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

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ABSTRACT

Residential energy efficiency is a component of individual and community resilience during extreme temperature events. However, the value of efficiency in resilience scenarios needs to be better understood. Less energy-efficient homes require more time to heat or cool during extreme temperature events due to gaps in building envelopes. More intensive energy use to withstand these events may contribute to energy burden, especially for those already disproportionately exposed to extreme temperatures. In the 1930s, the Homeowners' Loan Corporation developed mortgage lending maps of over 200 U.S. cities, scoring neighborhoods based on the perceived lending risk associated with demographic profiles and creating "redlined" neighborhoods. Over several decades, redlined neighborhoods primarily occupied by low-income and non-white residents received less investment than non-redlined neighborhoods. In this study, we explore how historical redlining has left a legacy of disinvestment in housing, which may contribute to inequities in residential energy efficiency compared to non-redlined neighborhoods and expose residents to extreme conditions during resilience events. Using the National Renewable Energy Laboratory's ResStock™ tool and geospatial analysis, we model temperature change over time in various building types under extreme temperature and power outage scenarios. We then examine performance differences for specific building types that are notably more prevalent in redlined and non-redlined neighborhoods in four cities with documented redlining practices: Durham, NC; Tampa, FL; Chicago, IL; and Seattle, WA. We aim to identify areas with the greatest need for efficiency upgrades, which can inform retrofit investments. Overall, this analysis will provide insight into potential inequities underlying residential energy efficiency associated with redlining practices. Layered with other consequences of neighborhood disinvestment, such as urban heat island effects, these inequities can threaten human health, energy affordability, and overall resilience during extreme temperature events.

INTRODUCTION

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 (Mitchell, 2018). 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). Maps included legends for residential security where green areas were scored as "A-first grade," indicating homes where investments were considered secure. The rankings included A-first grade in green, B-second grade in blue, C-third grade in yellow, and D-fourth grade in red. Neighborhoods predominantly occupied by low-income and non-white residents were considered "hazardous" or too risky for lending purposes. As a result, these neighborhoods were delineated by the D rating and highlighted in red, leading to the terminology of "redlined" neighborhoods for lenders to avoid during lending reviews, as illustrated in Figure 1. 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 neighborhoods with a D-rating 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).

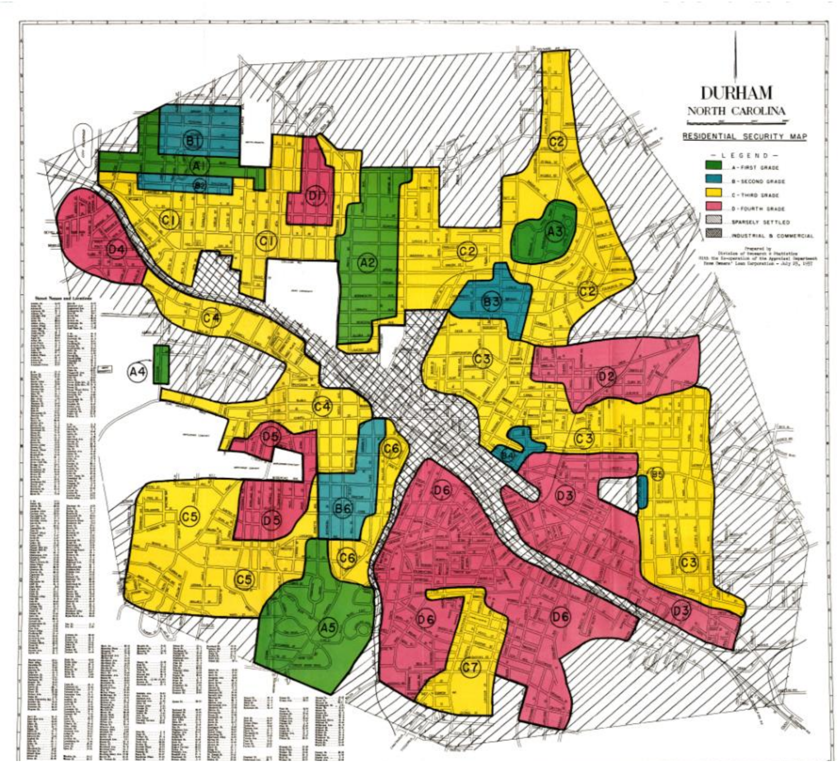

Figure 1. HOLC residential security Map of Durham, NC Digitized and sourced from the University of Richmond's Mapping Inequality project.

The systemic 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 currently lack appropriate adaptation solutions (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 in lower income brackets.

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 essential 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 (Gasparrini 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 heatwave 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 deaths due to heat-related illnesses (Popovich & Choi-Schagrin, 2021) and $8.9 billion in damages (NOAA, 2022), 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, 2021).

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 [in the U.S.] 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). Across the nation, 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 the U.S.

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). Across the nation, low-income households spend a more significant portion of their income on home energy costs than other households spend, a metric known as energy burden (DOE, 2019). People of color also experience a disproportionately high energy burden. 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 demographic categories (e.g., 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. The HOLC color-coded risk grades used 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 legacy consequences. Residential segregation persists in most historically redlined cities, as do associated systemic inequities (Li et al., 2022).

Redlined areas tend to exist 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).

Disparities in neighborhood investment are often reflected in housing quality (Li et al., 2022). 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). 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 (Bednar et al., 2017). Another study found EUI and income to be inversely related, and this relationship is stronger among black households, especially households headed by black females, 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 more significant 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 UHI effects and reduce the energy burden in homes, residents can seek energy bill assistance from state utility regulators and support from federal agencies (e.g., DOE and HHS) that 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 established energy efficiency standards and updated building codes, some studies have shown that access to energy efficiency technology varies by race and ethnicity and across income gradients (Lewis et al., 2019; Reames, 2016). Thus, it is important to parse out which homes and residents have the greatest need for upgrades to achieve more equitable resilience outcomes.

Research Gaps

While there is a demonstrated need for neighborhood-wide investment in underserved communities, namely for energy efficiency upgrades, there is a 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 hypothesized 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 compared energy performance in different types of residential buildings with varying prevalence in redlined and non-redlined areas in four cities with historical redlining practices: Chicago, IL; Durham, NC; Seattle, WA; and Tampa, FL. These cities were selected to represent a diverse range of climate zones susceptible to extreme heat and cold, population sizes and demographics, and residential building stocks. Our primary objective was to model scenarios of potential differences in residential energy performance between redlined and non-redlined areas during extreme temperature events. Going forward, 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 provides insights into the potential relationships between historical redlining, energy efficiency inequities, and implications for individual and community resilience against extreme temperature events.

METHODOLOGY OVERVIEW

ResStock Tool Description

The National Renewable Energy Laboratory (NREL)'s ResStock™ tool was used to model residential energy performance during coincident power outages and extreme temperature events. ResStock uses a physics-based simulation modeling tool, EnergyPlus^{TM}, 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 model the building stock for regions and environmental conditions. The model is 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 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, a ratio of 1:242. This ratio was used to generate statistically representative models of the building stock and building energy performance.

ResStock can model baseline energy use and energy efficiency upgrades, such as the addition of insulation, cooling services, heat pumps, sealing, and electrification. ResStock was used to analyze the impacts of envelope improvements on home energy performance under extreme temperatures in redlined areas compared to those historically graded "A" or "B" (i.e., non-redlined areas).

ResStock was used to model home characteristics under combined extreme temperatures that coincide with power outages in the four representative cities. Outage durations (e.g., 72 hours) were assigned during summer and winter seasons to account for extreme temperature events and to understand the thermal resilience of residential buildings in the different climate zones selected. Histograms of power outages were compiled using the Environment for Analysis of Geo-Located Energy Information (EAGLE-I) dataset (Tansakul, 2023) to inform durations and more prolonged than average outages were used to assess the long-term consequences of an outage on the thermal performance of residential buildings. Weather data from the National Solar Radiation Database (NSRDB) was used for the period coinciding with each outage, which incorporates NREL's Physical Solar Model (PSM) to generate temporal and spatial data for regional solar radiation climates (Sengupta et al., 2018).

A central focus of the ResStock outputs is the Standard Effective Temperature (SET). SET is 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 (Gagge et al., 1973). 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). "Livable" or comfortable SET degrees are between 54°F and 86°F (ANSI/ASHRAE Standard 55-2010).

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 while indoors. 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, defined as Quantity of Interest 1 (QOI1), and the first 24 hours of the outage, defined as Quantity of Interest 2 (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 1.

Table 1. Energy efficiency upgrade packages included in ResStock. Adapted from ResStock technical documentation.

Upgrade Package	Summary
Measure 1: Light Touch Envelope	● Attic floor insulation up to International Energy Conservation Code (IECC) - Residential 2021 levels for dwelling units with vented attics and lower-performing insulation ● General air sealing: 30% total reduction in ACH50 for dwelling units with greater than 10 ACH50
Measure 2: Advanced Envelope	● Everything in Measure 1 except for general air sealing ● 1” exterior extruded polystyrene (XPS) insulation (R-5/in) for wall insulation of less than R-19 ● ENERGY STAR windows (v7) ● Insulate finished attics and cathedral ceilings to R-30 ● Air seal to IECC 2021 requirements with energy recovery ventilator (ERV) added
Measure 3: Universal Cooling	● 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 ● 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

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. GIS polygons were compiled for Chicago, Durham, Seattle, and Tampa. Spatially correlated structure data was 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. Data was collected for Cook County (Chicago), Durham County (Durham), Hillsborough County (Tampa), and King County (Seattle) and selected for residential structures only, to align with the ResStock PUMA level analysis.

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 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 alignment 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.

Code was developed in R to cluster residential buildings based on the characteristics described in Table 2 and calculate the prevalence of different characteristics based on geographic location. Building characteristics with more than a 10% difference in prevalence between redlined and non-redlined areas were identified for deeper examination in ResStock SDH results. Identifiers were developed for the NSI for home types according to a) the combinations of building characteristics and b) the standard structure occupancy used by FEMA (NB: a complete list of identifiers is available in the NSI technical documentation). An example of an NSI identifier is wood40res1-1swb, which indicates a single-family, wood frame, one-story home with a basement built in the 1940s. These identifiers were used in the ResStock model to inform the home types that are most common in historically redlined areas.

Table 2. Building characteristics chosen for examination in both National Structure Inventory and ResStock data.

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

Once housing types with significant 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 visualization was 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

Thermal Resilience in Historically Redlined Cities

The thermal performance of home types within each representative city is summarized in this section. In Chicago, IL, three home types were found to be notably more (>10% difference) prevalent in redlined areas compared to non-redlined areas: brick one-story single-family homes with basements built in the 1950s, brick multi-family two-unit homes built in the 1940s, and wood frame multi-family two-unit homes built before the 1940s. For the summer and winter outages, at the first 24 hours of the outage and over the total outage duration, the latter two home types exhibited higher average SDHs compared to most other home types more prevalent in non-redlined areas, which included brick and wood frame single-family, two-story homes with basements, built in the 1950s and earlier.

In Durham, NC, five home types were more prevalent in redlined areas compared to non-redlined areas: wood frame single-family one-story homes without basements, built in the 1940s, 1950s, and 1960s; and wood frame multi-family two-unit homes built in the 1940s and 1960s.

For the summer outage, there was slight variability in SDHs. Still, most of these home types exhibited higher average SDH compared to home types that were more prevalent in non-redlined areas, mainly multi-family residences. For the winter outage, the difference in performance was more prominent between primarily redlined and primarily non-redlined home types, especially for the total duration of the outage (Figure 3). Interestingly, in the winter outage, a lower average SDH resulted in wood frame multi-family two-unit homes built in the 1960s compared to the summer outage. This home type had one of the highest average SDH measurements in hot weather but one of the lowest in colder weather. The red boxplots in Figure 2 represent home types more prevalent in redlined areas.

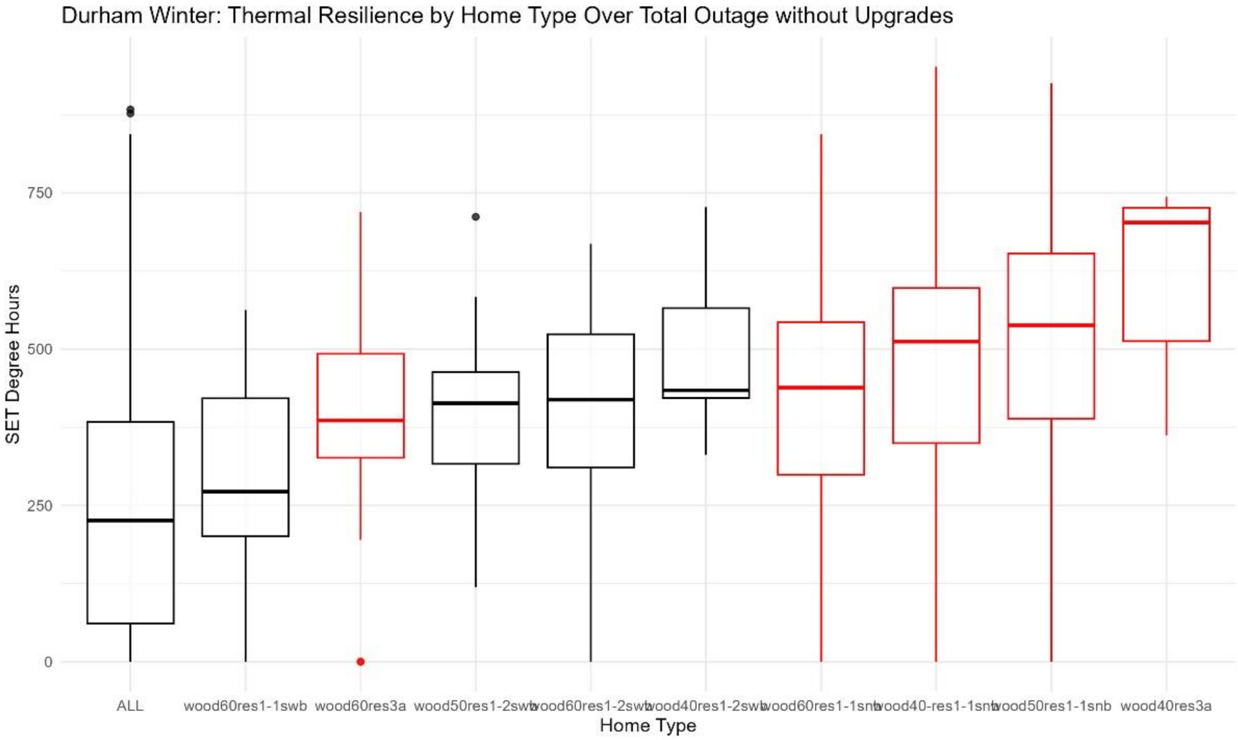

Figure 2. Boxplots illustrating the distribution of SDH measurements for different home types with notable differences in prevalence between redlined and non-redlined areas in Durham for the total duration of the winter outage. Boxplots are in order of least to greatest median SDH.

In Seattle, eight home types were found to be notably more prevalent in redlined areas compared to non-redlined areas: brick multi-family two-unit homes built before 1940; steel frame multifamily homes built in the 2000s with two units, 3-4 units, 5-9 units, 10-19 units, 20-50 units, and >50 units; and wood frame single-family one-story homes with basements built in the 1950s and 2000s. However, the first three steel multi-family home types could not be found in the ResStock modeling results, indicating a potential mismatch between ResStock and NSI datasets, discussed further in the Challenges and Limitations section. Thus, five of the eight primarily redlined home types were analyzed.

ResStock data for the summer outage in Seattle revealed SDHs of zero for several home types, including the one home type identified as notably more prevalent in non-redlined areas:

brick single-family two-story homes with basements built before 1940. SDHs of zero indicate that these home types likely did not exhibit temperatures outside of the comfortable zone of the SET. However, many of the home types more prevalent in redlined areas did exceed the SET threshold, suggesting that, while their average SDHs were relatively low compared to their counterparts in other cities, there was an observed average SDH increase in primarily redlined homes compared to primarily non-redlined homes.

In the winter outage simulation, no home type did not surpass the livable temperature threshold (54°F) at least once. Two home types more prevalent in redlined areas, brick multi-family two-unit homes built before 1940 and wood frame single-family one-story homes built in the 1950s without basements, consistently exhibited notably high SDHs compared to other home types, primarily redlined and primarily non-redlined, for both the 24-hour and total duration time points.

In Tampa, seven home types were found to be more prevalent in redlined areas compared to non-redlined areas: steel frame single-family one-, two-, and three-story homes without basements built in the 2000s, steel manufactured homes (e.g., mobile homes) built in the 2000s, steel multi-family two-unit homes built in the 2000s, wood frame single-family one-story homes without basements constructed before 1940, and wood frame single-family one-story homes with basements built in the 1970s. The steel frame multi-family homes, in fact, were found to only be present in redlined areas, not in non-redlined areas, potentially indicating strategic zoning decisions connected to redlining or neighborhood characteristics associated with redlining. However, like Seattle, two home types were not found in the ResStock modeling results: steel multi-family two-unit homes and wood frame 1970s homes. Thus, five out of the seven home types most prevalent in redlined areas were analyzed.

Like the Seattle results, the steel frame homes in Tampa built in the 2000s - apart from the steel manufactured homes - consistently exhibited some of the lowest average SDHs across the summer and winter outages and for both time points, potentially for similar reasoning as previously described. Additionally, the modeling of several of these home types in summer and winter outages resulted in SDH measurements of zero, again indicating zero hours outside of the livable temperature threshold of 54°F - 86°F.

Conversely, in Tampa, steel manufactured homes (e.g., mobile homes), built in the 2000s, had the highest average SDH measurements of all home types with notable differences in prevalence for the total duration of the summer outage. This result could indicate that mobile homes perform most inefficiently in hot weather scenarios, potentially putting residents at greater risk in these weather scenarios.

Lastly, wood frame single-family one-story homes without basements, also primarily in redlined areas, exhibited high average SDHs compared to other home types, regardless of redlining status, and had the highest average SDHs over the first 24 hours of the summer outage. This could suggest that these homes heat up more quickly than the others and then stabilize over the total duration of the outage. In the winter outage, however, this home type performed consistently in the mid-range across both time points, potentially indicating stable temperatures. However, in this outage scenario, this home type had lower average SDHs than two home types more prevalent in non-redlined areas: wood frame single-family two-story homes without basements, built in the 1950s and before 1940, respectively.

Our analysis revealed some similarities across the four cities. While both single-family and multi-family construction are prevalent in redlined areas, multi-family homes were often found to be more prevalent in redlined areas than in non-redlined areas. This aligns with more common multi-family zoning in redlined areas, 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).

Additionally, we observed lower SDHs among newer steel frame buildings, excluding mobile homes. As these homes were the newest builds (2000s) of the home types with notable differences in prevalence, they could have performed better due to adherence to newer building codes or could have lacked the characteristics of older homes that contribute to energy inefficiency (i.e., lack of insulation, leaks, less sealing). Instances where these home types did not exhibit temperatures outside of the livable threshold of 54°F and 86°F and resulted in SDH measurements of zero, could be a result of efficient energy performance due to the characteristics, whether that did not lead to an exceedance outside the threshold indoors (e.g., mild winter weather in Florida), or a combination of both.

Energy Efficiency Upgrade Simulations

Our simulations of energy efficiency upgrades revealed significant potential for reducing SDHs, even among homes with the highest SDH measurements without upgrades. As predicted, more intensive upgrade packages, particularly the Advanced Envelope with and without the addition of Universal Cooling, showed the most significant potential for reducing average SDH measurements, in many cases reducing average SDHs by over half—in some cases more if Universal Cooling was added. This reduction was especially notable for wood frame multi-family home types, which we denoted as more often in redlined areas than not. In the first 24 hours of the Chicago summer outage, for example, we observed a notable average SDH decrease for wood frame multi-family two-unit homes built before 1940 with the Advanced Envelope + Universal Cooling package (Figure 3). Overall, while some upgrades could reduce average SDHs of primarily redlined home types to levels comparable to primarily non-redlined home types, our results did not reveal a broad trend across the four cities indicative of more significant benefits for the former. 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.

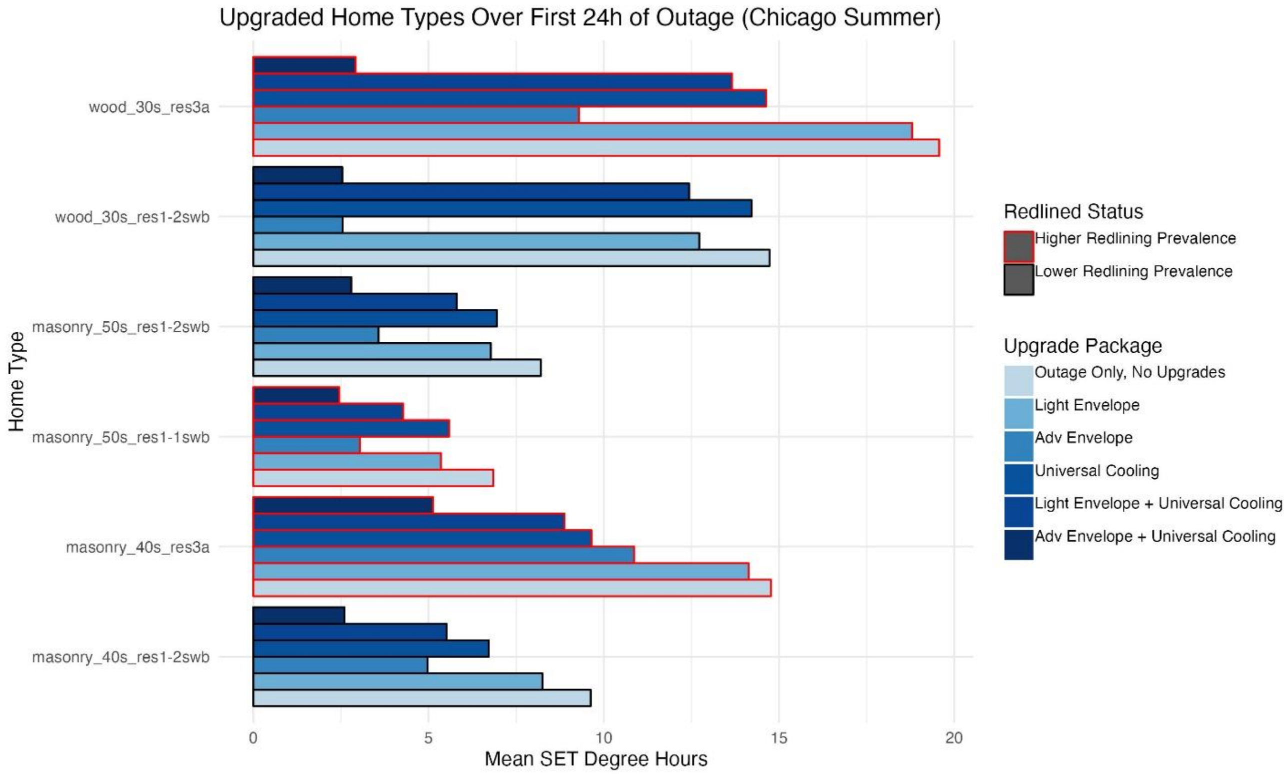

Figure 3. Bar chart depicting changes to SDH with the addition of energy efficiency upgrade packages for the first 24 hours of the Chicago summer outage. Bars with red outlines indicate home types more prevalent in redlined areas.

CONCLUSION

Residential energy efficiency is a potential component of individual and community resilience during extreme temperature events, such as heat waves and cold events. Less energy-efficient homes contribute to energy burden, especially for those already disproportionately exposed to extreme temperatures. This study explores how historical redlining has left a legacy of disinvestment in housing, contributing to inequities in residential energy efficiency compared to non-redlined neighborhoods. While this analysis focused on four historically redlined districts in different climate zones: Durham, NC, Tampa, FL, Chicago, IL, and Seattle, WA, the additional analysis could include cities across the nation where redlining issues may exacerbate the ability to shelter in place safely during extreme weather-related events. While further analysis is warranted, and refinement of the methodology would be beneficial, the initial results of this study identified potential efficiency upgrades to inform retrofit investments to address thermal resilience in historically redlined communities.

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. Data availability and granularity were challenging. Survey data on demographics and building characteristics used in ResStock are at the PUMA level, a lower level of granularity compared to the Census tract or block. 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 the actual performance of homes. While comparing NSI and ResStock data, misalignment was noted in home type representation (e.g., NSI home types were not represented in ResStock). This could be due to uncommon home types in real building stock, which are thus not represented by the model.

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. 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, redlining has created entrenched patterns of investment inequities, translating into housing quality and energy efficiency disparities that largely transcend the effects of neighborhood and building changes over time.

Overall, this analysis provides insight into potential inequities underlying residential energy efficiency associated with redlining. These inequities can threaten human health, energy affordability, and overall resilience during extreme temperature events, so the efficiency opportunities available in residential buildings in historically redlined districts can impact the lives and well-being of the American people.

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