Win-Win-Win? Evaluating the Climate, Health, and Equity Benefits of Retrofitting Low Income Housing in the US

by

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Abstract

Large scale energy efficiency and electrification of the US residential sector are needed to meet the Paris Agreement goal of limiting warming below two degrees Celsius. Energy efficiency retrofits can also provide significant health and economic benefits, especially for low-income residents. These non-energy benefits are often excluded from policy analysis of energy efficiency programs because they are not well quantified, especially at a local level. In this thesis I quantify a subset of these public and private health benefits and develop a cost benefit analysis at the county level across the continental US of a retrofit policy for low-income households that includes electrification and efficiency measures. The retrofit policy yields a positive average net present value in 29% of counties when considering only the private benefits of reduced energy consumption. However, retrofits yield positive net present value in all US counties when public and private health benefits are included. I also explored the potential impacts of a retrofit policy on household energy burden (household energy expenditures divided by household income). In most counties, retrofits would more than offset the additional cost of energy from a $51 per metric ton carbon price, the current social cost of carbon estimated by the federal government. The gap between public and private retrofit benefits prevents low-income households from implementing energy efficiency measures. Programs to subsidize low-income retrofits would reduce economic deadweight loss, climate emissions, and energy costs, while improving human health and wellbeing for low-income households that currently suffer disproportionately from inefficient housing.

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Introduction

The United States has committed to reducing greenhouse gas emissions 50-52% below the 2005 level by 2030 and to net zero by 2050, reductions needed to meet the Paris Agreement target to avoid the worst effects of climate change by limiting global warming to no more than 2°C. Meeting these targets requires extensive and swift emissions reductions in all sectors, including residential buildings, which account for 19% of US greenhouse gas emissions (US EPA 2021). Most residential buildings that will be in use in 2030 have already been built. Retrofits are essential to improve efficiency and electrify onsite fossil fuel heating systems and appliances to take advantage of a rapidly decarbonizing grid. Crucially, the technology for deep energy retrofits of buildings (retrofits that aim to reduce energy use by 50% or more) exists and can be deployed in time to help meet 2030 commitments (Larson et al. 2021).

At the same time, increasing efficiency of residential buildings has the potential to break cycles of poverty and improve the health of residents while creating well-paying jobs. These actions would particularly benefit communities of color, where high energy costs due to inefficient housing compound other long-lasting effects of continuing racial segregation and disenfranchisement (Goldstein, Reames, and Newell 2022; Lewis, Hernández, and Geronimus 2020). Low-income and formerly redlined communities are also likely to be hit the hardest by the effects of climate change and can benefit most from houses that can keep livable temperatures during power outages and extreme weather.

Despite the potential for energy efficiency retrofits to improve public health, reduce emissions, and increase equity, the federal government does not have a comprehensive plan for deploying retrofits at scale, and the focus on state and local efficiency initiatives, incentives, and standards varies significantly across the US (Bednar and Reames 2020). The DOE's Weatherization Assistance Program (WAP), the US's largest program to improve energy efficiency in low-income homes, upgrades less than 0.1% of eligible houses each year and has waiting lists that can be decades long (Ross, Drehobl, and Stickles 2018). While WAP estimates $2.78 in non-energy benefits for every $1 invested (U.S. DOE 2019), the program only pays for upgrades that individually pass an ex-ante cost-benefit test that excludes social benefits (Fowlie, Greenstone, and Wolfram 2018). Beyond WAP, most existing and historical investments in residential energy efficiency are implemented by affluent residential homeowners who can afford the cost of energy efficiency upgrades. While some electric utilities have low income energy efficiency programs they often do not include non-energy benefits in cost accounting or use an 'adder' of 10-25% of energy cost savings, an overly conservative measure, given that programs like WAP estimate non-energy benefits twice as large as the energy benefits (Northeast Energy Efficiency Partnerships 2017; U.S. DOE 2019). The omission of health and other co-benefits is consistent with trends across climate policy, where costs are often considered without broadly considering benefits, leading to biased policies that stop short of meeting climate and welfare goals (Karlsson, Alfredsson, and Westling 2020).

This thesis reviews the health benefits of deep energy retrofits (DERs) across the US and provides estimates of the net present value of a retrofit program at the county level for low- and moderate-income (LMI) households. The analysis accounts for county-level differences in energy use and costs, housing type and quality, construction costs, and other conditions that vary significantly across the country. Such estimates can help policymakers incorporate health when evaluating program costs and prioritize areas for investment that are locally appropriate. The sensitivity analysis addresses uncertainties created by limitations on available data, and areas for improved measurement are identified.

Housing Efficiency as a key lever to escape cycles of poverty

The lack of investment in energy efficiency in low-income households is more than simply a missed opportunity. Housing is a key determinant of health (Taylor 2018), and its quality and affordability shape the financial, mental, and physical health of residents. Based on a literature review of the causal pathways affected by housing efficiency, I built a qualitative system dynamics model representing five interdependent and reinforcing financial, mental, and physical health feedback loops that can trap people in cycles poverty (Figure 1). See (Sterman 2000) for explanations of causal loop diagrams.

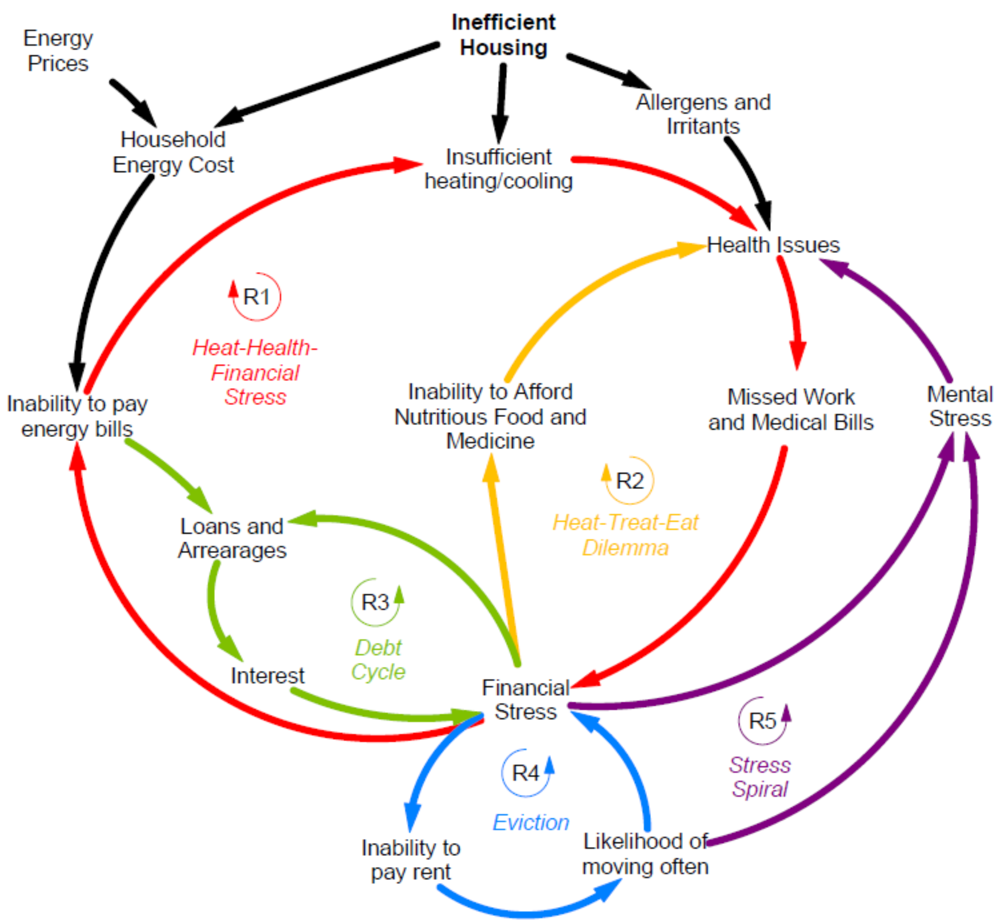


Figure 1: Reinforcing Loops of Poverty (or Prosperity) Impacted by Housing Efficiency

**All polarities are positive and therefore not shown explicitly.*

Reinforcing Loop 1 (R1): Heat-Health-Financial Stress

Energy inefficient housing is often caused by a lack of insulation and air sealing which can affect health by making it more expensive to keep the unit at a healthy temperature and creating an environment for environmental pollutants which can cause and exacerbate health issues. For example, insufficient heating can exacerbate chronic health issues, with increased risk of death (Liddell and Morris 2010). Health issues cause people to miss work and accumulate medical bills, which increase financial stress and in turn make it even harder to pay energy bills, resulting in even less sufficient heating or cooling.

More than one in ten US households report leaving their homes at an unhealthy temperature, which can exacerbate many chronic health conditions (EIA 2018). Excess cold in the home has been linked to influenza, pneumonia, asthma, arthritis, and diabetes, and can increase the likelihood of stroke, myocardial infarction (heart attacks), accidents at home, and pulmonary embolisms (Liddell and Morris 2010). Excess heat has been shown exacerbate chronic conditions, impair physiological functioning, impact mood and behavior, reduce productivity, and cause excess deaths (Maller and Strengers 2011; Weinberger et al. 2020). For example, the 2021 heatwave in the Pacific Northwest resulted in approximately 600 excess deaths in homes that were unable to keep cool temperatures (Popovich and Choi-Schagrin 2021).

Housing with limited insulation and poor air sealing can allow allergens and irritants, such as mold, pollen, particulate matter, pests, and noise pollution into the house. Mold, moisture, pollen, particulate matter, and certain pests can cause and exacerbate respiratory issues such as asthma (World Health Organization 2021b). Particulate matter has also been shown cause and exacerbate stroke, heart disease, lung cancer, and other chronic and acute respiratory diseases (World Health Organization 2021b). Excessive noise has been shown to have negative impacts on sleep and cognition and increases the incidence of hypertension and cardiovascular disease (Basner et al. 2014). Noise, particulate matter and other pollutants are at higher concentrations in Black communities, communities of color, and other low-income communities that are more likely to be located near highways, hazardous waste sites, and other polluting facilities (Mikati et al. 2018).

Reinforcing Loop 2 (R2): Heat, Treat, Eat Dilemma

In addition to being unable to pay energy bills, financial stress forces low-income individuals to choose between heat, food, and medicine (Snyder and Baker, Christopher A. 2010). Over one fifth of US households report reducing or forgoing food or medicine to pay energy costs (EIA 2018), which has serious impacts on health, especially for children and people with chronic diseases (Taylor 2018). These phenomena are known as the “Heat or Eat” and the “Eat or Treat” dilemmas, combined in this figure as the “Heat, Treat or Eat Dilemma” (Bhattacharyya et al. 2003; Berkowitz, Seligman, and Choudhry 2014). The “Heat, Treat or Eat Dilemma” creates a vicious cycle that adds to the initial harm from housing inefficiency and exacerbates this harm by making it even harder to pay energy costs in the future and worsen chronic conditions that can be affected by temperature.

Reinforcing Loop 3 (R3): Debt Cycle

Inability to pay energy bills can lead to arrearages that add late fees and interest to the original amount owed to the utility. Financial stress can lead struggling households lacking traditional forms of credit to take out high interest loans to pay for energy bills, rent, food, or medication. A 2012 study by the FDIC found that utility bills, living expenses, and rent were the top three reasons leading people to take out high interest loans such as payday loans, pawn loans, and direct deposit advance loans, which can trap people in cycles of debt, increasing financial stress (R. Levy and Sledge 2012).

Reinforcing Loop 4 (R4): Eviction

Financial stress exacerbated by knock on effects of inefficient, poor-quality housing can also make it difficult to pay rent. Even before the pandemic, during a period of low unemployment and steady economic growth, one in eight families nationwide faced eviction each year, often because they had to pay for utilities, food, or medicine instead of rent (McCarty 2016). Covid-19 has put even more people at risk of eviction (Himmelstein and Desmond 2021). Moving, especially when evicted, is expensive and disruptive because of moving costs, legal fees, lost worktime, and increased expenses, which worsens the financial stress that increases the risk of moving and eviction further.

Reinforcing Loop 5 (R5): Stress Spiral

Poor health, financial stress, and the fear or reality of eviction can cause significant mental stress, which increases health risks including mental health disorders such as depression and anxiety, as well as leading to reduced immune system function, cardiovascular disease, and gastrointestinal disorders (Yaribeygi et al. 2017). Housing insecurity is a health risk that has been linked to mental health disorders, substance abuse disorder, and infectious disease spread (Desmond and Kimbro 2015; Hernández, Phillips, and Siegel 2016). For example, almost 15% of Covid-19 pandemic-related deaths in 2020 could have been avoided with a nationwide ban on utility disconnections (Jowers et al. 2021). The connection between financial stress back to health forms the last feedback loop in Figure 1.

Overall, the impact of these reinforcing loops is to keep energy burdened households in poverty and poor health. Even after controlling for common predictors of poverty status such as income loss, illness, health, marital status, education, health insurance, and head of households, energy-burdened households are at 150-200% greater risk of transitioning into or extending the duration of poverty over a two-year timeframe (Bohr and McCreery 2020). The long-term consequences of poverty are particularly serious for children, who are the most likely of any age group to be living in poverty and for whom poverty has significant long-term costs, including learning and developmental delays, poor academic outcomes, lower earnings potential, short- and long-term physical and mental health issues, increased likelihood of criminal activity, and increased likelihood of teenage pregnancy (McCarty 2016).

Utility low-income specific energy efficiency programs are often more expensive than higher income energy efficiency programs on a dollars per Btu avoided basis, but this type of evaluation ignores the health impacts of energy inefficient and does not account for non-energy benefits and reinforcing feedbacks that further exacerbate financial and health effects for low income households (Schiller et al. 2020).

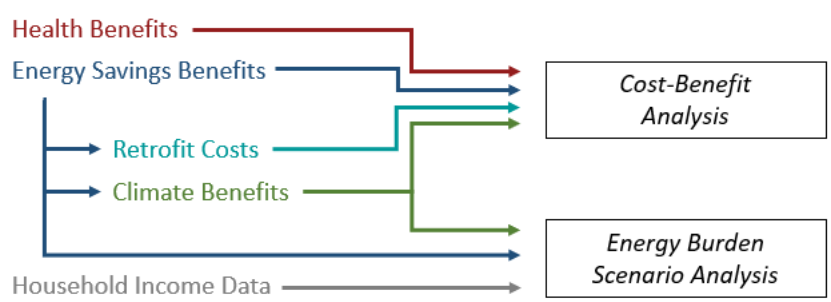
The reinforcing feedbacks in Figure 1 operate as vicious cycles that can drive people into poverty and trap them there. Policies such as deep energy retrofits that improve housing quality therefore have the potential to reverse these feedbacks. By reducing energy costs and exposure to other hazards in low quality housing, such retrofits can improve household income and reduce the incidence of health problems, leading to less missed work, still higher income, and still better health. Retrofit policies can be more effective than subsidies to LMI households such as fuel assistance. Fuel subsidies must be maintained indefinitely, whereas a one-time upgrade can last up to 30 years or more. Despite this, the federal government invests significantly more in the Low-Income Housing Energy Assistance Program

(LIHEAP), which subsidies energy costs for low-income households, than on WAP, which invests in long term energy efficiency upgrades. The prioritization of federal resources for LIHEAP over WAP is an example of a “capability trap” (Lyneis and Sterman 2015; Sterman 2015), wherein pressure to ensure immediate energy affordability for a larger group through energy assistance diverts resources from investment in long-term energy efficient housing and contributes to chronically high costs for the federal government for energy assistance and little progress for reducing energy insecurity long-term.

Methodology

Estimating the private and public return on investment of energy efficiency for low-income housing in the U.S. requires estimating (1) the public and private health benefits for low-income households, (2) the energy and emissions savings of a deep energy retrofit by household, and (3) the costs of an average deep energy retrofit. The analysis is conducted at the county level as these costs and benefits vary substantially by location due to differences in climatic conditions, energy costs, and other factors. I use twice the federal poverty line (200FPL) to define low-income households, which was the threshold used for the increased investment in Weatherization Assistance Program funding during the American Recovery and Reinvestment Act of 2009 (Bednar and Reames 2020).

Figure 2: Overview of Analysis



The costs of retrofits, energy savings, and health savings are used to estimate the net present value (NPV) of retrofits for low-income housing at the county level. The NPV is calculated for the private benefits arising from reductions in energy costs alone and for the private and public benefits, including reductions in energy-related morbidity and mortality, and associated health care costs. Additionally, the analysis estimates how retrofits would affect the energy burden of low-income households, with and without a price on carbon. Appendix A: Equations and Sources for Health Calculations provides full details on the data sources and analysis.

Health Benefits

While many different health effects and pathways are identified in Figure 1, only a subset of the health effects of inefficient housing have been quantified. Few studies quantify the health effects of deep energy retrofits, focusing instead on modest interventions such as adding insulation and weatherstripping (Blasnik et al. 2014; Hawkins et al. 2020; J. I. Levy et al. 2016; Nevin 2010; Tonn, Carroll, et al. 2014).

The health benefits of some studies of DOE's WAP program are self-reported and do not have sample sizes large enough to downscale results to the county level (Blasnik et al. 2014; Tonn, Rose, et al. 2014).

For each health impact, I reviewed the literature and used available data on the incidence and prevalence of health conditions that could be mitigated by energy efficiency upgrades, and how these conditions depend on resident exposure to excessive heat, cold, and indoor pollutants. The data support estimates of the health impacts of asthma, exposure to excessive heat and cold, and days of work lost due to these factors. Other health and social benefits, including success in school for children, risks of job loss, medical bankruptcy, homelessness, and other factors mentioned in the Introduction that affect life outcomes for low-income individuals cannot be adequately quantified and are omitted, a conservative approach that underestimates the benefits of DERs for low-income housing.

Asthma

The development of asthma and incidence of severe episodes requiring medical care arising in homes derive from two main sources: indoor gas stoves and insufficient air sealing and insulation. Low-income populations have higher asthma rates than high income populations: adults making less than $50K/year are 43% more likely to have asthma than adults making more (CDC 2021a). Asthma rates vary racially as well: Black children are more than twice as likely to have asthma than white children and black adults are 20% more likely to have asthma as white adults (CDC 2021b). Reducing the development of asthma and incidence of acute attacks in low-income households would reduce private and public healthcare costs and improve equity by reducing the gap in asthma prevalence by income and across socio-economic groups. The combustion products of gas stoves and ovens include nitrous oxides, carbon monoxide, and incompletely burned gas, and gas can also leak when the stove is off, all leading to poor indoor air quality (Lebel et al. 2022). Nitrous oxides in particular are respiratory irritants, and World Health Organization outdoor limits of 13ppb over 24 hours are regularly exceeded indoors in households with gas stoves and inadequate ventilation (Lebel et al. 2022). Ventilation for gas stoves is often absent or inadequate in low-income homes, and even households with adequate ventilation systems often do not use them (Lebel et al. 2022).

Insufficient air sealing and insulation can cause homes to be cold, drafty, damp, or even allow mold and pests to develop, all of which exacerbate asthma (World Health Organization 2021b). The impact of gas stove electrification and weatherization on asthma are estimated separately, despite potential interactions between asthma exacerbation from both sources.

Asthma from Gas Stoves

The annual per household cost of asthma from gas (and propane) stoves is estimated as the increased prevalence of asthma in homes with gas stoves multiplied by the average annual cost of asthma. I calculated the increased prevalence of asthma in homes with gas stoves based on the prevalence of asthma in low income populations by state (CDC 2021a), the percentage of homes with gas and propane stoves by county (DOE 2021; "ResStock Analysis Tool" 2021), and the increased risk of current asthma from gas stoves (Lin, Brunekreef, and Gehring 2013). Since gas stoves increase current risk of asthma, counties with higher percentages of gas stoves have a higher risk that contributes to state low-income prevalence. Solving for the baseline rate of asthma without any gas stoves allowed me to calculate the additional prevalence of asthma due to gas stoves by county. This calculation assumes that families with asthma not from gas stoves do not avoid living in homes with gas stoves. Since it is not common knowledge that gas stoves can exacerbate asthma and low-income households often have less choice in where to live, I believe this is a reasonable assumption. While data on gas stoves by income was not available, there is evidence that gas stoves are prevalent in both high and low income households, since they are both cheaper to operate and considered a status symbol (Leber 2021; Steinberg 2022).

I use the average annual cost of asthma calculated by Nurmagambetov et al., adjusted to $2020 using the CPI, and scaled at a county-level using a county-level healthcare cost index (Bureau of Economic Analysis 2021b; CMS 2021; Nurmagambetov, Kuwahara, and Garbe 2018). The estimated annual cost includes prescriptions, doctors' office visits, hospitalizations, outpatient visits and ED visits. I also add in the cost of a missing workdays from asthma, conservatively assuming statewide minimum wage for those employed, and accounting for a percentage of parents without a stay-at-home spouse who would miss work to care for a sick child. Figure 3 shows the total cost by county for the average household below 200FPL from the health effects of asthma arising from gas stoves. There is substantial geographic variation, due to variations in the prevalence of asthma, fraction of households using gas cooking, healthcare costs, and minimum wages. Costs per household range from $20 in Columbia County, WA, a rural county in western Washington, to $270 per household per year in Richmond County, NY (Staten Island, New York City), with average out of pocket costs ranging from 11-13% of total costs. High asthma costs in LMI housing in California and parts of the Northeast are due to high healthcare costs, minimum wages, and a high prevalence of gas stoves in these areas.

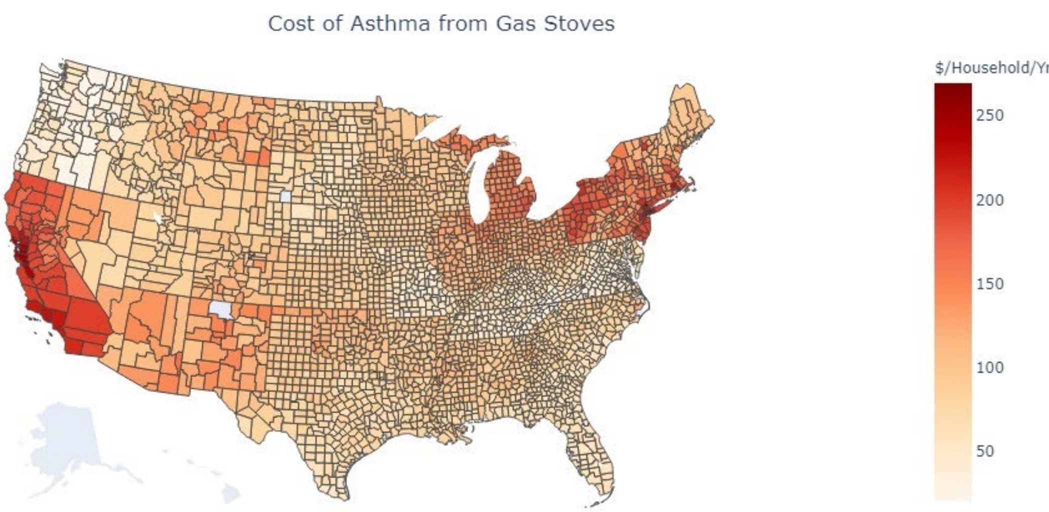


Figure 3: Cost of Asthma from Gas Stoves in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

Asthma Costs from Inadequate Air Sealing and Insulation

I calculated the potential reduction in asthma from air sealing and insulation using state level data from the DOE's Weatherization Assistance Program (WAP) that reported the reductions in hospitalizations, emergency department (ED) visits, and other direct medical costs (ODCs) from high-cost asthma patients (those experiencing symptoms in the past 3 months) (Tonn, Carroll, et al. 2014). The reductions in hospitalizations, ED visits, and ODCs from the WAP program are a lower bound for what could occur with a DER, because a DER includes more insulation, air sealing, and heat recovery ventilation (ventilation that recaptures the heat from exhausted air) that would keep the temperature in a healthier range and provide greater improvements to indoor air quality. In addition, the WAP program does not make any updates to gas stoves or ventilation systems, so it's likely in the modeled retrofit, where gas stoves are removed, and ventilation increased at the same time as insulation and air sealing are added would lead to even greater reductions in asthma costs.

The reductions in hospitalizations, ED visits, and ODCs from the WAP program were multiplied by the average cost of an asthma-related hospitalization, an asthma-related ED visit, and annual ODCs for asthma to yield the annual change in cost per person with asthma. The cost per household of asthma from poor insulation and air sealing was calculated by multiplying the annual change in cost per person with asthma by the incidence of asthma, the healthcare cost index, and the number of people per household. Missed days of work or school from asthma were not included in this calculation to avoid double counting with Missed Work avoided from air sealing and insulation (described below), which also uses data from WAP treated households.

Figure 4 shows the variation in costs of asthma from poor insulation and air sealing. Because data for the impact of air sealing and insulation on asthma health outcomes are not available at the county level, results are limited to the state level. The total costs for the average below 200FPL household for insulation and air sealing ranged from $60 throughout South Dakota to $145 per household per year in Washington, DC, with average out of pocket costs ranging from 10-13% of total costs. High rates of asthma in low-income communities and high healthcare costs are responsible for the high average cost per household in Oregon and the Northeast.

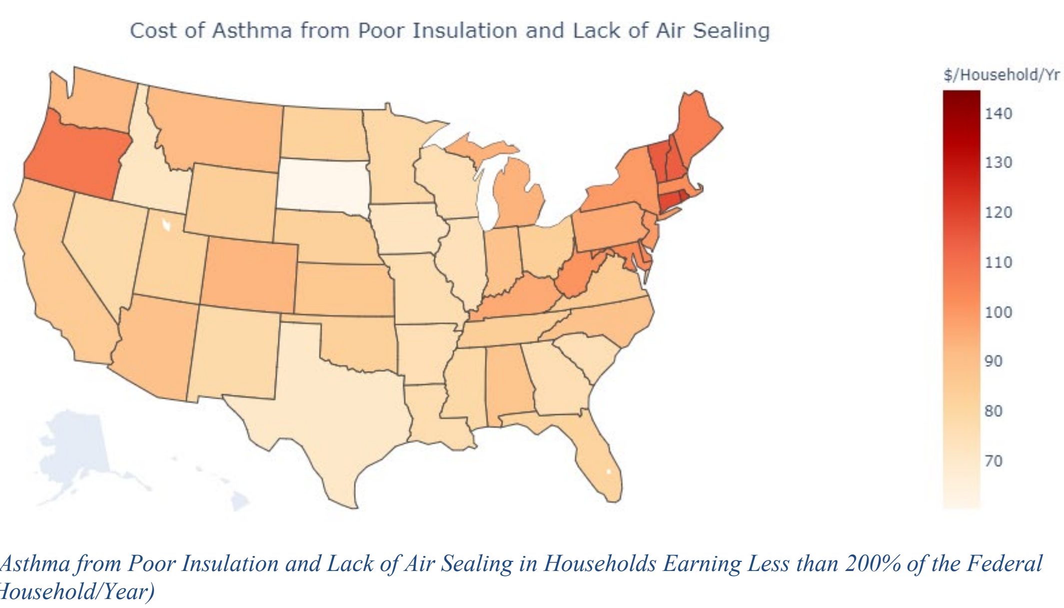


Figure 4: Cost of Asthma from Poor Insulation and Lack of Air Sealing in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

Cost of Temperature Stress from Energy Inefficient Housing

Exposure to excessively hot and cold indoor temperatures can trigger ED visits, hospitalizations, and deaths, particularly among those with pre-existing conditions including diabetes, cancer, and respiratory, and cardiovascular diseases (Gómez-Acebo, Llorca, and Dierssen 2013; Tseng et al. 2013; WHO 2018). Climate change exacerbates this threat for both heat and cold because of increasingly erratic weather patterns that resident homes are not acclimatized for. This was evident in 2021 both during the February cold snap in Texas, which resulted in over 700 excess deaths and the heatwave in the Pacific Northwest that resulted in approximately 600 excess deaths (Hirji 2022; Popovich and Choi-Schagrin 2021). Increasing this risk, chronic health conditions that are exacerbated by extreme temperatures are more prevalent among low-income and minority populations (Mode, Evans, and Zonderman 2016), and at the same time low-income and minority households are disproportionately exposed to extreme indoor temperatures because of poor quality housing and lack of green spaces in urban areas (Reames 2016; Hsu et al. 2021). Low income households in cities experience temperatures 0.7-1.0°F higher than those above 200FPL in cities and Black Americans in cities experience temperatures 1.7°F higher than white Americans in cities (Hsu et al. 2021). Inefficient, drafty, and poorly insulated housing raise energy costs, increasing the likelihood that residents will be forced to choose between heating and eating (and paying for rent, medicines, and other necessities). Similarly, in summer, inefficient, drafty, poorly insulated housing raises the cost of air conditioning—if it is available at all—forcing residents to endure high indoor temperatures, sometimes far higher than those outside. Furthermore, the urban heat island effect is more severe in low-income and minority urban areas than in more affluent neighborhoods (Hsu et al. 2021).

However, estimating the role of excessive indoor temperatures is difficult. Although the EPA reports heat-related deaths, many medical records and death certificates record the pre-existing health issue as the cause rather than hyperthermia or hypothermia (US EPA 2016). Additionally, despite many studies linking acute harms from chronic diseases to extreme indoor temperatures (Gronlund et al. 2018; Holmes, Phillips, and Wilson 2016; McCormack et al. 2016; Saeki, Obayashi, and Kurumatani 2015; Shiue and Shiue 2013; Tham et al. 2020; WHO 2018; Wolkoff, Azuma, and Carrer 2021), the dose-response curves often focus on outdoor temperature (Gómez-Acebo, Llorca, and Dierssen 2013; Lee et al. 2016; Shindell et al. 2020; Yang et al. 2012), even though most Americans (especially the elderly and those with chronic conditions) spend 87% of the day inside buildings (Klepeis et al. 2001). Few studies assess how indoor temperatures vary across the US by location and income.

Because of the multiple gaps in the data and confounding factors, instead of separately calculating the impact of extreme temperature on individual chronic conditions, I have used a top-down methodology adapted from an American Council on Energy Efficient Economy (ACEEE) research report (Hayes and Kubes 2020) to estimate all extreme temperature related deaths, emergency department visits and hospitalizations based on hyperthermia and hypothermia rates by state. Further research could focus on filling the data gaps mentioned above, which would allow for more refined estimates of the cost of temperature stress. Additionally, unlike the other health effect calculations in this paper, these estimates are done for an average household rather than households below 200FPL. Thus, the estimated potential health savings from reduced temperature stress are likely an underestimate because those below 200FPL are the most likely to experience hyperthermia and hypothermia due to poorly insulated homes or inability to afford the cost of heating and cooling the home to safe temperatures.

The heat and cold stress costs include morbidity costs, which are monetized using the EPA's value of statistical life (VSL) updated to $2020 using the CPI (Bureau of Economic Analysis 2021b; US EPA 2014). The VSL is based on estimates of people's willingness to pay for small reductions in risk of dying from adverse health conditions (US EPA 2014). However, it does not include private out of pocket costs and other actual economic harms of a death, such as funeral costs, potential loss of household income or childcare, and downstream effects stemming from income loss or grief. In this analysis the VSL is kept constant at $9.5M/life across the US for consistency and because of the moral implications of valuing lives different across the county, even though willingness to pay for small reductions in mortality risk may be influenced by income and geography.

Heat

To calculate the costs heat-related morbidity and mortality, I first calculated the number of heat-related deaths, hospitalizations and ED visits and estimated the fraction that could be avoided with a DER. I estimated the number of heat related deaths using available data on hyperthermia deaths by region in the US (Berko 2014). Because heat stress deaths increase sharply with age beyond 65 years, I adjusted regional hyperthermia rates for each state based on the state-wide low-income age distribution. Since the rate of deaths labeled as "hyperthermia" does not account for heat exacerbated chronic diseases, this rate was multiplied by the ratio of actual heat exacerbated deaths to deaths labeled as "hyperthermia" from New York City data (Metzger, Ito, and Matte 2010). This value is known for NYC because of their robust extreme heat death monitoring programs but is not widely available for other locations that do not measure heat deaths apart from hyperthermia. For this calculation I assumed that the NYC ratio was appropriate for the rest of the US.

I took a similar approach for heat-related ED visits and hospitalizations, where I multiplied the NYC ratio of heat-related ED visits and hospitalizations to hyperthermia deaths by the regional hyperthermia death rates. I assumed that all indoor heat-related morbidity and mortality could be avoided with a DER, which is supported by the fact that none of the heat related deaths in NYC occurred in homes with working AC units while the assumed retrofit would install a heat pump that can provide both heating and cooling. Approximately 80% of heat-related morbidity in NYC was indoors, and I assumed this rate held across the country (Metzger, Ito, and Matte 2010).

The cost of the excess morbidity and mortality from heat stress was calculated by multiplying the excess deaths by the VSL, and the ED visits and hospitalizations by average ED visit and hospitalization costs. The ED visit and hospitalization costs were not more specific because of the variety and range of severity of conditions exacerbated by heat stress. The ED visit and hospitalization costs were also adjusted based on the state healthcare cost index.

Figure 5 shows the costs associated with heat stress. The total annual cost for the average household for heat stress ranged from $528 in Vermont to $2,283 per household per year in Texas, with average out of pocket costs ranging from 0.2% to 0.3% of total costs. The percent out of pocket costs is low because the value of statistical life, which is conservatively allocated fully as a public cost, is so much higher than other medical costs. High regional hyperthermia death rates in the West and South Census Regions are responsible for a higher cost of heat stress across these regions and the lack of gradient from the West and

South into the Midwest and Northeast census regions. Data on heat stress are not available at the county level, but the census data on hyperthermia deaths also report deaths based on urbanization level and found that in general urban and rural areas are the most susceptible to heat stress, likely because of concentrations of poverty in urban and rural areas as well as higher exposure to heat through urban heat island effects in urban areas and farm work in rural areas (Hsu et al. 2021).

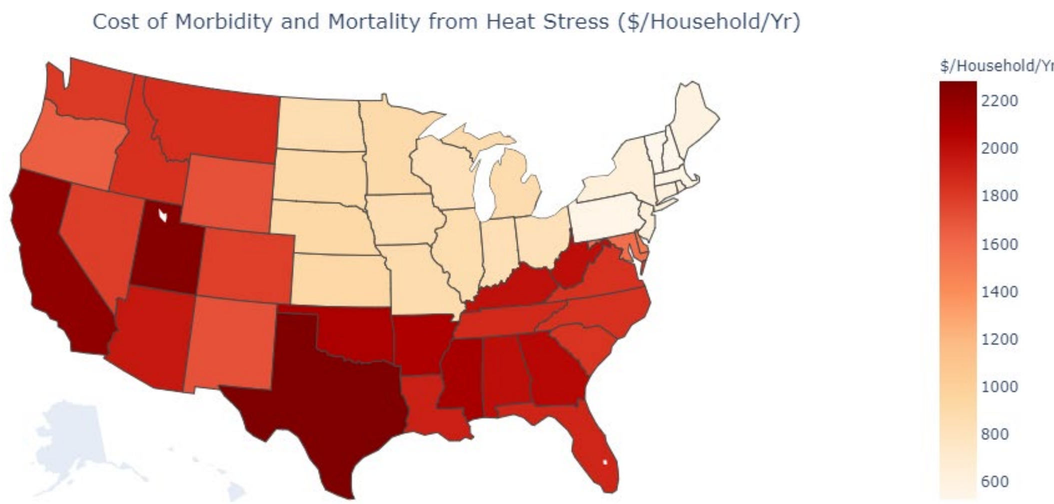


Figure 5: Cost of Mortality and Morbidity from Heat Stress in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

Cold

The cold-related morbidity and mortality cost calculations followed a similar methodology to the heat-related morbidity and mortality. However, I was able to find more geographically granular data for hypothermia deaths by metropolitan area rather than by region (Spencer 2015). I mapped the metropolitan areas to counties and for the remaining counties in each state, I took the state average of the metropolitan areas within the state and scaled the average for each remaining county based on it's urbanization level, using CDC data on hypothermia deaths by urbanization level (Berko 2014).

Since the rate of deaths labeled as "hypothermia" does not account for heat exacerbated chronic diseases, this rate was multiplied by 100 based on an estimate that approximately 1% of cold-related excess deaths in the US are due to hypothermia (Caplan 1999). For cold-related ED visits and hospitalizations, I multiplied the NYC ratio of cold-related ED visits and hospitalizations to hypothermia deaths by the county-level hypothermia death rates. I assumed that all indoor cold-related morbidity and mortality could be avoided with a DER, which would ensure that a house could be affordable heated to a comfortable temperature. The CDC estimate for percent of death from extreme cold that occur indoors was 23% (CDC 2006).

The cost of the excess morbidity and mortality from cold stress was calculated by multiplying the excess deaths by the VSL, and the ED visits and hospitalizations by average ED visit and hospitalization costs. The ED visit and hospitalization costs were not more specific because of the variety and range of severity of conditions exacerbated by cold stress. The ED visit and hospitalization costs were also adjusted based on the state healthcare cost index.

Figure 6 shows the total annual benefit for the average household for cold stress by county. Costs range from $705 in San Bernardino County, CA to over $60,000 per household per year on the Arizona and New Mexico border. This area was an extreme outlier for cold deaths, likely due to high poverty rates and often lack of basic services for Native American reservations in the area, including the Navajo Nation, and the Hopi, Ute, and Zuni tribal reserves. Extreme poverty, high rates of chronic disease, and sometimes lack of basic services such as electricity means that households in this area are particularly susceptible to cold stress, as average nighttime temperatures in this area reach 16F during the winter and average daytime highs around 91F in the summer. For cold stress, the average out of pocket costs range from 0.2% to 0.3% of total costs; because over 97% of the costs of heat stress come from the cost of cold stress deaths which are calculated with the value of statistical life and included as a public cost.

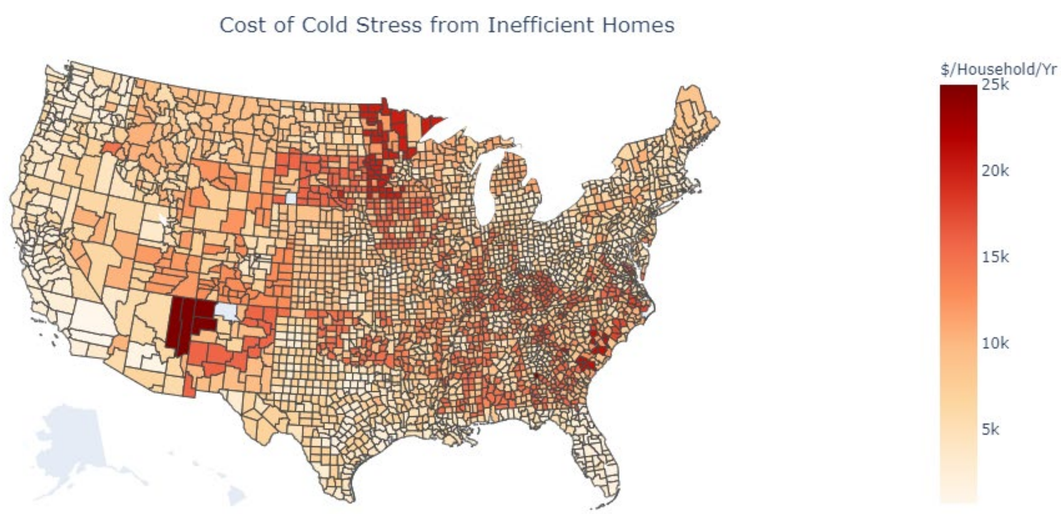


Figure 6: Cost of Morbidity and Mortality from Cold Stress due to Energy Inefficient Homes in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

Missed Work from Poor Household Health Exacerbated by Inefficient Housing

The health impacts of poorly insulated, drafty, inefficient housing can lead to missed work for adults and missed school for children. The estimates here account for missed work avoided due to reductions in asthma and exposure to extreme indoor temperatures arising from weatherization, as well as any other effects such as improved sleep or mental health. It also accounts for missed days of work due to a parent needing to stay home with a sick child. Secondary effects of missed work and income reduction, such as increased risk of losing a job or cascading effects for household health due to missed income were not included in this calculation. Long term effects of missing school were also not included. Self-reported data from homes treated with WAP were used to determine the number of days of missed work avoided. This was multiplied by the average cost of missed workdays, which was conservatively calculated based on the statewide minimum wage. For the 66% of low-income workers without paid sick leave (E. Gould 2021), the missed workdays were considered a private cost.

The total benefit for the average household for missed workdays ranged from $68 in states with the federal minimum wage and $142 in DC, which has the highest statewide minimum wage. Although some cities have higher minimum wages than their state, these variations are omitted, underestimating the costs of missed workdays.

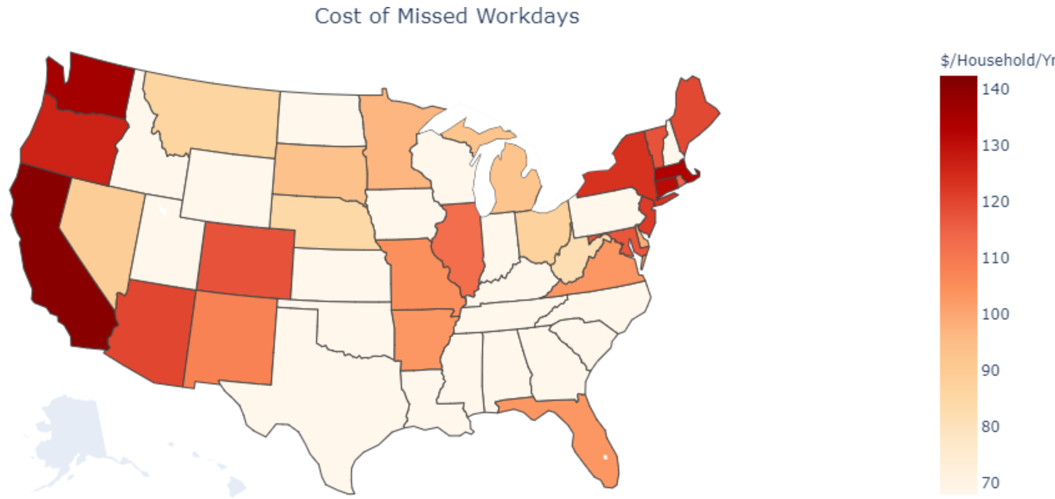


Figure 7: Cost of Missed Workdays from Poor Weatherization by State in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

Energy Benefits

To estimate the energy savings by household from a deep energy retrofit, I modeled the effect of these upgrades on electricity, gas, and fuel oil use on an average unit for five building unit types in each county in the continental US. The five building unit types are: single family detached, single family attached, 2-4 unit multifamily, 5+ unit multifamily homes, and mobile homes. Boats, RVs, and Vans were excluded.

Average annual electric, gas (utility and bottled), and fuel oil expenditures from 2018 were derived for all households below 200FPL from DOE's LEAD Data Tool by county and building type. First, these expenditures were converted to energy use in Btu/year by (1) adjusting for inflation from 2018 to 2020 using the CPI (Bureau of Economic Analysis 2021b) and (2) dividing by the cost per Btu from the EIA. Second, energy use by fuel type was broken out into end uses using RECS data for each census region and building type (EIA 2018). Efficiency upgrades and fuel changes from the prototypical retrofit outlined in Table 1 were then applied for each end use. The changes in fuel use from a retrofit with electrification are nuanced because electrification of a fossil appliance eliminates that fossil fuel use in exchange for increased electricity usage. The swap is not one-to-one, because electric appliances are typically significantly more efficient than fossil fuel appliances. In addition, improvements in the building envelope decrease the total energy required for heating and cooling. More details on the methodology for determining changes in energy use for each combination of building type and county are included in Appendix B: Equations and Sources for Energy Savings Calculations.

Table 1: Upgrades included in Modeled Deep Energy Retrofit

Upgrade	Effect on Energy Use
Envelope improvements: insulation and air sealing	Energy needed for heating and cooling will decrease
Replacement of fossil heating systems (if applicable) and electric air conditioning (if applicable) with air source heat pumps	If replacing a fossil heating system, gas or fuel oil use for heating will be eliminated and replaced with a smaller amount of electricity use because of the higher efficiency of heat pumps compared to fossil heating systems. If replacing a typical electric air conditioning system, electricity use will decrease because heat pumps are more efficient than both non-heat pump AC units and window AC units. Window AC units are by far the least efficient of these three options, in part because of leaks between the window and the unit.
Replacement of electric resistance water heater with electric heat pump water heater **OR** Replacement of fossil water heating system with heat pump hot water heating system	Energy needed for electric water heating will decrease **OR** Gas or fuel oil use for water heating will be eliminate and replaced with a smaller amount of electricity use
Replacement of existing refrigerator with ENERGY STAR refrigerator	Reduction in electricity needed for refrigeration

Note that the replacement of gas stoves and oven with induction stoves and electric ovens, as well as reductions in plug load (lighting, electronic device charging, other kitchen appliances, etc.), have not been included. Use of cooking appliances and other plug loads vary significantly across and within the US so estimating energy changes to these categories was not within the scope of this project. However, while the energy savings from switching from gas to electric cooking are a small fraction of total energy savings from retrofitting, the health benefits are quite significant, so these are included in the health benefits.

Retrofit Costs

The cost of implementing residential energy efficiency retrofits increases with higher energy savings goals. For example, replacing lightbulbs and adding insulation to the attic are inexpensive and deliver moderate energy savings, while replacing HVAC systems, adding solar PV, and super insulation are more expensive, but deliver much larger savings. A deep energy retrofit can use integrated design, where all building systems are analyzed to find synergies and achieve high energy reductions with lower retrofit costs (Bertoldi 2014; Moser et al. 2012). For example, replacing a furnace with a heat pump to cover the peak winter load may require a large heat pump, but combined with an increase in insulation, tighter envelope, and high-performance windows the peak heating load will fall, reducing the capacity and cost of the heat pump required. In the 2009 deep energy retrofit of the Empire State building, a planned $17.3 million replacement of the building's chiller plant was avoided by reducing cooling loads for the building through insulation, replacement of the windows, and other measures, which also reduced peak heating load (Bertoldi 2014). Piggybacking on required maintenance activity can also reduce the marginal cost of deep energy retrofits. The marginal cost of adding insulation to walls and roofs is small when a planned roof replacement or remodeling project mean the walls will be opened, siding stripped off, and roof replaced. Projects to address deferred maintenance, or required to remediate mold, lead paint, asbestos, and other hazards, offer the opportunity to reduce energy use beyond building code at low marginal cost, and can yield significant savings (Lyneis and Sterman 2016).

Studies assessing the costs of deep energy retrofits are few because they are much less common than moderate or light energy efficiency retrofits. Most existing energy efficiency programs reduce energy use by less than 50% and do not use integrated design that can realize larger energy savings at lower costs. In addition, existing studies have found significant variation in DER costs arising from differences in existing condition of building elements, the accessibility or complexity of a dwelling, customer preferences, dwelling size, moisture problems, asbestos, lead paint, or electrical and structural problems.

Because calculating bottom-up estimates of retrofit costs for an "average" house was not possible, I estimated the cost per square foot of a DER based on data on cost and energy savings from three state energy efficiency programs (Connecticut, New Jersey, and Vermont) and from 1,739 single family residential energy efficiency retrofits compiled by the Lawrence Berkeley National Laboratory (LBNL) and clustered into six retrofit types. Since the cost of a retrofit per square foot is driven by the amount of retrofitting done, I fit a power function cost curve to the retrofit cost per square foot versus percent energy savings (data table and graph of fit power curve is shown in Appendix C: Retrofit Costs). The average square foot cost of the retrofit was then estimated by applying the fit power law function to the total site energy savings calculated by county. The cost per square foot is then multiplied by the regional low-income average square footage per unit for people making less than $60,000 per year (approximately twice the federal poverty limit for a family of four) from RECS (EIA 2022a) to estimate the average cost of that retrofit across the county. The average retrofit cost per unit is then adjusted by a construction cost index for each state based on labor and materials costs (Oelze 2020).

The method I describe below makes a few assumptions. First, almost a third of households making below $60,000 live in multifamily housing and 9% live in mobile homes, while the estimated cost curve is based on studies primarily considering single family detached housing because of limited data on costs per square foot for retrofits of multifamily buildings (EIA 2018). However, deep energy retrofits of multifamily buildings are likely less expensive per square foot than single family buildings. As the number of units in a building grows, the ratio of building envelope to volume decreases so it needs less external insulation and air sealing, and fewer window upgrades. Larger buildings that share systems for heat, hot water, and air distribution can also offer economies of scale, reducing the cost of retrofit compared to the same number of units in single-family homes. Lastly, available studies on DER costs and benefits overrepresent states that have taken more action to incentivize retrofits such as California, Connecticut, New Jersey, New York, and Vermont. Because most of these states have higher construction costs than areas in the South and Midwest, the cost curve likely overestimates the cost, leading toto underestimates of the NPV in these areas.

Cost-Benefit Comparison (NPV)

The net present value for the cost-benefit comparison is calculated using a flow of benefits discounted over the assumed 30-year lifetime of the retrofit. I calculate the NPV of the DER using four different measures for the flow of benefits: (i) energy savings only, (ii) energy and private health savings, (iii) energy, private health savings and public health savings, and (iv), the energy, public and private health cost savings. For more detailed NPV calculations see Appendix D: Cost Benefit Comparison.

Results

Cost Benefit Analysis

Table 2 summarizes the average cost per household for the 34 million households under 200% of the federal poverty line in this analysis. Overall, health contributes the most to benefits across households, mostly from reduced morbidity and mortality from excess cold. Energy savings contributed an average of $543 per household annually.

The total potential emissions reductions from this retrofit policy would be 82 million metric tons, or approximately 38% of annual emissions from <200FPL housing or 10% of emissions from the US residential sector (US EPA 2021). The cost of reducing these emissions comes out to just under $0 per MT CO_2e with public and private benefits and $219 per MT CO_2e if only including private benefits. In comparison, unsubsidized rooftop solar is estimated at $287 per MT CO_2e (Friedmann et al. 2020).

Table 2: Summary of Costs and Benefits across the Continental US

Summary Metrics (national weighted average for counties in the continental US)	Average per Household ($/year)	Total Benefit Across all Households <200FPL ($Billion/year)
Energy Savings	$543	$19
Health Benefits	$6,965	$240
Asthma from Gas Stoves	$119	$4
Asthma from Lack of Insulation and Air Sealing	$88	$3
Excess Heat	$1,582	$55
Excess Cold	$5,080	$175
Annual Public and Private Benefits	*$7,630*	*$263*
Total Retrofit Cost	$41,140	$1,418
NPV including Public and Private Benefits over Retrofit Lifetime (with 3% discount rate over 30 years)	$175,279	$6,041
Annual Emissions Avoided (CO_2e)	*2.39 MT/year*	*82 MMT/year*

Figure 8 shows the average annual energy saving from retrofits for <200FPL households by county and Figure 9 shows the NPV based on these energy savings. While all counties save in annual energy costs post retrofit, in the northern and western parts of the country the energy savings do not make up for the initial DER cost. Because the DER includes electrification, in areas where electricity is significantly more expensive compared to natural gas or fuel oil, electrifying reduces the annual savings that come from reducing energy use. In addition, the effect of a higher statewide construction cost index is visible along the east and west coasts. While this map does not account for energy efficiency incentives available at the state level, it makes it clear that existing incentives are severely inadequate for making up the NPV gap in states where the NPV of energy savings is negative. For example, Massachusetts offers some of the highest energy efficiency rebates in the country with up to $2,000 rebate for purchase of an air source heat pump, $1,700-3,500 for the upgrade of a water heater more than 30 years old, $400 for replacement of an old clothes washer with ENERGY STAR washer, and $250 for replacement and recycling of old refrigerator with ENERGY STAR refrigerator, as well as discounts on items like LED lightbulbs and power strips (Mass DoER 2020). These rebates, in the best case totaling $6,150, pale in comparison to the value needed to close the negative NPV gap of $15,000 to $50,000 for a DER in Massachusetts (Mass DoER 2020). Still, for 29% of counties, mostly in the south, the average NPV only including energy savings is positive.

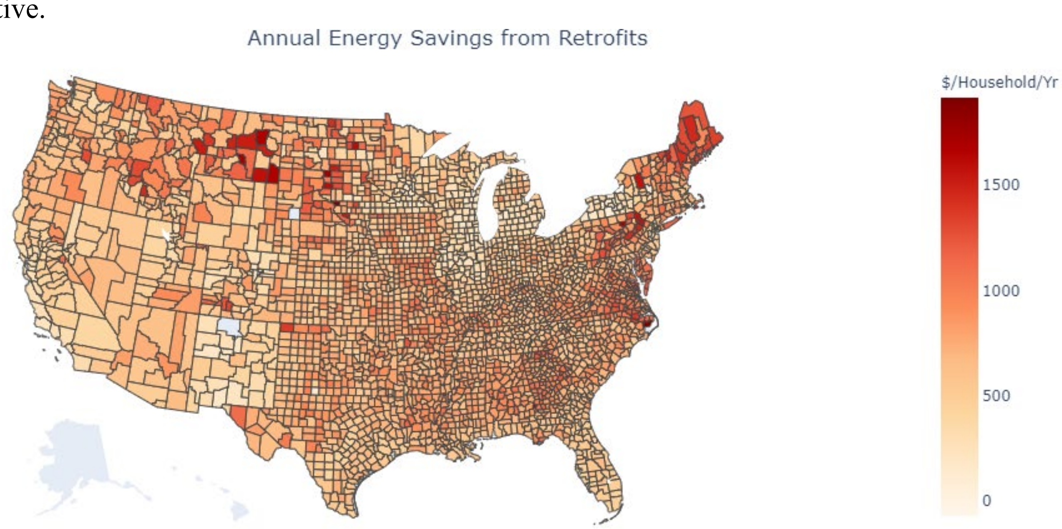


Figure 8: Energy Benefits from Retrofits in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)

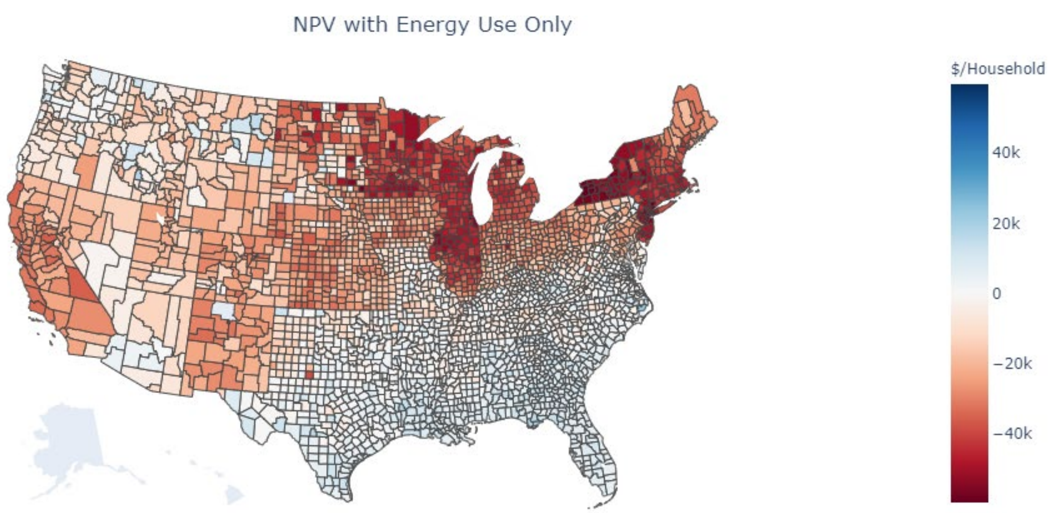


Figure 9: Net Present Value of Retrofits Considering only Energy Benefits in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)[1]

Figure 10 shows the average private health benefits from DERs for <200FPL households by county across the US and Figure 11 shows the private benefit NPV for DERs, which includes private energy and

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[1] Energy expenditure data from Rio Arriba County in New Mexico and Oglala Lakota County in South Dakota are missing from the LEAD Tool

health benefits. Figure 11 looks fairly similar to the energy only benefits map shown in Figure 9 because private health costs are low compared with annual energy savings. Most health costs for low-income populations are publicly covered by Medicare, Medicaid, or other insurance. Including private health benefits and energy savings, means that 37% of counties have average positive NPVs.

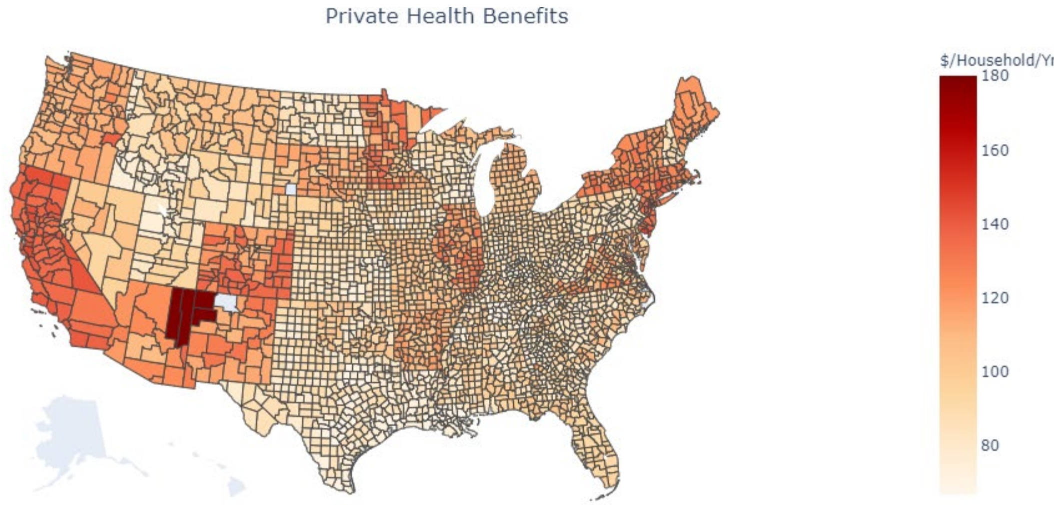

Figure 10: Private Health Benefits from Retrofits in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year) [2]

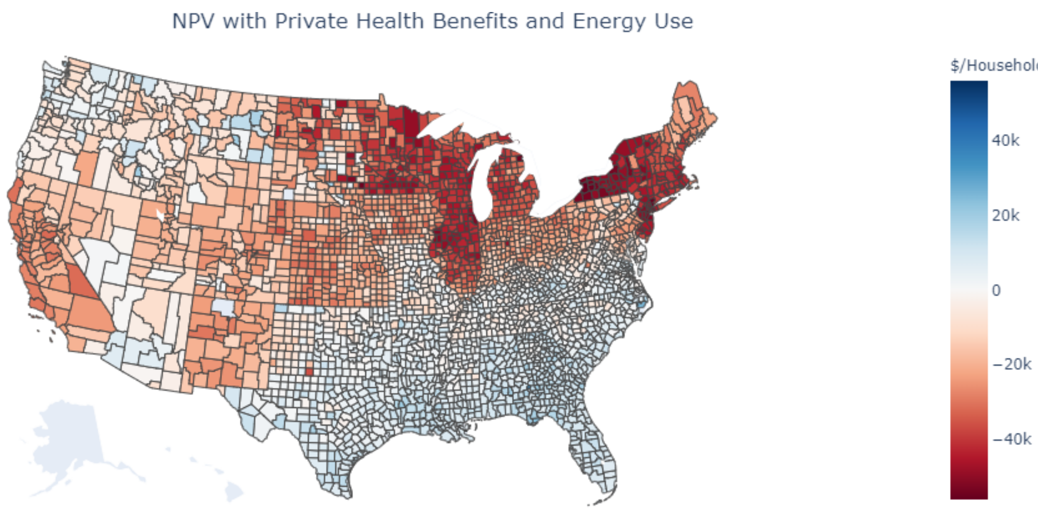

Figure 11: Net Present Value of Retrofits Considering only Private Benefits in Households Earning Less than 200% of the Federal Poverty Level ($/Household)[3]

Figure 12 shows the average annual public and private health benefits per household from DERs across the US and Figure 13 shows the NPV for those DERs including public and private health benefits and

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[2] Counties with Native American Reservations in Arizona and New Mexico had such high death rates from Cold Stress that the scale in this figure had to be truncated to see variation in the other counties. The outliers are visible (non-truncated) in Figure 10: NPV Range of Retrofits for US Counties

[3] Counties with Native American Reservations in Arizona and New Mexico had such high death rates from Cold Stress that the scale in this figure had to be truncated to see variation in the other counties. The outliers are visible (non-truncated) in Figure 10: NPV Range of Retrofits for US Counties

energy benefits. The public health benefits dwarf the energy and private health benefit making NPV positive for every county analyzed. Thus, when considering a range of public and private benefits, it is, on average, economically worthwhile to do a DER on all <200FPL units in the contiguous US.

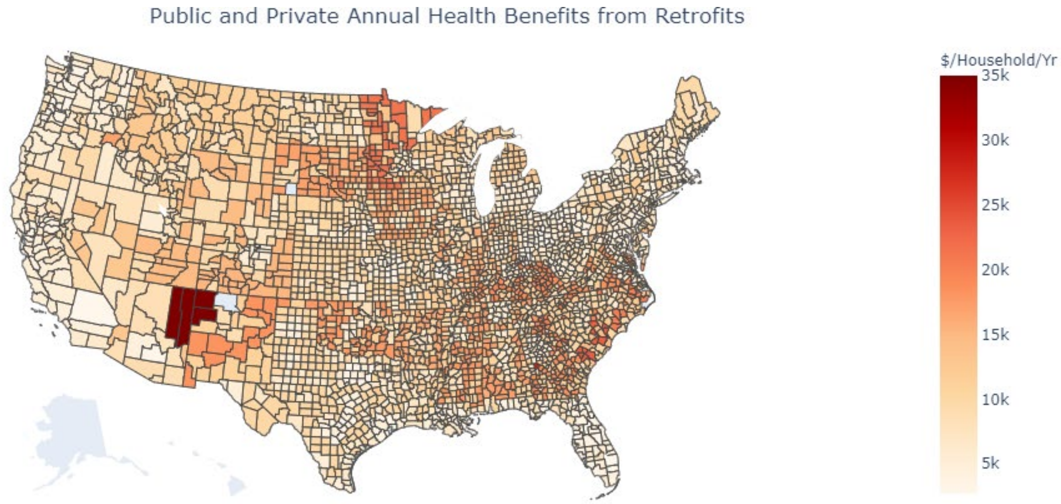

Figure 12: Public and Private Health Benefits from Retrofits in Households Earning Less than 200% of the Federal Poverty Level ($/Household/Year)[4]

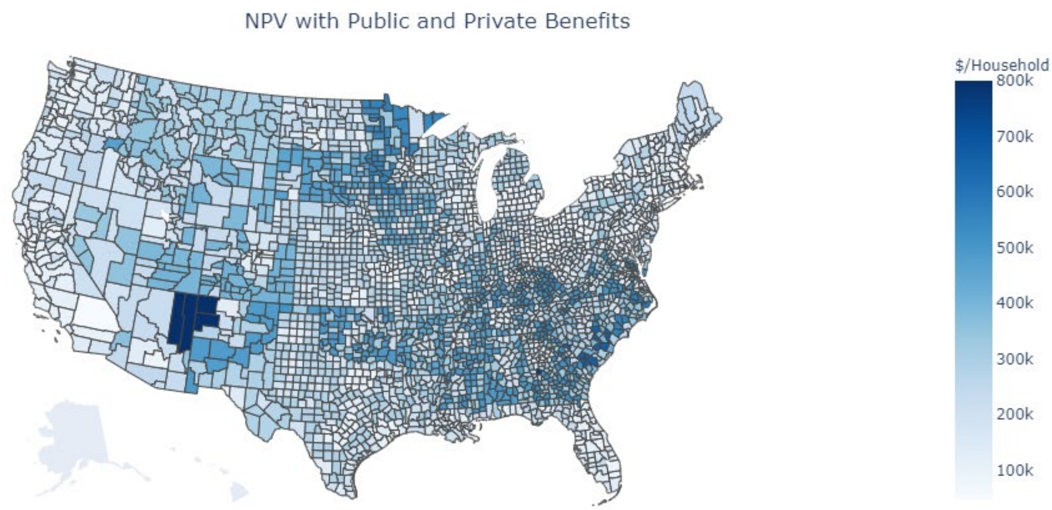

Figure 13: Net Present Value of Retrofits considering Private and Public Benefits in Households Earning Less than 200% of the Federal Poverty Level ($/Household)[5] [6]

Finally, Figure 14 shows the range of NPVs across counties in a boxplot for NPV calculations included different benefits. While the median NPVs for both private and energy only calculations are negative,

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[4] Counties with Native American Reservations in Arizona and New Mexico had such high death rates from Cold Stress that the scale in this figure had to be truncated to see variation in the other counties. The outliers are visible (non-truncated) in Figure 10: NPV Range of Retrofits for US Counties

[5] Counties with Native American Reservations in Arizona and New Mexico had such high death rates from Cold Stress that the scale in this figure had to be truncated to see variation in the other counties. The outliers are visible (non-truncated) in Figure 10: NPV Range of Retrofits for US Counties

[6] Energy expenditure data from Rio Arriba County in New Mexico and Oglala Lakota County in South Dakota are missing from the LEAD Tool

there are a significant number of counties for which the average NPV is positive. Meanwhile, if public benefits are included, all counties have positive NPVs over a significant interquartile range from under than $0.1M to over $0.5M. Notably, the extent of the outliers from Arizona and New Mexico can be fully seen, whereas in the heatmap figures ranges had to be truncated to see the variation across the rest of the country.

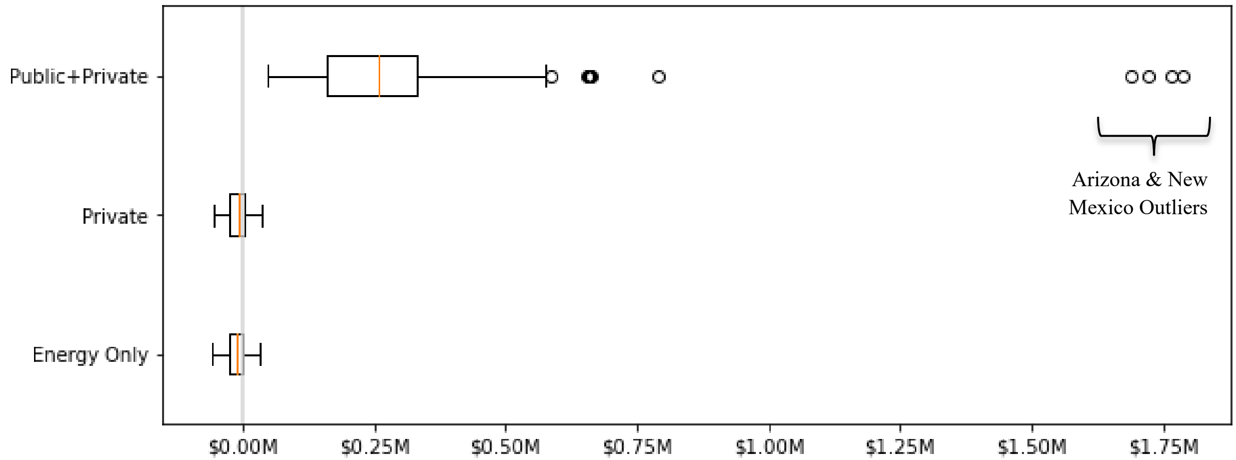


Figure 14: County Average Net Present Value Range of Retrofits for in Households Earning Less than 200% of the Federal Poverty Level ($/household)[7]

Sensitivity Analysis

The cost benefit results have significant uncertainty because limitations on and uncertainty in the data and assumptions used in the analysis. To assess the impact of these uncertainties I performed a Monte Carlo simulation varying four key parameters: energy prices, health costs, retrofit costs, and the discount rate used to calculate the NPV. The energy prices and health costs have been bundled to reduce the dimensionality of the uncertainty analysis. The assumption made in bundling energy prices and health costs is that all components of each bundle are perfectly correlated. While this simplification means that the resulting range of NPVs is overestimated, there is good evidence that this is a reasonable assumption. The majority of electricity in the US is generated from natural gas in recent years, so these prices are strongly correlated and, my review of historical residential energy prices found that fuel oil, electricity and natural gas prices are positively correlated from 1978-2020 (EIA 2022d; 2021; US EPA 2021). I used the weighted variation in these historical prices to determine an appropriate range for the sensitivity analysis (EIA 2022d; 2021). The bundling of disparate health costs also likely overestimates the resulting range of NPVs because the components of the health costs are not perfectly correlated. Due to the inherent uncertainty in these calculations, particularly the extreme temperature morbidity, I applied a larger range of uncertainty to this bundle. Retrofit costs include both labor and materials costs, and vary by region, unit size, remediation required, and other factors. The probability of cost overrun is more likely than cost overestimates on construction projects, which is reflected in the longer right-tailed range (Aljohani 2017). Lastly, the discount rates range reflects the range of cost of capital for low income

[7] Counties with Native American Reservations in Arizona and New Mexico had such high death rates from Cold Stress that the scale in this figure had to be truncated to see variation in the other counties. The outliers are visible (non-truncated) in Figure 10: NPV Range of Retrofits for US Counties

households from various government programs and private sector sources (Gellerman 2022; "Loans for Homeowners" 2022; USDA 2015). Table 3 shows the range and distribution of values for these four key components. Further information about how these ranges were chosen and distributions calculated is available in Appendix E: Sensitivity Analysis.

Table 3: Range of Sensitivity Variables for Uncertainty Analysis

Variable	Values	Distribution
Discount Rate, r	(1%, 6%)	Uniform
Energy Price	(-16%, +28%) of local energy price from EIA	Triangular
Health Costs	± 50% of local total annual health cost calculations	Triangular
Retrofit Costs	(-30%, +50%) of calculated retrofit cost	Triangular

Figure 15 shows how the results vary with ten thousand simulations with samples from each distribution used to calculate the NPV. Specifically, the left graph of Figure 15 shows the distribution of the population weighted median NPV across all counties for each simulation, and the right graph shows the number of counties with positive NPV. While the NPV itself varies substantially when including public health costs (left graph), in almost every simulation all counties in the US have positive NPV. This means that even with significant uncertainty involved in the discount rate, energy prices, health and retrofit costs, when including public costs in the cost benefit analysis, it will be worthwhile to retrofit all low-income housing in almost every county.

In comparison, the median NPV of the energy savings and private health care costs across all counties hovers around $0, but changes in the parameters significantly affect how many counties have positive NPV. This means that when only considering private costs even small changes in discount rates, energy prices, private healthcare costs and retrofit costs can significantly change how many counties for which it is worthwhile on average to retrofit low-income units. As noted throughout, the private NPV is underestimated since many direct impacts of inefficient housing and the impacts from the reinforcing feedback loops highlighted in the introduction were not quantified. Because the private NPV is so sensitive to these costs, it is important for future work to fully account for more of the private benefits. In addition, the sensitivity results highlight the importance of considering the private and public health benefits of retrofits in analyses of energy efficiency policy. Subsidies could play an important role to reduce the economic inefficiency created from the large difference between public and private costs for low-income DERs.

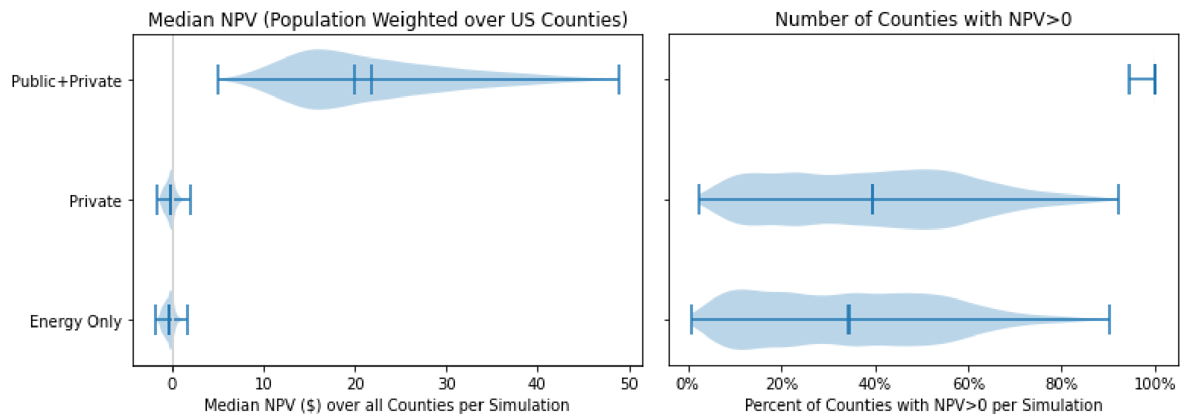
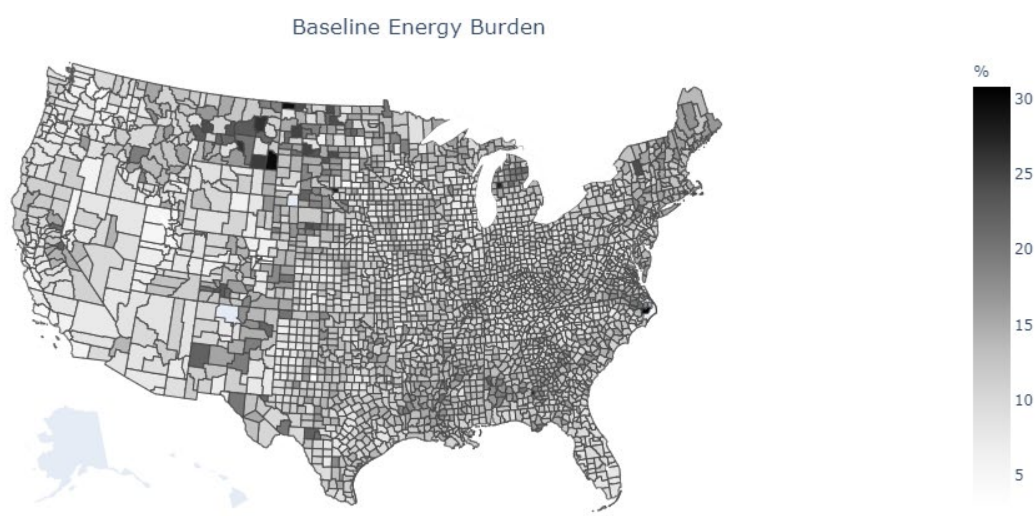


Figure 15: Monte Carlo Sensitivity Analysis Results for the Net Present Value of Retrofits in households earning less than 200% of the Federal poverty level

Energy Burden Analysis

Using the data on baseline emissions and emissions reductions due to DERs in LMI housing across the US, I calculated the impact of $51/t CO_2e[8] carbon price on household energy burden (annual household energy expenditures divided by household income) across the US for baseline energy use and energy use after DER implementation. The spatial analysis of energy burden builds on recent work from Green and Knittel that looked at the full impact of a carbon price across the US at the census block level (Green and Knittel 2020). Similar to Green and Knittel's findings, coal-heavy states in the the Upper Midwest and Appalachia took the hardest hit on energy burden with a carbon price, with counties in North Dakota seeing increases upwards of 10%. Meanwhile coastal states and states with significant wind or solar in their electricity mixes such as Texas, Nebraska and Iowa mostly had increases of less than 5% (Figure 17). However, these figures assume the baseline, existing energy use. After retrofits, states in the Midwest and Eastern US saw equally if not more significant decreases in energy burden (Figure 18).



[8] This current interim value of Social Cost of Carbon under the Biden Administration (Brown 2022)

Figure 16: 2018 (Baseline) Energy Burden (Energy Expenditures/ Household Income) for Households Earning Less than 200% of the Federal Poverty Level (%)

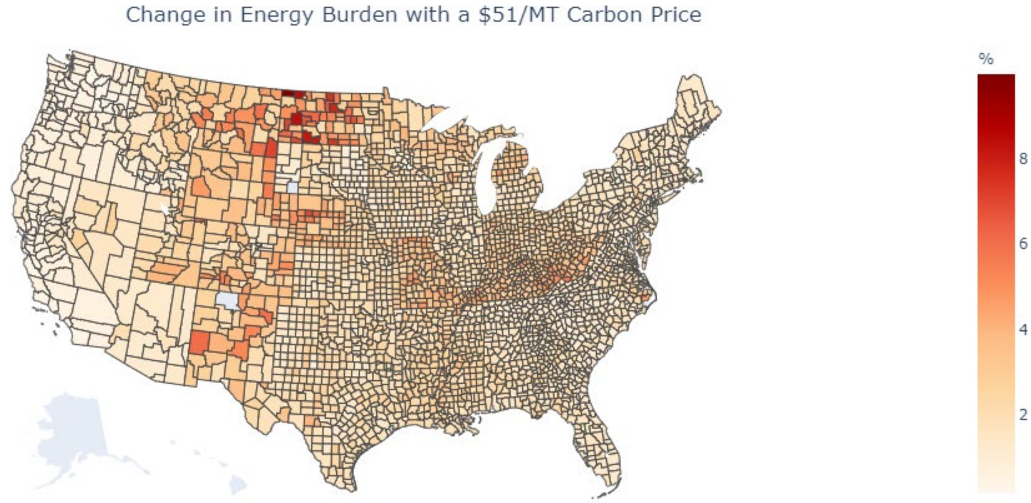


Figure 17: 2018 Energy Burden with a Carbon Price in Households Earning Less than 200% of the Federal Poverty Level (%)

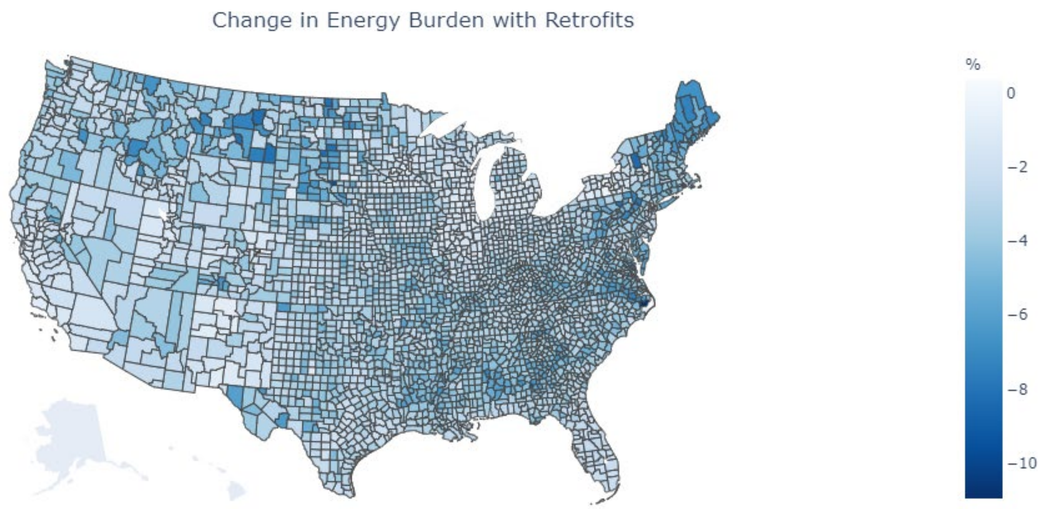


Figure 18: Change in Energy Burden from Retrofits in Households Earning Less than 200% of the Federal Poverty Level (%)

In fact, a carbon price on top of energy efficiency retrofits would decrease the energy burden for the average household below 200FPL compared to the baseline, as shown in Figure 19. However, while the vast majority of counties would have a decreased energy burden after retrofits and a carbon price, a few areas would not, specifically New Mexico and parts of North Dakota (Figure 20). The increase in costs after a retrofit and carbon price is due to high carbon intensity of electricity in these areas; continued decarbonization of the electric grid will mitigate these costs.

Based on these results, in most areas of the US mass scaling of energy efficiency retrofits could be a complementary strategy to eliminate the potentially regressive impact of a carbon price on low-income communities and further reduce emissions. However, in areas where this would further increase the energy burden, additional support for these households would be needed to not burden them further. One way to do this would be rebating the revenue generated from the carbon price.

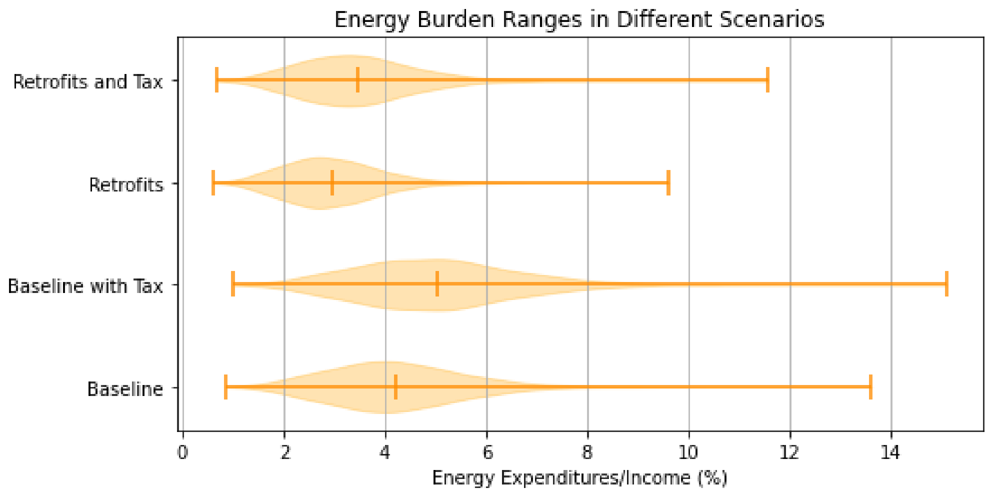


Figure 19: Energy Burden in Different Scenarios for Households Earning Less than 200% of the Federal Poverty Level (%)

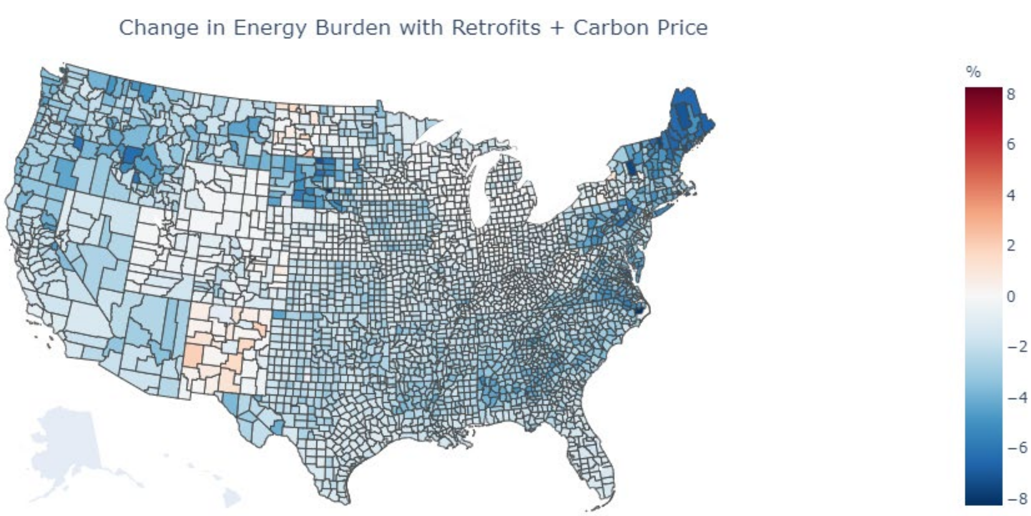


Figure 20: Change in Energy Burden from Carbon Price + Retrofits in Households Earning Less than 200% of the Federal Poverty Level (%)

Discussion

The results show deep energy retrofits in the US for low- and moderate-income housing have large potential to simultaneously reduce greenhouse gas emissions and yield economic, health, and equity benefits. Such retrofits are on average cost effective—yield positive net present value—in all counties in the contiguous US when including both private and public benefits. However, the average net present value of the energy reductions and private benefits alone are positive for only about 37% of counties. wide-scale implementation of DERs across the US for low-income households therefore requires funding to address the externality gap between public and private benefits. Some of the costs would be quickly paid for by reductions in Medicare, Medicaid, and LIHEAP funding; others would accrue over time as reductions in the energy burden and health issues faced by low-income individuals fall, as their income improves, as they face lower risks of job loss, eviction, homelessness, and as their children do better in school. Nevertheless, even in counties where DERs are on average net positive with only private benefits, owners and occupants of low-income housing may still face barriers in getting credit and require subsidies and other policies to overcome institutional and market failures limiting the uptake of retrofits. The remainder of this section discusses considerations for and consequences of implementing a large scale residential retrofit policy in the United States. These include how to identify the best homes for energy efficiency retrofits, realigning incentives for owners and tenants, incentivizing utilities to pursue energy efficiency, ensuring adequate labor and material supplies, and equitable policy implementation.

Prioritizing Retrofits at the Local Level

For all counties on average, it is worthwhile to retrofit every <200FPL unit when public and private health benefits are included, and worthwhile for 37% of counties when considering private benefits alone. However, county averages conceal significant heterogeneity in many aspects relevant to the implementation and prioritization of retrofits, including health vulnerability, initial home condition, heating fuel type, and more.

Federal and state programs could use the county-level estimated private and public NPVs of retrofits to identify areas where programs to bridge the gap will be most effective, similar to the way WAP primarily focuses on homes in the Upper Midwest and Northeast. However, in addition to regional targeting of programs, program implementation would benefit from more granular analysis at a local level to identify the houses where DERs provide the most "bang for the buck." Prioritizing these households would increase NPV and even allow programs where the county-wide private average NPV is negative to identify NPV positive LMI housing units to retrofit. For example, a retrospective analysis of WAP programs found that better targeting of retrofits for a subset of WAP programs could have increased average private energy benefits per subsidy dollar from -$0.18 to $2.53 (Allcott and Greenstone 2017). Access to highly granular utility data on energy use load profiles and building characteristics would enable these households to be identified.

Another way to optimize societal benefits would be to identify those whose health issues could be improved through weatherization to participate in a retrofit program. Currently, eligibility for WAP is assessed primarily on the cost of retrofits relative only to the energy costs saved. Consequently, the housing in most need of improvement is often disqualified, even though the people living in such poor-quality housing are most likely to suffer adverse health impacts. Criteria for eligibility should be assessed using the return on both the direct energy savings and the private and public health and economic benefits of retrofits. For example, the program Warm-up New Zealand provided insulation to low-income renter households who were first identified as having high health needs (Grimes et al. 2012). Such prioritization maximizes health benefits so much so that a cost benefit analysis found that the health savings were more than 50 times greater than the private energy savings. The best way to collect data on health impacts of DERs would be to do a randomized control trial collecting actual health expenditures and health indicators before and after a retrofit. Existing randomized controlled studies for WAP rely on a limited list of self-reported health indicators and thus do not accurately capture the full range of health costs. A larger study would also allow for measurement of changes in rarer but costly or fatal conditions.

While optimizing for the highest NPV would improve the cost effectiveness of retrofit programs, it is important from an equity perspective to consider homes with low NPV due to the extra costs for remediation of lead, asbestos, mold, and structural damage often present in the oldest, least energy-efficient housing. These homes are often excluded from programs like WAP because they require more work, but they also have the highest energy burdens and health risks, many of which, like lead poisoning, are not included in my analysis. Low-income homes with these issues are common: in a review of low-income weatherization programs in Connecticut from 2017 to 2019, 23% of eligible households faced barriers to participating in the weatherization program from combinations of asbestos, mold, vermiculite and pests (Connecticut Energy Efficiency Board 2020). Addressing these issues will require expanding program capacity to deal with asbestos, mold and lead remediation and developing a clear referral system to other programs for homes with problems beyond the scope of the retrofit program. Retrofitting housing early can also prevent issues such as mold, pests, and structural problems from developing in the first place.

Measuring and optimizing for both health and climate outcomes are important for efficiently delivering on health and climate priorities and for tracking results. A successful large-scale retrofit program would need to utilize and enable the development of more detailed data and models to identify benefits and costs at a more granular level and results to be monitored. These costs of analysis and monitoring would likely be paid back quickly with the ability to better identify costs and benefits.

Realigning Landlord and Tenant Efficiency Incentives

Almost two-thirds of households <200FPL are renters, so any low income retrofit program must work for owners as well as renters (DOE 2021). When tenants are responsible for paying their full energy bill, owners are disincentivized to invest in energy efficiency because they do not reap the benefits of lower energy costs. At the same time tenants are unlikely to invest in energy efficiency measures both because implementation may not be permitted or feasible, and they aren't guaranteed to reap the benefits over the length of their tenancy. These dynamics are referred to as the landlord-tenant split incentive, which results in 4% higher heating and 3% higher cooling costs for US tenants than demographically similar owners (Melvin 2018).

One way to address the split incentive is for utilities or government entities to fully subsidize energy efficiency upgrades for landlords. For example, the Massachusetts state energy efficiency program MassSave offers 100% rebates for insulation and sealing to building owners (MassSave 2021). While a full subsidy eliminates capital costs of installing upgrades, it does not eliminate the "soft costs" of coordination between landlords, tenants, and contractors. These soft costs can contribute to the landlord split incentive even when direct costs are covered, which makes it crucial to have streamlined, user-friendly programs.

Governments at all levels can also engage with groups representing owners and tenants to develop guidelines and model contracts for rental housing to address the split incentive, and to speed communication and training that can increase adoption. Such "green lease" rental contracts have been developed California ("California Green Leasing Report and Toolkit" 2017). A green lease contract allows for tenants and owners to split the benefits of energy efficiency savings. Because a green lease requires the ability to track baseline energy usage to accurately calculate savings from energy efficiency, they can be deployed quickly in buildings with utility metering at the apartment level. Installation of submetering, smart meters and other means to track energy use more finely would lead to further adoption.

A third option is to require an energy efficiency audit or disclosure of utility bills at the time of rental (or sale, in the case of owners) to overcome the low visibility of energy efficiency compared to monthly rent. For example, New York's Truth in Heating law requires the release of utility data for residential buildings at the time of sale or rental (ACEEE 2020).

Realigning Utility Goals with Customers and the Climate

Under traditional regulation, gas and electric utilities are disincentivized to help customers become more energy efficient because they recover fixed costs of electricity generation or gas distribution infrastructure through sales of gas or electricity, making it more profitable to sell more energy. These misaligned incentives have led to utilities lobbying against stricter energy efficient building codes and appliance standards (Balaraman 2020) and organizing coordinated campaigns to prevent policies encouraging electrification (Holden 2020).

Restructuring rates so that utilities are instead incentivized to provide reliable service at the lowest cost, called "decoupling", can realign utility incentives with customers and the climate. Twenty-three states already have legislation requiring decoupling for either electric and/or gas utilities and these policies could be adopted for both fuels nationally (NRDC 2018). Variations on this policy that similarly incentivize utility investments in energy efficiency, such as requiring treatment of energy efficiency as an energy resource on similar footing to supply resources, setting aggressive energy saving targets, and providing shareholder incentives to reward investor-owned utilities for cost-effective energy efficiency (NRDC 2018).

Beyond realigning incentives, there is a larger issue faced by natural gas utilities that view electrification an existential threat to their business of selling natural gas. In response, the American Gas Association (AGA), which represents gas utilities, has succeeded in persuading twenty states (mostly in the south) to pass laws prohibiting bans on new residential natural gas hookups (CNN 2022). Natural gas utilities have also been running media campaigns in support of gas by advertising gas stoves as luxury goods, paying Instagram influencers to show themselves using gas stoves, and even distributing pro-natural gas activity workbooks to elementary school children in Massachusetts (Holden 2020; *The Associated Press* 2021). To prevent these actions some public utility commissions have instituted rules that prevent utilities from using ratepayer funds to advocate against energy efficiency or electrification and have required increased transparency and disclosure of spending. While these rules are helpful, they do not address the root of the issue, which is the need for plans for the phaseout or transition of natural gas utilities as the residential and commercial sectors electrify.

Ensuring Sufficient Labor and Materials

The COVID-19 disruptions to labor availability and supply chains have highlighted the consequences of increasing prices due to insufficient labor and materials. Even without large scale retrofit policies, the energy efficiency sector, and particularly the construction sector, is already facing serious labor shortages that are limiting growth and raising prices (Foster, Nabahe, and Siu Hon Ng 2020). The main reason for this difficulty is the lack of a sufficient pipeline through vocational programs for technicians, mechanical support, electricians, and installation workers that are needed to implement home retrofits. For the US to limit emissions to meet a 1.5C target, an additional 750,000 energy efficiency jobs would need to be filled annually (Foster, Nabahe, and Siu Hon Ng 2020). Energy efficiency jobs are inherently local and not easily automated, which means that if retrofit demand rises, lack of local energy efficiency installers may lead to higher prices and delays. Filling these jobs will require a ramp up of programs at community colleges with coordination between the private sector, unions, and public sector to ensure that the workforce training programs are teaching the newest skills and to smooth the school-to-job pipeline. It is also crucial there is public funding for energy efficiency incentive programs stable enough to encourage long-term capacity building for education and energy efficiency and construction businesses in the private sector. Such collaborations and steady public support have been effective in other energy sectors to ensure enough well trained labor for the workforce (Foster, Nabahe, and Siu Hon Ng 2020).

Beyond labor, it is important to ensure an adequate supply of the materials needed. In the past two years there have been disruption in the supply chains of raw materials such as steel, aluminum, copper, lumber, and plastics, as well as key components for HVAC and parts like semiconductors. One way to dampen disruption is to increase transparency throughout the supply chain to allow different levels to prepare for shocks as well as to invest in increased fabrication, for example through the Defense Production Act, as is currently being done to reduce semiconductor shortages (Dept. of Commerce 2022). Ensuring adequate supplies of labor and materials for deep energy retrofits can reduce the chance of price increases and slowdowns for retrofits.

Ensuring Equitable Policy Implementation

Another key consideration of a large-scale DER policy for low-income housing is ensuring equitable implementation without causing further harm in low-income communities, for example through "green gentrification." Green gentrification occurs when sustainable development meant to help low-income communities actually ends up raising housing prices and pushing low-income people out of their neighborhoods (K. A. Gould and Lewis 2016). While there are best practices for these policies, such as rent increase limits for building owners who receive housing efficiency assistance, the best way to ensure that that short- and long-term impacts are fully considered is involving key stakeholders such as people who have or will receive retrofits, housing, community and economic development experts, and utility sectors for designing and implementing the policy (Bolon et al. 2021). For example, The City of Seattle's racial equity toolkit requires community stakeholder involvement in development of policies, programs, and budget decisions (Yuen et al. 2017). Working with stakeholders in lower income communities of color has allowed the city to receive feedback and improve on urban planning programs in ways that city leaders had not previously considered (Yuen et al. 2017). Bouyé and Waskow lay out a framework and guidelines for moving beyond a conception of co-benefits toward an equitable approach for policy planning in Figure 21 (Bouyé and Waskow 2021).

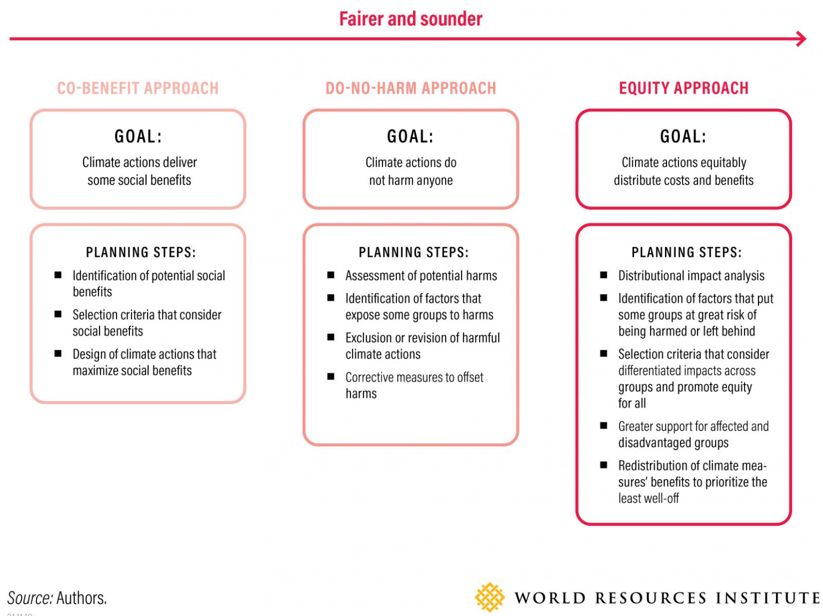


Figure 21: Framework for Improving Approaches to Social Benefits in Climate Policy Planning (Bouyé and Waskow 2021)

Uncertainties and Further Research

As shown in the Monte Carlo sensitivity analysis, the NPV calculations include significant uncertainty. However, in almost every case of uncertainty I chose the most conservative option so that the analysis can provide a lower bound on the net present value of deep energy retrofits.

For example, I do not quantify many well documented health benefits, including morbidity and mortality from reduced outdoor exposure to pollutants including PM2.5 and NOx from fossil fuel combustion in buildings (Vohra et al. 2021), cognitive and physical health impacts of reduced indoor noise pollution (Casey et al. 2017; Basner et al. 2014), lower chances of respiratory disease spread from improved ventilation (World Health Organization 2021a), reduced infectious disease spread from evictions and utility disconnections (Lou et al. 2021; Jowers et al. 2021), and reductions in cognitive impacts and mortality from unintentional non-fire-related carbon monoxide poisoning from fossil fuel appliances (Shochat and Lucchesi 2021; Hampson 2015). Additionally, the analysis does not include the cumulative impacts of mitigating the reinforcing feedbacks identified in Figure 1 that currently act as vicious cycles that amplify the economic, social, and health harms facing low-income households, harms triggered by poor energy efficiency and resulting high energy burdens.

Beyond health benefits, DERs have other economic and societal benefits. DERs can improve home value and prevent structural damage from ice dams, mold, and pests (Ford 2019; Cluett and Amann 2014). They also increase disaster preparedness and climate resilience by allowing houses to keep habitable temperatures for longer during grid outages, which low-income and minority households are more likely to experience (Holmes, Phillips, and Wilson 2016; Wilson 2018; Garnham 2021; EPA 2021). A large-scale DER policy would also increase jobs in the construction, materials, design, appliance, and program management sectors (Griffith and Calisch 2020), and create more and higher paying jobs per million dollars in investment than fossil or renewable energy (Garrett-Peltier 2017).

On the energy side I conservatively assumed that all electrified households would continue to get their energy from the grid. While electrification almost always reduces emissions and annual energy expenditures, it would reduce emissions and energy costs even more for households to source energy from community choice or rooftop solar. Solar PV is now less expensive than conventional sources of electric power (Evans 2020). Further, the greater the fraction of household energy provided by solar the less vulnerable the household is to price spikes in fuel costs, and the lower the risk of triggering the vicious cycles identified in Figure 1. Retrofit policies are complementary to programs designed to provide low income communities better access to community and rooftop solar (Farthing, Popkin, and Tyson 2022). I also do not assume any real time pricing for electricity or demand response implementation, which could make energy efficiency measures even more effective.

For retrofit costs I estimated costs based on many studies that did not use integrated design, which can reduce the cost of retrofits when insulation and air sealing can reduce heating demand enough to allow downscaling of heating system capacity. I also did not assume any timing of retrofits so that fossil systems or other appliances are replaced at end-of-life, which would reduce the net cost significantly, since a new system would have to be purchased anyways. In addition, as the number of retrofits grows, there will likely be learning by doing dynamics and economies of scale that could decrease appliance costs and labor hours required. Already a study of 2012-2017 of natural gas utility energy efficiency programs (before the currently high energy prices due to the war in Ukraine) found that the cost of energy efficiency was 60% cheaper per therm than natural gas (Schiller et al. 2020).

Further research and expanded data availability are needed to assess the value of the benefits I did not quantify, and dynamic modeling could reveal the effectiveness of a DER in converting the vicious cycles of poverty into virtuous cycles that help people escape poverty traps, as described in Figure 1.

Implementing a large scale retrofit strategy for low-income housing will be no small task, but offer large benefits for health, equity, and the climate. The technology needed to scale residential deep energy retrofits exists and is NPV positive across the continental US when health benefits are included along with the direct energy savings. Deploying and scaling retrofits can yield health, productivity, and financial benefits that can help break cycles of poverty and lead us towards a future where all Americans can have healthy, green, and comfortable homes.

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The following appendices include the equations, sources and further information for calculations not included in the main text. The data, spreadsheets, python code for sensitivity analysis and other information needed to replicate and extend the work are available at https://github.com/helenacaswell3/thesis2022.

Appendix A: Equations and Sources for Health Calculations

Throughout this section, in many equations the variables vary by county. To simplify, the county index, i, is suppressed.

The following calculations for cost of a missed workday, fraction of private health costs, and value of a statistical life are used in multiple places in estimating the health costs of inefficient housing:

Average Cost of a Missed Workday/School Day

Missed schooldays are assumed to have the same cost as a missed workday because a parent will have to stay home to take care of a child, particularly for single parents who cannot bring a sick child to daycare and low-income households who cannot afford daycare at all. The assumption may slightly overestimate the costs for two-parent households as some may choose to have the lower-paid or part-time working parent stay home to care for a sick child. The average cost of a missed work/school day also does not include any long term developmental and social costs of children of missing a day of school or marginal increased likelihood of layoffs due to missed workdays and other cascading effects captured in Figure 1 of the main text.

Table 4: Variables Included in Calculation of Cost of a Missed Work and School Days

Variable	Value	Sources and Notes
Minimum Wage ($/hour)	Varies by State (ranges from $7.25/hr-$15/hr)	Paycor ("Minimum Wage by State and 2022 Increases" 2021)
Low-income workers without sick leave (dmnl)	65%	(Bureau of Labor Statistics 2021a, 6)
Average Workday (hours/day)	6.94	("Average U.S. Working Week: December 2021" 2022)
Low-income households with employed primary wage earner (dmnl)	75%	The proportion of families receiving SNAP benefits with at least one person working was 75% (Census Bureau 2020), which tracks with the US Average of 78.2% (Bureau of Labor Statistics 2021b)

Private Out of Pocket and Non-Private Healthcare Costs

The average fraction of healthcare costs that are covered out of pocket (OOP) by a household versus those covered by private or government insurance is calculated based on the percent of costs OOP for private insurance, public insurance, and uninsured multiplied by the percentage of the state population that has private insurance, public insurance, or no insurance. These averages are used to separate private and non-private costs of healthcare.

$\theta_{private,state} = \%OOP_{private}\ \%Private_{state} + \%OOP_{public}\ \%Public_{state} + \%OOP_{uninsured}\ \%Uninsured_{state}$

$\theta_{public,state} = 1 - \theta_{private,state}$

Table 5: Health Costs Covered out of Pocket by Insurance type

	Private (Hawkins et al. 2020)	**Public (Medicare, Medicaid, and Military)** (Hawkins et al. 2020)	**Uninsured** (Coughlin and Samuel-Jakubos 2021)
% Costs Out of Pocket (OOP)	12.50%	8%	20%
% Societal Costs (any costs not covered by the households)	87.50%	92%	80%

Table 6: Variables Included in Calculation of Private and Public Health Costs

Variable	**Value**	**Sources and Notes**
% Costs OOP and Societal for Private, Public and Uninsured (dmnl)	See Table 1	
% Public, Private and Uninsured for below 200FPL (dmnl)	Varies by state	Health Insurance Coverage of Non-Elderly (0-64 years) below 200FPL("Health Insurance Coverage of the Nonelderly (0-64) with Incomes below 200% Federal Poverty Level (FPL) | KFF" 2020) adjusted with percent of Elderly (65+) in population below 200FPL by state (Census Bureau 2021a), assumed to be on Medicare

Value of a Statistical Life

EPA's Value of Statistical Life (US EPA 2014) was scaled to 2020$ from 2006$ using the Consumer Price Index (CPI) from BEA(Bureau of Economic Analysis 2021b), yielding VSL = $9.5M = $7.4M × CPI 2020/ CPI 2006

Asthma from Gas Stoves

The household cost of asthma from gas stoves is calculated as the products of the increased prevalence of asthma from gas stoves and the annual household cost of asthma. The increased prevalence of asthma from gas stoves is the product of asthma prevalence by state for low-income populations without gas stoves ($Prev_{A0}$), the prevalence of gas stoves in this population ($Prev_G$), the increased risk of asthma in households with gas stoves ($R_{A,G}$) and the household cost of asthma. The asthma prevalence for low-income populations without gas stoves is calculated based on the statewide prevalence of asthma for low-income populations, the prevalence of gas stoves, and the increased risk of asthma in households with gas stoves.

Cost per Household of Asthma from Gas Stoves ($/Household/Year)

$$= Prev_{A0} \cdot Prev_G \cdot R_{A,G} \cdot \text{Household Cost of Asthma}$$

where:

$$Prev_{A0} = Prev_A / (R_{A,G} \cdot Prev_G + 1)$$

$$\text{Household Cost of Asthma} = \rho\, I_H\, C_A + C_{Work}\,(S \cdot W/S \cdot \rho_{child} + W \cdot \rho_{adult})$$

Separating Private and Non-Private Costs

Non-private (public and insurance covered) cost of Household of Asthma from Gas Stoves ($/Household/Year)

$$= \rho\, I_H\, C_A \cdot (1 - \theta_{private}) + C_{Work} \cdot \varphi_{leave}\,(S \cdot W/S \cdot \rho_{child} + W \cdot \rho_{adult})$$

Private Cost per Household of Asthma from Gas Stoves ($/Household/Year)

$$= \rho\, I_H \cdot C_A \cdot \theta_{private} + C_W \cdot (1 - \varphi_{leave})\,(S \cdot W/S \cdot \rho_{child} + W \cdot \rho_{adult})$$

Table 7: Variables included in Calculation of Costs of Asthma from Gas Stoves

Variable	Description	Value	Sources and Notes
$Prev_{A0}$	Baseline low-income adult asthma prevalence without gas stoves (%)	Varies by county	Calculated (see equation above)
$Prev_A$	Baseline low-income adult asthma prevalence (%)	Varies by state	CDC BRFSS Asthma Prevalence, Table 17, weighted average taken across all income brackets <=$75,000 (CDC 2021a)
$Prev_G$	Prevalence of gas or propane stoves in <200FPL population (Dmnl)	Varies by county	DOE LEAD Data(DOE 2021) for <200FPL by county and heating fuel matched with NREL's ResStock Data ("ResStock Analysis Tool" 2021) of gas and propane stove use by Census Region and heating fuel
$R_{A,G}$	Increase in Risk of Current asthma from gas stoves (Dmnl)	42%	(Lin, Brunekreef, and Gehring 2013)
I_H	Healthcare cost index (Dmnl)	Varies by locality	Geographic Practice Cost Indices (GPCIs) (CMS 2021)

C_A	Annual Cost of Asthma Care ($/person with asthma/yr)	$3,566	Values from study of Asthma Burden Cost in US, scaled from $2015 to $2020 (Nurmagambetov, Kuwahara, and Garbe 2018). Includes prescriptions, office visits, hospitalizations, outpatient visits, and ED visits.
$\theta_{private}$	Private Out of Pocket and Public Cost Percentages (dmnl)	Varies by state	See Calculations used below in multiple places
C_{Work}	Average Cost of Missed Workday/School Days ($/day)	Varies by state	See Calculations used below in multiple places
φ_{leave}	Percent of low-income (10^{th} percentile) workers without paid sick leave (Dmnl)	66%	(E. Gould 2021)
S	Number of missed schooldays per child with asthma (school days/child with asthma/yr)	2.3 days	(Nurmagambetov, Kuwahara, and Garbe 2018)
W/S	Number of missed adult workdays per missed school day (workdays/ school days)	0.33	Assumes that households of children under 18 with no partner present (15%)[9] and households with a partner present (84%)[10] where are both partners are employed (21%)[11] will miss a day of work (0.33=0.15+0.84*0.21)*
W	Number of Missed Workdays per adult with asthma. (workdays/person with asthma/yr)	1.8 days	(Nurmagambetov, Kuwahara, and Garbe 2018)
ρ, ρ_{child} , ρ_{adult}	People, children, adults per household (people/household)	1.96 adults, 0.57 children	(Census Bureau 2021b) Table AVG1

*The estimate of missed adult workdays per missed school day is conservative because more households under 200FPL have no partner present than average in the US population, also the 21% of households with both partners employed is for married couples, but there are likely more households where partners are unmarried have both partners working.

Asthma Reduced from Air Sealing and Insulation

I calculated the potential reduction in asthma from air sealing and insulation using state level data from the DOE's Weatherization Assistance Program (WAP) that reported the reductions in hospitalizations, emergency department (ED) visits and other direct medical costs (ODCs) from high-cost asthma patients (those experiencing symptoms in the past 3 months) (Tonn, Carroll, et al. 2014). The reductions in

[9] (Census Bureau 2021b), Table A3
[10] (Census Bureau 2021b), Table FG1
[11] (Census Bureau 2021b), Table A3

hospitalizations, ED visits and ODCs from the WAP program were multiplied by the average cost of an asthma-related hospitalization, an asthma-related ED visit, and annual ODCs for asthma to yield the annual change in cost per person with asthma. The cost per household of asthma from poor insulation and air sealing was calculated by multiplying the annual change in cost per person with asthma by the incidence of asthma, the healthcare cost index at a state level, and the average number of people per household.

Cost per Household of Asthma Exacerbation from Lack of Air Sealing and Insulation ($/Household/Year)

$= Prev_A \, I_H \, (C_{A,\,ED} \, R_{A,\,ED} + C_{A,\,H} \, R_{A,\,H} + C_{A,\,ODC} \, R_{A,\,ODC})$

Separating Private and Non-Private Costs

Non-private (public and insurance covered) Cost per Household of Asthma Exacerbation from Lack of Air Sealing and Insulation ($/Household/Year)

$= \text{Cost} \, (1 - \theta_{private})$

Private Cost per Household of Asthma Exacerbation from Lack of Air Sealing and Insulation ($/Household/Year)

$= \text{Cost} \;\; \theta_{private}$

Table 8: Variables Included for Calculation of Cost of Asthma exacerbation from Lack of Air Sealing and Insulation

Variable	Description	Value	Sources and Notes
$Prev_A$	Low-income asthma prevalence (persons with asthma/persons)	Varies by state	CDC BRFSS Asthma Prevalence, Table 17, weighted average taken across all income brackets <=$75,000(CDC 2021a)
I_H	Healthcare Cost Index (Dmnl)	Varies by locality	Geographic Practice Cost Indices (GPCIs) from CMS(CMS 2021)
$C_{A,\,ED}$	Asthma ED Visit Cost ($/Person in ED/yr)	$2,317	Average Asthma ED Cost(Wang et al. 2014) updated from 2007$ to 2020$ using the Consumer Price Index (Bureau of Economic Analysis 2021a) and adjusted to account for 23.6% increased annual likelihood of readmittance (Steiner, Barrett, and Hunter 2010)

$C_{A, H}$	Asthma Hospital Cost ($/Person Hospitalized/yr)	$8,355	See calculation in Table 2
$C_{A, ODC}$	Average Asthma Other Direct Costs for High-Cost Asthma Patients ($/ Person with Asthma/Yr)	$2,767	Scaled to $2020 using CPI (Tonn, Rose, and Hawkins 2015)
$R_{A, ED}$	Reduction in asthma ED visits after basic air sealing and insulation	11.5%	Value taken from National Survey of WAP recipients
$R_{A, H}$	Reduction in asthma hospital stays after basic air sealing and insulation	3%	Value taken from National Survey of WAP recipients
$R_{A, ODC}$	Reduction in high-cost asthma patients after basic air sealing and insulation	11.8%	Value taken from National Survey of WAP recipients
ρ, ρ_{child} , ρ_{adult}	People, children, adults per household (people/household)	1.96 adults, 0.57 children	(Census Bureau 2021b) Table AVG1

Average asthma hospital costs for adults and children differed enough to warrant calculation of a weighted average cost per person hospitalized, which includes the cost per hospitalization as well as the average rate of recurrence in the year for someone who is hospitalized.

Table 9: Variables Included for Weighted Hospital Cost (including Remittance) for Children and Adults with Asthma Exacerbation Requiring Hospitalization

	Adults	Children	Total
Frequency of hospital readmittance (Tonn, Rose, and Hawkins 2015)	27.30%	22.90%	
Hospital Cost (source scaled to $2020) (Tonn, Rose, and Hawkins 2015)	$7,622	$4,347	
Cost per person	**$9,703**	**$5,342**	
Percent child/adult in WAP households (Census Bureau 2021b)	*77%*	*23%*	
National Asthma prevalence of WAP children compared with adults[12]		*69.6%*	
Weighted Child-Adult Hospital Cost per Person Hospitalized	**$7,517**	**$838**	**$8,355**

[12] Used in place of hospitalization incidence of low-income children compared with low-income adults. This is conservative given that children often have less well-controlled asthma leading to more hospitalizations.

Cost of Heat Stress from Energy Inefficient Housing

Calculations for the household cost of heat stress are laid out below. The first step is estimating the increased heat deaths from too hot housing. The number of increased heat deaths is multiplied by the costs of heat deaths using the value of a statistical life, and the costs of heat-stress morbidity. The morbidities evaluated are heat-caused hospitalizations and ED visits, and a frequency compared to heat deaths is known for each. The average cost of hospitalizations and ED visits is used along with the county healthcare cost index to determine the cost of the morbidities.

Heat deaths from excessive indoor temps = $R_{Heat,Death} \cdot \rho \, E_{Heat} \, Q_{Heat} \, P_{Heat}$

Cost per Household from Excessive Heat ($/Household/Year)

= Heat deaths from excessive indoor temps $\cdot$ ($VSL + N_{Heat, ED} \, C_{ED} \, I_H + N_{Heat, Hosp} \, C_{Hosp} \, I_H$)

Separating Private and Non-Private Costs

In separating private and non-private costs, value of a statistical life is considered a non-private cost since it will not be directly paid by a household. The assumption that deaths have no private costs is extremely conservative and does not account for the economic and emotional harm to survivors, such as potential loss of childcare or income, funeral expenses, and downstream effects of these emotional and economic consequences.

Non-private (public and insurance covered) cost per household from excessive heat ($/Household/Year)
$= R_{Heat,Death} \cdot \rho \, E_{Heat} \, Q_{Heat} \, P_{Heat} \, (VSL + (1 - \theta_{private}) \, N_{Heat, ED} \, C_{ED} \, I_H + (1 - \theta_{private}) \, N_{Heat, Hosp} \, C_{Hosp} \, I_H)$

Private Cost per Household of Asthma from Gas Stoves ($/Household/Year)
$= \theta_{private} \, R_{Heat,Death} \cdot \rho \, E_{Heat} \, Q_{Heat} \, P_{Heat} \, (N_{Heat, ED} \, C_{ED} \, I_H + N_{Heat, Hosp} \, C_{Hosp} \, I_H)$

Table 10: Variables Included for Calculation of Costs from Excessive Heat

Variable	Description	Value	Sources and Notes
$R_{Heat,Death}$	Heat Death Rate (deaths classified as caused heat/yr)	Varies by region and urbanization level	CDC 2014 (Berko 2014)
ρ	Number of people per household (people/household)	2.53	(Census Bureau 2021b) Table AVG1
E_{Heat}	All deaths caused by extreme heat per deaths classified as caused by extreme heat (deaths caused by heat /deaths classified as caused by heat)	35	Ratio used is from New York City(Metzger, Ito, and Matte 2010)

Q_{Heat}	Percent of Deaths from Extreme Heat that Occur Indoors (dmnl)	80%	Only indoor deaths can be avoided from retrofits. Value used is from New York City, this may over or underestimate the percentage of deaths that occur from extreme heat indoors in other climates and urbanization levels (NYC Health 2021)
P_{Heat}	Percent of Indoor Deaths from Extreme Heat Avoided from Retrofit (dmnl)	100%	Assumption based on the fact that none of the heat related deaths in NYC occurred in homes with working AC Units (Vant-Hull et al. 2018)
VSL	Value of a Statistical Life ($/death)	$9,223,914	See Calculations used below in multiple places
$N_{Heat, ED}$	Number of ED Visits directly attributed to heat per death attributed to heat (ED Visit/death)	34.4	Value from New York City (Wheeler et al. 2013)
$N_{Heat, Hosp}$	Number of Hospital Admissions directly attributed to heat per death attributed to heat (Hospital Admission/death)	11.7	Value from New York City (Wheeler et al. 2013)
C_{ED}	Average Cost of ED Visit ($/ED Visit)	$530	Average Cost of all ED Visits in the US. (Moore and Liang 2020) Since heat can exacerbate a range of pre-existing health conditions, the ED visit cost of treating just hyperthermia may not be representative.
C_{Hosp}	Average Cost of Hospital Admission ($/Hospital Admission)	$11,700	Average Cost of all Hospitalizations in the US (Moore and Liang 2020)
I_H	Healthcare cost index (Dmnl)	Varies by locality	Geographic Practice Cost Indices (GPCIs) from CMS (CMS 2021)

Cost of Cold Stress from Energy Inefficient Housing

The cold-related morbidity and mortality cost calculations follow a similar methodology to the heat-related morbidity and mortality. First the number of excess deaths from cold indoor temperatures is calculated and then multiplied by the VSL and the cost of cold-related ED visits and hospitalizations.

Cold deaths from excessively cold indoor temps = $R_{Cold,Death} \cdot \rho\ E_{Cold}\ Q_{Cold}\ P_{Cold}$

Cost per Household from Excessive Heat ($/Household/Year)

= Cold deaths from too cold indoor temps $\cdot$ (VSL+ $N_{Cold,\ ED}\ C_{ED}\ I_H + N_{Cold,\ Hosp}\ C_{Hosp}\ I_H$)

Table 11: Variables Included for Calculation of Costs from Excessive Cold

Variable	Description	Value	Source and Notes
$R_{Cold,Death}$	Cold Death Rate (deaths classified as caused heat/yr)	Varies by county	Metropolitan county values assigned from (Spencer 2015). All other state values assigned the average value for metropolitan areas in the state and adjusted by urbanization level index from the CDC (Berko 2014)
ρ	Number of people per household (people/household)	2.53	(Census Bureau 2021b) Table AVG1
E_{Cold}	Extreme Cold Deaths Exacerbation (deaths exacerbated by heat /deaths classified as caused by heat)	100	Based on estimate that 1% of cold-related excess deaths are due to hypothermia (Caplan 1999)
Q_{Cold}	Percent of Deaths from Extreme Cold that Occur Indoors (dmnl)	23%	CDC estimate for US (CDC 2006)
P_{Cold}	Percent of Indoor Deaths from Extreme Cold Avoided from Retrofit (dmnl)	100%	Assumption that retrofit homes could stay at comfortable temperatures cheaply
VSL	Value of a Statistical Life ($/death)	$9,223,914	See Calculations used below in multiple places
$N_{Cold,\ ED}$	Number of ED Visits directly attributed to heat per death attributed to heat (ED Visits/Death)	12	Value from New York City (Lane et al. 2018)

$N_{Cold, Hosp}$	Number of Hospital Admissions directly attributed to heat per death attributed to heat (Hospital Admissions/Death)	16	Value from New York City (Lane et al. 2018)
C_{ED}	Average Cost of ED Visit ($/ ED visit)	$530	Average Cost of all ED Visits in the US (Moore and Liang 2020)
C_{Hosp}	Average Cost of Hospital Admission ($/Hospital Admission)	$11,700	Average Cost of all Hospitalizations in the US (Moore and Liang 2020)
I_H	Healthcare cost index (Dmnl)	Varies by locality	Geographic Practice Cost Indices (GPCIs) from CMS(CMS 2021)

Missed Work from Poor Household Health Exacerbated by Inefficient Housing

The cost of missed work from poor health exacerbated by inefficient housing average cost of a missed work or school day (calculated above) by the reduction per unit in missed days of work.

Cost per Household of Missed Work Avoided with Weatherization ($/Household/Year)
$= C_{Work}\ W_{all}$

Separating Private and Non-Private Costs

Non-private (public and insurance covered) cost of missed work avoided due to weatherization ($/Household/Year)
$= \varphi_{leave}\ C_{Work}\ W_{all}$

Private cost of missed work avoided due to weatherization ($/Household/Year)
$= (1 - \varphi_{leave})\ C_{Work}\ W_{all}$

Table 12: Variables Included for Calculation of Missed Work Avoided from Weatherization

Variable	Description	Value	Sources and Notes
C_{Work}	Average Cost of Missed Workday/School Days ($/workday)	Varies by state	See Calculations used below in multiple places
W_{all}	Reduction in Missed Days of Work (workdays/household/yr)	1.8	(Hawkins et al. 2020)
φ_{leave}	Percent of low-income (10^{th} percentile) workers without paid sick leave (Dmnl)	66%	(E. Gould 2021)

Appendix B: Equations and Sources for Energy Savings Calculations

The data from LEAD provided energy expenditures by fuel type. These prices first were converted from 2018$ to 2020$ using the CPI (Bureau of Economic Analysis 2021b) and then converted into energy use using cost data from EIA (Table 11).

To determine the effect of electrification, I needed to estimate fuel by end use for each county. I used RECS data on average energy use by end use and fuel type for four census regions across five different uses to estimate the breakout of energy use by fuel type into end use categories for each county and building type using the methodology explained below. First, I provide a table of energy efficiency constants used in the calculations and their sources (Table 10).

Table 13: Efficiency Constants Used in Retrofit Energy Savings Calculations

Variable name	Description	Value	Units	Source
eh_f	Efficiency of Fossil Heating System	0.8	Btu/watt-hr	(Otter Tail Power Company n.d.)
eh_e	Coefficient of Performance (COP) of Heat Pump	2.64	Btu/watt-hr	(ENERGYSTAR n.d.)
ec	Efficiency of older AC	2.9	Btu/watt-hr	(Trane n.d.)
ec_{hp}	Heat Pump Cooling COP	5.0	Btu/watt-hr	(ENERGYSTAR n.d.)
ee	Improvement in Efficiency from air sealing	Varies by Climate Region from (14-38%)	Btu/Btu	(ENERGY STAR 2014)
ee_{fridge}	ENERGY STAR refrigerator energy use compared to old refrigerator	0.7	Btu/Btu	(Sense 2020)
ew_r	Efficiency of resistance water heater	0.95	Btu/watt-hr	(HTProducts 2018)
ew_{hp}	Coefficient of performance of heat pump water heater	2.6	Btu/watt-hr	(HTProducts 2018)
ew_f	Efficiency of fossil water heater	0.6	Btu/watt-hr	(Fast Water Heater Company n.d.)

Estimating Heating and Cooling Energy Savings from Insulation and Air Sealing

ENERGY STAR reports the relative cost-effective savings from air sealing and insulation for housing in each climate zone. However, these savings account for air sealing and only a small amount of insulation and are quite small in comparison to what can be done with a DER. ENERGY STAR assumes these reductions come from reducing the total air infiltration by 25% (ENERGY STAR 2014). Reducing air infiltration even further and adding super insulation could conservatively double the possible savings for the equivalent of reducing air infiltration by 50%. The calculations to determine energy savings from further reducing air sealing are as follows:

A = Surface Area of Unit (m^2)
$\langle P^h \rangle, \langle P^c \rangle$ = power consumption for heating, cooling, averaged over the year (W)
HDD, CDD = heating, cooling degree days (K d)
R = thickness of insulation (in)
$\langle U \rangle$ = average weighted thermal conductance ($Wm^{-2}K^{-1}$)
U_i, U_o = thermal conductance through insulation, other ($Wm^{-2}K^{-1}$)
w_i, w_o = weight of area that has insulation, other (%)
τ = days per year (d)

The power consumed for heating and cooling, averaged over an entire year, is given by

$$\langle P^h \rangle = \mathrm{A}\langle U \rangle \frac{HDD}{\tau}, \qquad \langle P^c \rangle = \mathrm{A}\langle U \rangle \frac{CDD}{\tau}$$

Assuming the retrofit leaves the area of the home unchanged and solely decreases the thermal conductance of the home, the power consumed for heating and cooling post-retrofit averaged over the year would be:

$$\langle P^h \rangle = A\langle U \rangle' \frac{HDD}{\tau}, \qquad \langle P^c \rangle = A\langle U \rangle' \frac{CDD}{\tau}$$

The effect of the retrofit, given by the ratio of the thermal conductances is:

$$\frac{\langle P^h \rangle'}{\langle P^h \rangle} = \frac{\langle P^c \rangle'}{\langle P^c \rangle} = \frac{\langle U \rangle'}{\langle U \rangle}$$

Separating out a fraction of the total surface area as the insulated fraction and assuming the other areas do not change, the ratio of the thermal conductances can be rewritten as a weighted ratio.

$$\frac{\langle U \rangle'}{\langle U \rangle} = \frac{w_i U_i' + w_o U_o}{\langle U \rangle}$$

Substituting $w_o U_o = \langle U \rangle - w_i U_i$ gives:

$$\frac{\langle U \rangle'}{\langle U \rangle} = \frac{w_i U_i' + \langle U \rangle - w_i U_i}{\langle U \rangle} = 1 - w_i \left(\frac{U_i - U_i'}{\langle U \rangle} \right)$$

Overall savings can then be written as the product of the original heat lost through the insulated area and the reduction in heat loss through the insulated area.

$$S_c = 1 - \frac{\langle U \rangle'}{\langle U \rangle} = \frac{w_i U_i}{\langle U \rangle} \left(1 - \frac{U_i'}{U_i} \right)$$

The ENERGY STAR guide notes that the reduction in heat loss from air infiltration was 25%, which led to S_c overall savings by climate zone, implying a different fraction of heat lost through the channel by climate zone (ENERGY STAR 2014). A 25% heat loss from air infiltration implies that $\frac{U_i'}{U_i} = \frac{3}{4}$ and a 50% heat loss from air infiltration implies $\frac{U_i'}{U_i} = \frac{1}{2}$. Since $U_i \propto \frac{1}{R_i}$, this implies a doubling of R value. Given that uninsulated walls have an R value of ~3 and ENERGY STAR recommends R13-R21 on walls, the estimate for what is possible for uninsulated to mildly insulated walls is conservative (ENERGY STAR 2008). Homes in Germany under Passive House design standards have reduced energy by up to 90% (International Passive House Association n.d.). The final heating and cooling energy savings I assumed from insulation and air sealing are shown in Table 11. The resulting heating and cooling energy reductions also match utility estimates of possible reductions for insulation and air sealing in Massachusetts. The calculated energy reductions range from 14% in Climate Zone 1 (Southern Florida) to 38% in Climate Zone 7 (Upper Midwest and Northern Maine) (see Figure 1). These percentages by climate zone were applied at the county level for the retrofit energy savings calculations.

Table 14: Heating and Cooling Energy Savings from Insulation and Air Sealing by Climate Zone from Retrofit

Climate Zone	Energy Savings
7	38%
6	36%
5	32%
4	34%
3	28%
2	18%
1	14%

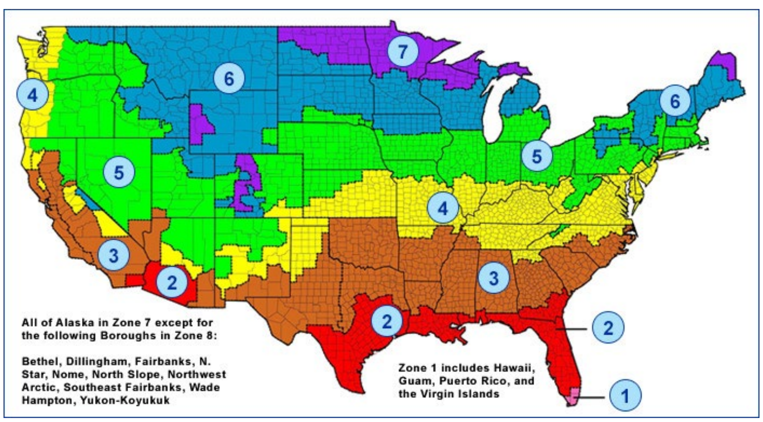


Figure 22: US Climate Zones used for Heating and Cooling Energy Savings Calculations (ENERGY STAR 2008)

Retrofit Total Energy Savings Calculation Methodology

This section shows the algorithm I created to estimate the total energy savings from a DER with electrification for one county and building type combination, combining the LEAD and RECS data.

Example for *Detached Single Family Housing* in *Autauga County, AL*:
Step 1): Populate the table with known data

- Percentage total energy use for each end use from RECS for the applicable Census Region
- Percentage of total gas and propane use by end use from RECS for the applicable Census Region
- Energy Use by Fuel Type from LEAD Data
- Gas and Propane are not used for Air Conditioning or Refrigeration
- Assume Fuel Oil is only used for Heating, so all fuel oil is allocated to heating[13]

Key:

(yellow)	Data from LEAD for Autauga County
(red)	Data from RECS for 'South' Census Region
100,000	New calculations changed from the last step

	End Use	Space heating	Water heating	Air conditioning	Refrigerators	Other
	million BTU/year	Ph	Pw	Pc	Pr	Po
RECS overall %		54.1%	20%	6%	1%	18%
RECS Gas + Propane %		54.4%	30%	0%	0%	15%
Electric	187,426					
Gas + Propane	157,821			0	0	
Fuel Oil	3,235	3,235	0	0	0	0
Overall	348,483	188,511	71,424	21,751	4,782	62,014

Step 2): Apply RECS percentages to known data to fill in the table

2.1) Apply RECS percentage of Overall Energy by End Use to Overall Energy Use Data from LEAD
$E_{o,x} = E_o P_x \; for \; x \in \{h,w,c,r,o\}$

2.2) Apply RECS percentage of Gas and Propane by End Use to Determine the Gas and Propane by End Use
$E_{g,x} = E_g G_x \; for \; x \in \{h,w,o\}$

2.3) The remaining electricity for each end use is the total Energy for the end use minus the other fuels
$E_{e,x} = E_{o,x} - (E_{g,x} + E_{f,x}) \; for \; x \in \{h,w,c,r,o\}$

[13] A small amount of fuel oil is used for water heating in detached single family and 5+ unit buildings in the Northeast. To simplify, the calculation this fuel oil was assumed to be used for space heating.

	End Use	Space heating	Water heating	Air conditioning	Refrigerators	Other
	million BTU	Ph	Pw	Pc	Pr	Po
RECS overall %		54.1%	20%	6%	1%	18%
RECS Gas + Propane %		54.4%	30%	0%	0%	15%
Electric	187,426	99,462	23,645	21,751	4,782	37,786
Gas + Propane	157,821	85,813	47,779	0	0	24,228
Fuel Oil	3,235	3,235	0	0	0	0
Overall	348,483	188,511	71,424	21,751	4,782	62,014

Step 3): Apply Energy Efficiency Measures

3.1) Insulation and Air Sealing increase efficiency of all heating and cooling by the efficiency reduction for the relevant climate zone (e_e)

$E_{E,h} = E_{E,h}(1 - e_e)$ for $E \in$ {e,f,g}

$E_{e,c} = E_{e,c}(1 - e_e)$

3.2) Replacement of electric resistance water heaters with a heat pump water heater ($e_{w,r}/e_{w,hp}$)

$E_{e,w} = E_{e,w}e_{w,r}/e_{e_{w,hp}}$

3.3) Replacement of Average Refrigerator with ENERGY STAR Refrigerator (e_{fridge})

$E_{e,r} = E_{e,r}e_{fridge}$

End Use	million BTU	Space heating (h)	Water heating (w)	Air conditioning (c)	Refrigerators (r)	Other (o)
Electric (Ee)	137,047	71,613	8,639	15,661	3,348	37,786
Gas + Propane (Eg)	133,793	61,786	47,779	0	0	24,228
Fuel Oil (Ef)	2,329	2,329	0	0	0	0
Overall (Eo)	273,169	135,728	56,419	15,661	3,348	62,014

Step 4): Electrification

4.1) Replacement of fossil heating system and electric air conditioning with an air-source heat pump (eh_f/eh_e, ec/ec_{hp})

$E_{e,h} = E_{e,h} + (E_{g,h} + E_{f,h})(eh_f/eh_e)$
$E_{g,h} = E_{f,h} = 0$
$E_{e,c} = E_{e,c}(ec/ec_{hp})$

4.2) Replacement of a fossil water heating system with a heat pump water heating system (ew_f/ew_{hp})
$E_{e,w} = E_{e,w} + E_{g,w}(ew_f/ew_{hp})$
$E_{g,w} = 0$

End Use	million BTU	Space heating (h)	Water heating (w)	Air conditioning (c)	Refrigerators (r)	Other (o)
Electric (Ee)	160,702	91,058	19,298	9,212	3,348	37,786
Gas + Propane (Eg)	24,228	0	0	0	0	24,228
Fuel Oil (Ef)	0	0	0	0	0	0
Overall (Eo)	184,930	91,058	19,298	9,212	3,348	62,014

This algorithm is applied to all 3,107 counties and five building types for each county included in the analysis. The energy savings by county are then summed over all building types to get net changes in energy use (see equations below). The changes in energy use by fuel are then multiplied by the emissions factors and prices shown in Table 11, respectively, to yield the net emissions reductions and energy savings from retrofits.

Table 15: Energy Source Emission Factors and Price Data

Energy Source	Emission Factor	Price
Electricity	Varies by state, (EPA 2022)	Varies by state (c/kwh) (EIA 2022d)
Gas	Natural Gas - 52.91 kg CO_2e/MBtu Propane – 62.88 (EIA 2022c)	Varies by state ($/thousand cubic ft) (EIA 2022b)
Fuel Oil	74.14 kg CO_2e/MBtu (EIA 2022c)	Varies by state ($/gal) (EIA 2022e)

$$\Delta C = \sum_E \Delta U_E P_E$$

$$\Delta GHG = \sum_E \Delta U_E EF_E$$

Where:

ΔC, change in annual household cost of energy over all fuels
ΔGHG, change in annual GHG emissions per household from retrofit
ΔU_E, change in annual energy use for fuel type E {electricity, gas, fuel oil} from retrofit
EF_E, fuel type E emission factor
P_E, Price of fuel type E

Appendix C: Retrofit Costs

The costs of retrofits were estimated by first searching the literature for studies quantifying the reduction in energy use and costs per square foot of the retrofits. Four studies were found, spanning a range of retrofit actions and costs, from simply adding insulation to projects seeking to achieve net zero energy use (ACEEE 2019; Less et al. 2021). One of the studies, from Lawrence Berkeley National Lab reported six types of retrofits by cost and emissions reductions from their database of DER project data (Less et al. 2021). Table 13 summarizes the data; Figure 2 plots the reduction in energy use as a function of the cost per square foot. Retrofit costs were calculated by fitting a power law to the data. The estimated power law function was then used to estimate a per square foot cost for the retrofit based on the calculated energy savings.

A few notes about data limitations: The LBNL data spans the US, but most of the retrofits included were in California with many of the rest located in New England. California and New England regularly rank highly on the ACEEE State Energy Efficiency scorecard, so it is not surprising to see them overly represented in this dataset. The LBNL study clustered the retrofits according to costs across a variety of dimensions (HVAC, insulation, etc.). The cost data, normalized by home size, and the percent energy savings from both the LBNL clusters and the state energy efficiency programs were used to estimate a retrofit cost curve, shown in Table 2 and Figure 2. Note that there have been limited studies on deep energy retrofits; this can be seen in the smaller sample sizes in Table 2 for data points with higher energy savings. As described in Uncertainties and Further Research, these cost estimates are conservative because these studies did not use integrated design, and I did not assume any end-of life replacements, economies of scale or learning by doing dynamics.

The retrofit cost curve was fit with a power law formula, getting the formula:

$$\text{Retrofit Cost per Square Foot } (C_R) = 7.3\, {S_E}^{2.25}$$

Where $S_E = Total\ \%\ Energy\ Savings$

Table 16: Energy Savings vs. Retrofit Cost per Square Foot

Retrofit Data Point	Average* Cost ($)	Average* Home Size (sqft)	Average Cost* ($/sqft)	Average* Percent Energy Savings	Number of homes
Basic Retrofits (LBNL)	$3,849	1,700	$2	20%	671
HVAC (LBNL)	$10,105	1,713	$6	33%	857
Advanced HVAC (LBNL)	$26,228	2,426	$11	40%	136
Large Home Geothermal (LBNL)	$120,802	4,648	$23	56%	14
Super insulation (LBNL)	$109,059	1,670	$57	64%	15
Electrification with PV (LBNL)	$54,098	1,987	$28	72%	43

Retrofit Data Point	Average* Cost ($)	Average* Home Size (sqft)	Average Cost* ($/sqft)	Average* Percent Energy Savings	Number of homes
Connecticut Home Energy Solutions Program (Connecticut HES)	$1,000	1,804	$1	10%	Thousands
New Jersey Home Performance with ENERGY STAR Program (NJ HPwES)	$16,108	1,740	$9	29%	50
Vermont Net Zero Energy Now Program (Vermont NZE)	$57,613	1,815	$32	79%	24

*LBNL reports median values, while the state programs report means. However, the state-run programs likely have fewer high-cost outliers, due to cost limits, making the mean similar to the median. For more information on the clusters, see (Less et al. 2021).

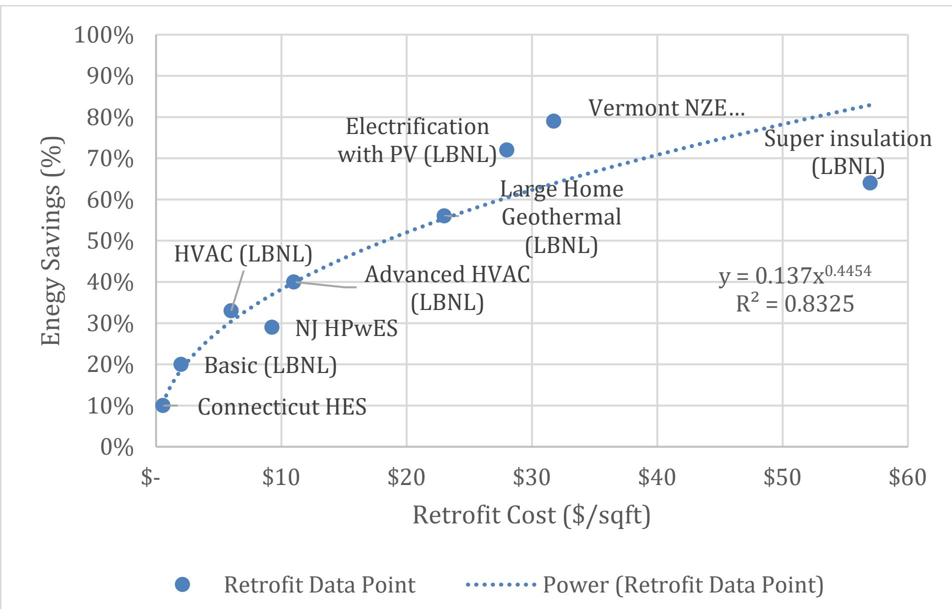


Figure 23: Energy Savings vs. Retrofit Cost per Square Foot

Appendix D: Cost Benefit Comparison

Calculating the net present value required determining the discounted benefit of the retrofit over the retrofit lifetime or as long as the retrofits can be assumed to be providing benefits. The discounted benefit from time t=0 to the retrofit lifetime, T, is calculated below, where
B_0 = Annual Benefit (%)
T = retrofit lifetime (years)
r = discount rate (%)

$$\int_0^T B_0 e^{-tr} dt = \int_0^\infty B_0 e^{-tr} dt - \int_T^\infty B_T e^{-tr} dt$$

$$B_T = B_0 e^{-Tr}$$

$$\int_0^T B_0 e^{-tr} dt = B_0 \int_0^\infty e^{-tr} dt - B_0 e^{-Tr} \int_T^\infty e^{-tr} dt$$

$$= \frac{B_0}{r} (1 - e^{-2Tr})$$

The Net Present Value (NPV) is calculated as the discounted annual flow of benefits minus costs, where the Annual Benefit is the sum of the annual energy and the health savings:

$$B_0 = H + \sum_E C_E U_E^R$$

$$\text{NPV} = \text{Discounted Annual Flow of Benefits } (B_0) - Costs$$

$$NPV = \frac{1}{r} (1 - e^{-2Tr}) \left(H + \sum_E C_E U_E^R \right) - C_R \mathrm{A}$$

Variable	Description	Value
r	Discount rate (%)	3% used by LBNL 2021, 6% is cost of capital for Investor owned utilities, 1-3% in environmental assessments (Less et al. 2021)
T	Retrofit Lifetime (years)	30yr estimate used (Less et al. 2021)
H	Health costs avoided by the retrofit ($/yr)	Evaluated for three scenarios: 1) H = 0 (considering energy savings only) 2) H = only private health savings 3) H = private + public health savings
E	Fuel Type	Fuel types evaluated are electricity, gas, and fuel oil
C_E	Cost of Fuel E ($/Btu)	From (EIA 2022d; 2022e; 2022b)
U_E^R	Energy Use of Fuel E after retrofit (Btu/year)	Calculated in Energy Savings
C_R	Retrofit Cost ($/sqft)	Calculated based on the overall energy savings over all fuel types using the retrofit cost curve $f(U^R)$
A	Unit area (sqft)	Average unit area for low-income housing by census region (EIA 2018)

Appendix E: Sensitivity Analysis

This section provides detail on the sensitivity analysis included in the main text. The instructions, data and code for running this sensitivity analysis are available at https://github.com/helenacaswell3/thesis2022.

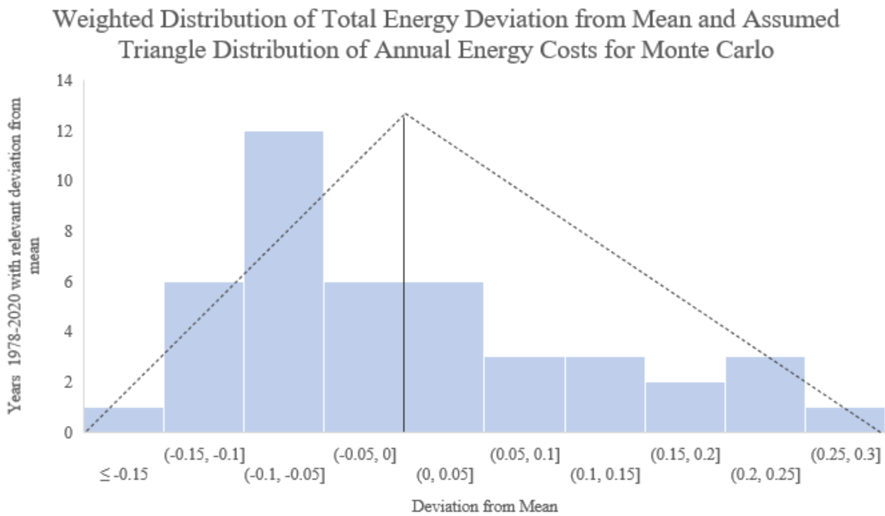
Table 17: Range of Sensitivity Variables for Uncertainty Analysis

Variable	Values	Distribution
Discount Rate, r	(1%/year, 6%/year)	Uniform
Energy Price	(-16%, +28%) of local energy price from EIA	Triangular
Health Costs	± 50% of local total annual health cost calculations	Triangular
Retrofit Costs	(-30%,+50%) of calculated retrofit cost	Triangular

Discount Rate: The discount rates used in this analysis were based on a review of both the cost of capital for low-income households and the social discount rate used in integrated assessment models of climate change to calculate the social cost of carbon (Bressler 2021; Daniel, Litterman, and Wagner 2019; Burke, Hsiang, and Miguel 2015; Kikstra et al. 2021; Weitzman 2010; Dietz and Stern 2015; Drupp et al. 2018; Dietz et al. 2021). The cost of capital for low-income households varies significantly and can be quite high for people in the private debt market. However, in this analysis I assume that people getting capital for DER in LMI housing would primarily rely on lower costs of capital available in programs for low-income home repair. For example the USDA's Program for Home Housing Repair Loans offers 1%/year interest for energy efficiency upgrades for low income rural single family housing (USDA 2015), whereas other house repair loans programs for low income households offer 5% interest ("Loans for Homeowners" 2022). In multi-family housing landlords may qualify for loan programs aimed towards multifamily housing or use commercial loan rates, which for retrofits average around 4%/year (Gellerman 2022).

The social discount rate is generally agreed among economists to range from 1-3% (Drupp et al. 2018). A smaller discount rate means a higher valuation of discounted value in later years.

Energy Price: The nominal energy prices for this analysis at the state level and are taken from EIA (EIA 2022b; 2022d; 2022e) and adjusted to 2020$ using CPI (Bureau of Economic Analysis 2021b). To determine the range of energy prices to be used in the sensitivity analysis, I calculated the range of the annual weighted (based on 2018 average percentage expenditures for each fuel for low income households in the US) total energy expenditures and then divided by the mean of the time series to normalize (DOE 2021). The combined weighted normalized price varied from -15% below to 28% above the mean, with more samples closer to the mean, leading me to sample from a (-15%, +28%) triangular distribution for the sensitivity analysis of the total energy cost, as shown in Figure 24. Here I assumed an equivalent increase for all years in the analysis, which allows us to get upper and lower bounds on the NPV variation based on historic variation in energy prices. A higher energy price leads to a higher NPV because all households save energy with retrofits. The bundling of energy price over all three fuels assumes that they are perfectly correlated, and so does not account for the possibility that electricity prices might rise more than natural gas prices or visa-versa which would affect the economics of electrification. However, in recent years largest portion of the US grid mix has been produced with natural gas, so it is reasonable to expect the two to be highly correlated in the near future (in the past 8 years they have had 80% correlation) (EIA 2022d; 2022e; 2022b). While fuel oil is somewhat less correlated with natural gas and electricity, it comprises only 5% of low-income energy expenditures (DOE 2021).



**The values for both the EIA data and triangle distribution actual range from -0.152 to 0.277, which is not visible based on the granularity of the histogram.*

Figure 24: Weighted Distribution of Annual Energy Cost Deviation from Mean Annual Energy Cost and Assumed Distribution for Monte Carlo

Health Costs: The health costs for this analysis are estimated using the best available data, but in many places, particularly for the temperature causes of health impact calculations, I had to make significant assumptions. Since the temperature causes of health impacts includes an estimate of deaths due to extreme indoor temperature, it includes the VSL, which at $9.5M in 2020$, is an order of magnitude larger than the medical costs. The temperature effects dominate because they include deaths, accounting for 92% of total health effects costs over all households. Because such a large proportion of the cost is from temperature effects, for which I use a top-down methodology to scale hyper and hypothermia deaths by multistate census region and metropolitan area, respectively, it was appropriate to include a larger range for the health cost bundle uncertainty, for the Monte Carlo analysis. I sampled the health costs from a triangular distribution ± 50% of the total annual health costs.

Retrofit Costs: The retrofit costs are calculated based on average cost/sf, which can vary by region, size of house, remediation required or other factors. For the Monte Carlo analysis, I sample from a triangular distribution of (-30%, +50%) of the price determined by mapping the percent reductions onto the estimated retrofit cost curve. The possibility of cost overrun is much more likely than cost savings for construction projects, which is reflected in the larger positive side of the triangle (Aljohani 2017).