: Weather and Climate*. <https://www.epa.gov/climate-indicators/weather-climate#:~:text=Rising%20global%20average%20temperature%20is,with%20human%20Dinduced%20climate%20change>. Last updated July 2023. Accessed August 15, 2023.
45. U.S. Environmental Protection Agency (EPA, 2023b). *Climate Change Indicators: Heat Waves*. <https://www.epa.gov/climate-indicators/climate-change-indicators-heat-waves>. Last updated July 2023 and accessed August 15, 2023.
46. U.S. Environmental Protection Agency (EPA, 2021). *Climate Change Indicators: Cold-Related Deaths*. <https://www.epa.gov/climate-indicators/climate-change-indicators-cold-related-deaths#ref2>. Last updated April 2021. Accessed April 26, 2024.
47. Woolf, S., Morina, J., French, E., Funk, A., Sabo, R., Fong, S., Hoffman, J., Chapman, D., Krist, A. (2023). The Health Care Costs of Extreme Heat. Center for American Progress. <https://www.americanprogress.org/article/the-health-care-costs-of-extreme-heat/#:~:text=Extrapolated%20nationally%2C%20heat%20event%20days,health%20care%20costs%20each%20summer>.
48. Zeitlin, M. (2023, June 21). *How the Texas Power Grid Has Dodged Disaster So Far*. Heatmap News. <https://heatmap.news/economy/how-the-texas-power-grid-has-dodged-disaster-so-far>