Heating with justice: barriers and solutions to a just energy transition in cold climates

Claire McKenna,[1] Carina Gronlund,[2] Parth Vaishnav[1]*
[1] School for Environment and Sustainability, University of Michigan, Ann Arbor, MI
[2] Institute for Social Research and School of Public Health, University of Michigan, Ann Arbor, MI
* Corresponding author: parthtv@umich.edu; 440 Church St, 2575 Dana Building, Ann Arbor, MI 48109

Abstract

Residential heat pumps could reduce greenhouse gas emissions, but increase energy burdens, the proportion of income households spend on utility bills. We analyze utility bills, thermostat settings and energy burdens for a sample of 51 households in Michigan, half below median income. We recruit a contractor to conduct energy assessments of these households and provide them with energy retrofit recommendations, including estimated costs and savings. We find that low-income households choose similar temperature setpoints to higher-income households, but live in less efficient homes. Below-median income households, which today experience a median energy burden of 6%, would see it rise to 10% if they shifted to electric heat pumps from natural gas. Weatherization could offset this increase, bringing burdens down to pre-electrification levels. However, median payback is 24 years, making retrofits infeasible for the poorest. Our results are indicative of an energy poverty trap that could hinder an equitable energy transition.

Key Words

Energy burden, heat pump, electrification, energy efficiency, energy audit, retrofit

Spotlights

- Converting fossil-fuel based home heating to electric could reduce pollution but make bills less affordable
- Switching to electric heating results in low-to-moderate income households paying a high percentage of income on energy
- Retrofitting homes could make electric heating more affordable but it is expensive and therefore infeasible
- High-cost energy efficiency home retrofits could hinder an equitable energy transition
- Future work will investigate homeowner attitudes regarding electrifying their homes and barriers to equitable transition

Main Text

1. Introduction

In recent years, US state policy (“Climate Leadership and Community Protection Act, S. 6599.,” n.d.; “An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy, SB9.,” n.d.; “Climate Commitment Act (CCA) SB 5126.,” n.d.) has signaled a commitment to reducing greenhouse gas emissions by transitioning home heating from fossil fuels to electricity. U.S. federal policy has sought to use subsidies to lower the upfront cost of heat pump adoption (Inflation Reduction Act, H.R. 5376). Electrification has been projected to increase annual utility cost for households in more than half US states (Vaishnav and Fatimah 2020; Deetjen, Walsh, and Vaishnav 2021), with the worst effects in cold climates (Walker, Less, and Casquero-Modrego 2022). Rising energy costs could have a large impact on households across the income spectrum.

1.1 Literature Review

Higher utility bills could increase the economic and physical hardships in households already experiencing energy insecurity. 25% of American households spend a high proportion (>6%) of their income on utilities, defined as energy burden (Drehobl, Ross, and Ayala 2020). High energy burden is associated with poor health outcomes (Tony Gerard Reames 2016), and households with certain vulnerabilities, such as older adults, choose uncomfortable and sometimes unsafe indoor temperatures to reduce bills (Cong et al. 2022). Lewis et al. center deteriorated housing conditions concentrated in racially segregated neighborhoods in their discussion of energy insecurity, which encompasses financial, behavioral and physical hardships related to home energy use (Lewis, Hernández, and Geronimus 2020).

Households with lower energy burdens are not entirely precluded from the effects of higher ongoing costs associated with heating electrification because these costs are associated with building characteristics that are prevalent across the US housing stock. Old homes heated by natural gas have been shown to result in the greatest operational costs for heating with a heat pump (Vaishnav and Fatimah 2020). 64.5 million American homes use natural gas for heating and 57% of them were built before energy codes were implemented in the US (U.S. Energy Information Administration. 2023). Knowledge of household demographics, housing characteristics, and occupant behavior are essential to understanding the barriers to equitable access to heat pumps and a just distribution of harms and benefits associated with policy that facilitates the clean heating transition.

Current research about residential energy equity includes only one or two of these critical components. Studies that quantify the link between racial disparities in energy use and housing quality (Goldstein, Reames, and Newell 2022; Bednar, Reames, and Keoleian 2017), and demonstrate that households of color are more likely to have trouble paying their bills (Graff et al. 2021) do not take into account behavior. Studies that evaluate specific retrofit opportunities and quantify their the savings potential by employing national scale modeling do not address behavior impacts associated with those changes (Bradshaw, Bou-Zeid, and Harris 2014; E. J. H. Wilson et al. 2019). Likewise, studies that examine the economics of heat pump adoption for low income households, whether in observed system performance (Ceglia et al. 2022; Flower, Hawker, and Bell 2020; Calver, Mander, and Abi Ghanem 2022; Pastore, Lo Basso, and de Santoli 2022; Liu et al. 2018) or simulations (Donaldson and Lord 2018; Barrella et al. 2020; Liu et al. 2020; Abbasi et al. 2022; Savage et al. 2022) focus on housing and heat pump technology characteristics without an empirical analysis of occupant behavior and preferences for heating and cooling.

Several recent studies examining the energy savings potential of residential retrofits in the European context point to the importance of incorporating household behavior in home energy assessments (Palma, Gouveia, and Barbosa 2022; Barrella et al. 2020; Koasidis et al. 2022; Domínguez-Amarillo et al. 2020). The literature addressing the effect of energy consumption behavior on the cost effectiveness of energy retrofits in the US commonly uses economics theory and analysis. Gillingham and Palmer (2014) conducted a literature review of explanations for limited uptake of home energy efficiency including that flawed decision making could reduce the utility of energy efficiency to customers. Three studies followed that examined this question using home energy efficiency project data from the US Department of Energy Weatherization Assistance Program (WAP). Zivin and Novan (2016) measure the treatment effect of retrofits on energy use of 275 households and provide evidence that electricity savings due to WAP are overstated. Allcott and Greenstone (2017) and Fowlie, Greenstone and Wolfram (2018) use large samples of primary empirical data to estimate the benefits of providing energy efficiency services to low-income homes. Though these studies consider behavioral explanations for under performance of projects compared to engineering estimates, they do not provide detail on the housing conditions prior to intervention or the specific work performed. See Table C.7 for a comparison of this paper's contributions to those of the literature.

Other large empirical studies that address impacts of high utility costs on vulnerable households similarly do not provide data on the housing characteristics of the populations they examine (Cong et al. 2022; White and Sintov 2020), and therefore do not address why these impacts occur. Although Booth and Choudhary (2013) estimate the rebound effect, identify specific upgrade parameters, and focus on public housing in their assessment of uncertainty in retrofit performance (Booth and Choudhary 2013), they do not address the transition in heating technology. Recent research has signaled the potential for heat pumps to contribute to residential sector clean heating transition where countries push for climate action and fossil fuels remain the predominant fuel source (Fitó, Dimri, and Ramousse 2021; Thomaßen, Kavvadias, and Jiménez Navarro 2021; Besagni et al. 2020).

1.2 Research Gaps

There remains a gap in quantifying the impacts of residential heating electrification across income and in examining interventions specific to both housing quality and energy consumption behavior. Previous studies that have taken this form to assess the reasons for disproportionate impacts of energy cost across income (Cong et al. 2022; Jones et al. 2023) only examine it in the context of air conditioning, not heating. To bridge this gap, this study aims to disentangle the sources of inequality embedded in the economic impact of heat pump adoption and assess fixes available for real homes. The present work has three main contributions. First, we provide evidence that energy burden impacts across income are associated with housing quality rather than behavior. Second, we compare economic impact of heating fuel transition across income groups. Third, we test the idea that there is a way to mitigate the utility cost premium for heat pumps.

We conduct a year-long field study of 51 homes in Southeast Michigan, during which we perform a comprehensive energy audit of each home to observe envelope and HVAC system characteristics, including thermal imaging to identify temperature gradients indicative of air leakage and poor insulation, and blower door testing to measure air infiltration rate, as well an examination of the on-label efficiency of all appliances. We gather metered daily gas and hourly electric consumption data over the study period and collect energy assessment contractor recommendations for energy efficiency retrofits for each home. Our approach to examining residential energy equity is novel because we compare results derived from observed data with simulations derived from statistical sampling of large public data sources (E. Wilson et al. 2022).

Following this introduction, we present the methods, then results, then we will discuss the findings and conclude. We present our findings in five parts. First, we examine the existing conditions of the homes in the study and compare them across income, including key housing characteristics and indoor temperature preferences. Next, we quantify the impact that replacing natural gas heating with heat pumps would have on household energy burden. We then examine the sensitivity of time of use utility rates on the annual energy bill impact of fuel switching. Following that, we quantify the cost savings potential of energy efficiency envelope improvements and compare it to the utility bill impact. Finally, we explore energy efficiency retrofit recommendations provided to participants during home energy audits and assess the feasibility of these improvements to mitigate the ongoing cost impact of heating electrification on the sample.

2. Methods

This study uses observed household energy use and indoor temperature data along with a reduced complexity air source heat pump coefficient-of-performance model to determine energy cost and energy burden impacts of switching to a heat pump. We gather energy retrofit recommendations and estimate upfront costs, energy cost savings, and payback from a contractor who conducted a detailed energy audit for each home. We then quantify annual utility bill impacts for fuel switching and energy retrofits using a building energy model that provides detailed sub-hourly simulations a large sample of archetypal homes that are representative of the study region and compare them to our findings for the sample.[1]

2.1 Participants

As described below, we recruited 51 participants from Wayne and Washtenaw Counties in Michigan, which encompass the Detroit and Ann Arbor metro areas. We chose Southeast Michigan for three factors that make this study applicable to global contexts including the Midwest, New England, and the Mountain West regions of the US; Northern Europe; and the United Kingdom: cold climate, predominance of natural gas for heating, and older homes**.**

Participant recruitment included three steps. First, we circulated an expression of interest form through local media, university email lists, and local environmental and energy justice community groups that drew more than 1,300 responses. Second, we asked these respondents to complete a demographic survey to assess the presence of key factors associated with energy insecurity: race, income, disability, children, and health vulnerability (Drehobl, Ross, and Ayala 2020; Tony Gerard Reames 2016; Hernández 2016). We received 883 responses to the demographic questionnaire. Third, we identified a random sample stratified using survey answers to ensure representation across four key, binary, classes of vulnerability: has a disability, has at least one child at home, foregoes paying energy bills at least once a year, controls heating or cooling for a vulnerable occupant. These four classes correspond to 16 combinations, and we had respondents who corresponded to only 10 of them.

Next, we identified 418 survey respondents living in single family homes. We then classified the respondents into 10 categories representing the unique combinations of the key categories listed above. We calculated how many households we would need to invite to have an equal number across these categories and randomly selected that many households from each group. Where the quantity of respondents in a category was not great enough to provide an equal weighting, we invited all the respondents in the category. Ultimately, we compiled a list of 90 potential participants to whom we sent invites to join the study. Our recruitment rate was 58%. Demographic questions and descriptive statistics can be found in Note D.3 and Table C.1. 90 respondents were asked to join the study. Demographic questions and descriptive statistics can be found in Note D.3 and Table C.1.

All households in the sample live in single family homes. 50 of the 51 households are homeowners; 1 is a renter. All homes use natural gas for heating with the exception of 1, which uses propane. The sample includes a diversity of housing vintage (i.e. common building practices) from every decade since 1900: 9 homes were built before 1940, 17 homes were built between 1940 and 1960, 12 built between 1961 and 1980, 6 built between 1981 and 2000, and 7 built after 2000.

The study sample is representative of the populations of the two counties of Southeast Michigan along two key characteristics. (1) Income: the median income (in 2022 dollars) is $57,223 for Wayne County and $84,245 for Washtenaw County (U.S. Census, 2024). The sample includes 11 households reported earning annual income <$25k, 18 earning $25-50k, 9 earning $50-75k and 13 earning >$75k. (2) Race: 54.6% white, 38.3% Black, and 7.1% all other races in Wayne County and 73.9% white, 12.4% Black, and 13.7% all other races in Washtenaw County (U.S. Census, 2024). The sample includes 29% Black (n=15), 45% white (n=23) and 25% (n=13) all other races, including one participant who prefers not to answer.

Households were provided $100 compensation.

2.2 Data collection

We obtained one year of utility data for each household, including hourly metered electricity use and daily metered gas use where available. We conducted one visit to each home, during which we installed a smart thermostat where the heating and cooling system could accommodate the product (Ecobee 3 lite)

[1] See Data Availability statement for more information on how to access data that can be made available under the Institutional Review Board guidelines for human subjects research. See Supplemental Methods for additional detail on justification for model and calculation assumptions and Supplemental Figure, Tables, and Notes for detail on participant demographics, supporting findings, and literature review.

(n = 40). For homes that could not receive the smart thermostat, we set up a wi-fi connected thermo-hygrometer (Govee H5179). Both devices record data at 15-minute intervals. An accredited energy audit contractor accompanied the research team and performed an ASHRAE Level 2 energy audit at each home.

Participants provided income ranges, so we estimate energy burden based on the arithmetic midpoint, i.e., if a participant reports their income to $25k-50k, the energy cost burden for that household was calculated at the proportion of their actual annual utility bills to $37.5k. We did not apply an equivalence scale to energy expenditure and income because we observed occupancy in some homes to which the published equivalence scales would not readily apply, for example, households with adult children that may live at home for periods of time varying duration and frequency throughout the year. See Supplementary Methods for detail on energy burden calculation.

2.3 Housing quality analysis

To assess participant behavior, we estimate indoor temperature setpoints in two ways. First, we estimate the heating inflection temperature (HIT) (ambient temperature at which a household begins heating) for each home using a splitwise regression of metered daily gas use on hourly average ambient air temperature (obtained from NOAA Local Climatological Data (LCD) for the data collection period). Second, we evaluate the observed heating and cooling setpoints and the observed indoor temperature for the heating and cooling season for a subgroup that received a smart thermostat (n = 40). We calculate cooling and heating season means for setpoint temperature as well as the standard deviation for setpoint and indoor temperature using this interval data.

2.4 Heat pump cost analysis

Our energy cost analysis for switching to all-electric heat pumps from natural gas-based heating consists of three steps. See p A for detailed calculation methodology and model specifications.

- *Heat load calculation.*
  - *Existing furnace gas use.* To determine heating natural gas use, we first estimated the inflection point for temperature dependent gas use using a split-wise regression of heating degree hours (a measure of the intensity of the space heating needed for a given time and place) on hourly total gas use. We assumed that the slope of the piecewise linear function (found with the segmented() function in R) past this inflection point indicates heating related natural gas usage. From that, we derived the slope which is the natural gas usage per heating degree hour. We then obtained the amount of gas used during each hourly time step for heating by multiplying the slope by the difference between the outside ambient air temperature departure from the indoor heating setpoint gathered during the initial data collection period when the energy audit took place.
  - *Deriving head load.* We multiplied the hourly gas use by the furnace efficiency to obtain the hourly heating load for each house. We obtained the hourly ambient temperatures for each home during the window of time the utility data was provided by the utility (e.g. 11/10/2020 to 11/11/2021) using the NOAA Local Climatological Data (LCD) Tool for the closest available weather station.

- *Heat pump model.* We calculated the heat pump hourly temperature-dependent coefficient of performance (COP) using the following equation:

$$COP'_i \times \left(1 - l(t_i)\right) = COP_i \qquad Tmin < t, i \ \in 8760$$
$$COP_i = 1 \quad t < Tmin$$

  Where:
  - ***i* indexes hour;**
  - ***COP'* = manufacturer reported coefficient of performance** using the efficiency curve (ambient temperature vs. COP) of the Mitsubishi M2i cold climate ASHP for heating;
  - ***l()* = defrost efficiency loss for give temperature, t (%)**;
  - **t = hourly dry bulb temperature (F)** using the NOAA LCD weather data for the same period for which had metered natural gas data for each home;
  - ***COP* =** observable coefficient of performance;

  - **T_{min} = 10°F** reflecting ambient temperature change over point from heat pump to backup heating mode via electric resistance coil;
  - **<T_{min} COP = 1** reflecting the heating efficiency of an electric resistance coil used for backup to ensure that heating setpoints are met below the change over point.

  We calculated percentage improvement in cooling energy by dividing the Mitsubishi H2i SEER rating (SEER = 17) by the on-label AC efficiency obtained from the energy audits for each home. This kind of high efficiency equipment comes with a first cost premium over a standard furnace replacement. It is therefore expensive for low- and middle-income households and is likely not affordable without a subsidy that covers most of the cost. Selecting this equipment is a conservative assumption. We then applied this factor to an average cooling energy percentage obtained from the Resstock End Use Savings Shapes (E. Wilson et al. 2022) to determine the annual energy cost savings.

- *Energy cost calculation.* We calculated the energy cost using a model we developed in R that takes in the hourly estimated electric and daily gas usage for the hypothetical heat pump scenario and calculates the total bill costs in the manner calculated by the utilities as published in the electricity and gas rate schedules ("DTE Electric Company Rate Book for Electric Service" 2023). For example, to calculate the annual electricity cost for each home, we apply the flat rate service charge per month, capacity and non-capacity energy charges assessed per kWh, as well as surcharges and credits. We completed this process for three electricity rates and two gas rates to test the sensitivity of our results to rates available to participants. See Figure B.7 for rate summary and Note D.5 for rate description. We do not include tariff changes from one year to the next because future rate changes are unpredictable and beyond the scope of the analysis. Changes in consumer behavior associated with changes in utility tariffs are also beyond the scope of the paper and therefore not included in the analysis. Additionally, incorporating behavior changes would not have a meaningful impact on the results because short term elasticities are low for electricity and natural gas in the US (U.S. Energy Information Administration 2021).

2.5 Resstock

We analyzed the potential for energy efficiency to mitigate cost increase due to heat pumps by calculating energy costs derived from four modeled retrofit scenarios included in the NREL Resstock End Use Savings Shapes database (Wilson et al., 2021). We selected hourly load profiles available for a baseline case and three "upgrades" including full electrification with or without deep efficiency retrofits, and deep efficiency retrofits with no change to the HVAC systems. To these scenarios, we applied the utility rates for all sensitivity cases as described above. We then calculated the mean incremental annual energy costchange resulting from a series of these changes across a random sample of 400 homes in the database representative of Detroit, MI.

2.6 Retrofit Cost Analysis.

The contractor recommended energy efficiency measures and provided first cost and utility cost savings estimates for the recommended work. We used the "Return on Investment and Rebate Report" prepared for each study participant to summarize the recommended energy efficiency upgrades to code the unique efficiency measures recommended across the sample.

The parameters we used for estimating the feasibility of retrofitting were economic payback in years for the package of all recommended retrofits (calculated as the first cost divided by the annual energy cost savings), the first cost of the total package, and the modeled utility cost savings for the individual measures. The values for these parameters were obtained from the retrofit reports provided to participants by the energy audit contractor. The payback parameter described above follows the US Department of Energy Methodology and Procedures for Life Cycle Cost Analysis (Code of Federal Regulations. 10 CFR Part 436 Subpart A). No discount rates are used, making this the best-case estimate of the payback period. Given our findings, the decision to use an undiscounted payback period is conservative: if a discount rate were applied, the payback period would be even longer, strengthening our argument that the retrofits are not attractive on the basis of utility bill savings. Additionally, we show the rates that participants were provided as part of their energy audit, so payback periods not inclusive of a discount rate are more representative of the data participants have to inform their decision making.

3. Results

We find that electrifying homes with heat pumps increases annual energy cost by 58% on average (range: 11% - 182%) when compared to natural gas heating and considering a flat electricity rate, higher than previous estimates. This change exacerbates already high energy burdens for low-and-moderate income (LMI) households. While we find energy retrofit opportunities that saved energy cost for every home, they came with substantial obstacles that could limit uptake. There is an average payback period of 24 years and homeowners can be left without sufficient information to act, even after a visit from a home energy auditor. Willand et al. (2020) identified this situation as the retrofit trap in their 2020 analysis of Australian home retrofit programs. It can be understood as a form of poverty trap, defined Azaiadis and Stachurski as a reinforcing mechanism that acts as barrier to adoption of techniques that can alleviate poverty (Azariadis and Stachurski 2005). The clean energy transition is hindered by an energy poverty trap because the extensive retrofits needed to make electrification affordable are themselves too expensive for low-income households.

3.1 Housing quality vs. set-point choices

We estimate energy burden for each household by calculating the proportion of their annual combined electricity and gas cost (sourced from utility bills) to the self-reported income range. The 5 highest energy burdened households have rates ranging from 10-40%. 32% of homes have energy burdens greater than 6%, which is considered a high energy burden and twice the national average (Drehobl, Ross, and Ayala 2020). All these households have below-median incomes. 37% are between 3-6%. 31% of homes have an energy burden below 3%; all but one of these homes have incomes that exceed the local median (see Figure B.1). See Table C.1 for descriptive statistics on utility costs and energy burden. Table C.6 provides a list of self-identified household income ranges and a comparison to the area median income (AMI) by zip code.

Not all homes in our sample were of the same age and quality. The homes were on average 60 years old and built in an era during which Michigan did not have energy efficient building codes[2]. They were adopted for the first time 1977 when ASHRAE 90-1975 was adopted state-wide("US Dept. of Energy Building Energy Codes Program" 2024). 13 homes (5 in the <$25k income group and 8 in the $25-50k group) had been retrofit by Habitat for Humanity of the Huron Valley (Habitat) resulting in higher quality for their age. Improvements had been made 1-10 years prior to participating in this study.

Homes retrofit by Habitat perform consistently better than market rate homes in the sample [Fig 1]. To understand the impact of these retrofits on overall home energy efficiency, we examine the difference between trends of annual energy use per unit floor area (or energy use intensity) and per occupant across income in market rate homes compared to the Habitat homes. When treating self-reported income categories as an ordered set (<$25k, $25-50k, $50-75k, and >$75k) in a least squares regression of energy use intensity (EUI) per occupant on income, we find a significant downward trend (p-value=0.048) for market-rate homes, indicating that low-income households either live in less energy efficient homes or there is significantly different behavior across income levels.

[2] They were adopted for the first time 1977 when ASHRAE 90-1975 was adopted state-wide. (US Dept. of Energy Building Energy Codes Program, www.energycodes.gov/status/states/michigan)

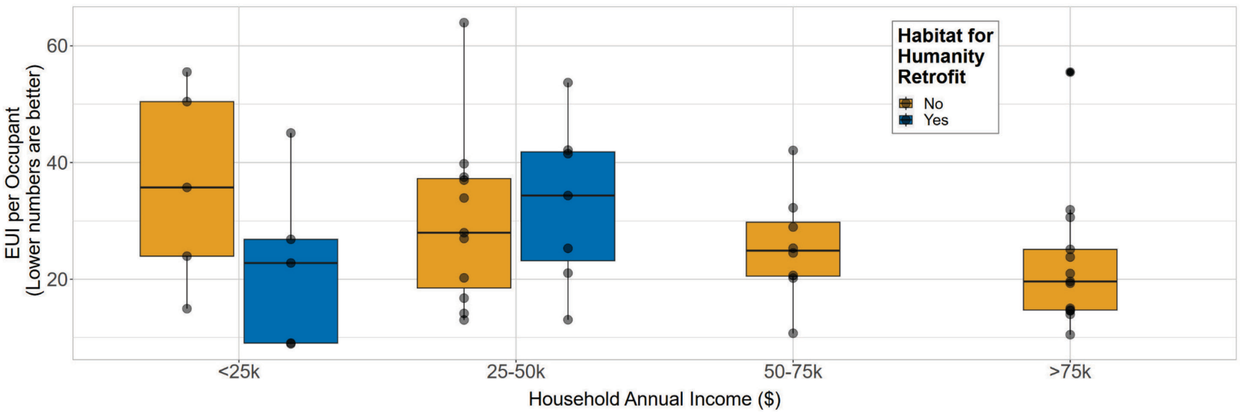


Fig 1: **Energy use intensity per occupancy by income group.** Annual energy use per floor area divided by the number of occupants is shown here. The x-axis represents four income categories to which participants were assigned given the income range they provided. Each box plot shows the median (middle line), first and third quantiles (lower and upper box bounds), and minima and maxima (whiskers). The blue boxes represent homes that have been retrofit by Habitat for Humanity, which perform better than market rate homes in the sample (represented by oranges boxes) for homes earning less than $25k. Each dot represents one household. Using a non-linear least squares regression, we find a significant downward trend (p-value=0.048) among market rate homes, indicating that those with lower incomes live in less efficient homes.

The latter explanation would suggest, for example, that lower-income households start to use heating at higher ambient temperatures and cooling at lower ambient temperatures. Cong et al. provide evidence to the contrary. They find that lower-income families wait for ambient temperatures to rise higher before turning on air conditioning compared to those with higher incomes (Cong et al. 2022). This would imply that low-income families use less energy, a seeming contradiction of our results. However, we believe that there is no contradiction, since the Cong et al. results are not directly comparable to ours for two reasons. First, we report energy use per square foot per occupant, which Cong et al. do not observe. Second, Cong et al. have studied air conditioning, whereas energy use in our sample is dominated by heating. Huang et al (2023) do find evidence that low-income households start to heat earlier in the season and heat for more months of the year than higher-income households. However, these results are also not comparable to ours since there is no normalization by area or occupancy. We estimate the heating inflection temperature (HIT), or the outdoor temperature at which each household turns on the heat because in every case heating constitutes the highest proportional energy expenditure (>60%). To estimate the HIT, we calculate a linear splitwise regression of metered daily gas use on ambient air temperature. We find no significant trend in HIT across income (see Figure B.2). Combined, our findings and those of Huang et al. (2023) suggest that behavior-driven energy use patterns are unlikely to explain the higher energy use of low-income homes.

Observed heating and cooling setpoints—read from participants' smart thermostats—likewise reveal that lower income households do not on average choose higher setpoints in winter or lower setpoints in summer [Fig 2a]. We do observe greater variance in the set points that households in the lowest income group (<$25k) choose [Fig 2b], as well as in the indoor temperatures that they experience [Fig 2c]. This suggests that, even though they have higher energy use intensity, these households are actively trying to manage their energy use and comfort by manipulating their set points. This provides evidence that the higher EUI is in fact due to poorer building envelopes and not because lower-income households are choosing consistently different setpoint temperatures.

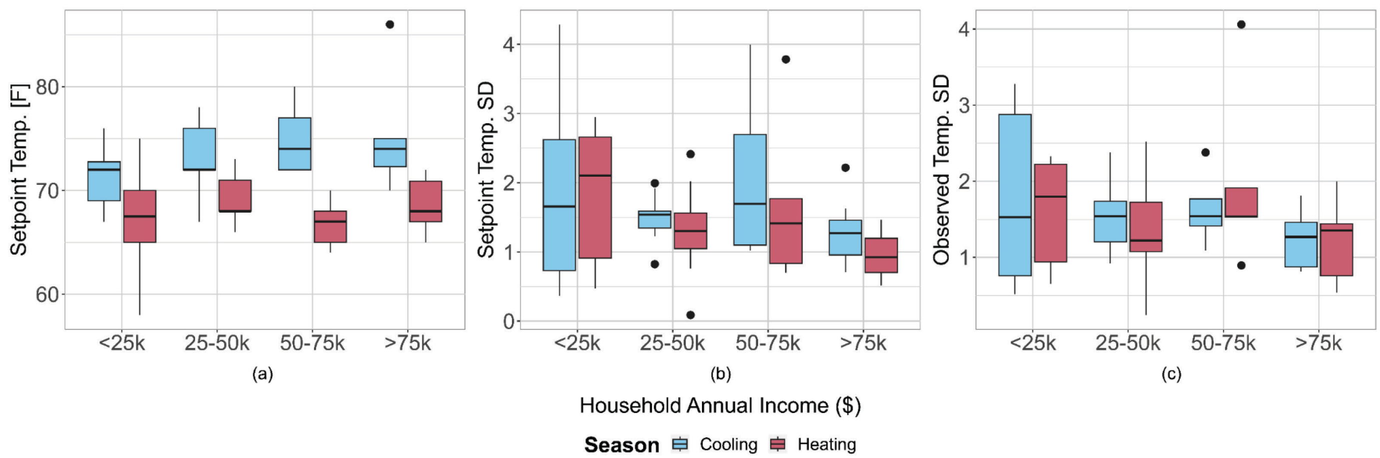


Fig 2a-b-c: **Thermostat setpoint and observed indoor temperature by income.** Observed heating and cooling setpoints (a), setpoint standard deviation (b), and indoor temperature standard deviation (c) on smart thermostats for each home.

We look at housing characteristics to explore whether the homes occupied by low-income households are in fact less efficient. Blower door testing conducted at each home provides an empirical measure of efficiency by measuring air infiltration. Low infiltration signifies high efficiency. We find that the homes retrofit by Habitat have better performance than market-rate homes in the sample. The median measured air infiltration rate of Habitat homes is almost half that of their counterparts (4.2 ACH 50 and 7.7 ACH 50, respectively) with less variability (range: 2.9 - 5.9; IQR = 3.4 - 5.3 and range: 3.2 - 17.5; IQR = 5.8 - 10.9, respectively). Applying the same regression method described above, after excluding Habitat homes, we find a significant downward trend (p-value=0.023) for market-rate homes, indicating that the lower-income homes are indeed less efficient (Figure B.3).

3.2 Energy burden

For the 51 houses in our sample, we calculate the electricity loads that would result from replacing natural gas furnaces with air source heat pumps for space heating (see Supplementary Methodology for more detail on reduced complexity model and load derivation) and apply the most prevalent gas and electric utility rates across the sample to determine the energy cost change associated with this replacement. We calculate change in annual energy bills and energy cost burden which refers the difference in energy expenditures and percentage of income spent on utilities, respectively, between the baseline scenario and the heat pump scenario. 41/51 households were on a standard time-invariant rate, which will be discontinued as of May 2023. 10 had elected different rate structures, which include time-of-use rates, interruptible cooling rates, and specialty rates designed for low-income households. We find that switching to a heat pump would increase annual utility bills for every household in the sample, and that the cost goes up by $1154 on average (see Table C.3).

Our results show variability in median cost change across income and a disproportionate concentration of high energy burden increase below median income (<$25k and $25-50k). The median cost increase for below median income households is $801 (n=28), constituting a 37% utility spending increase on average. There is a 49% utility spending increase for above median income households on average (n=22) [Fig 3a-1]. Even though the median cost increase is nominally lower for below median income households, their energy burden increase is 4 times higher on average than those at or above median income [Fig 3b-1]. Additionally, all households earning median income ($50-75k) and above (>$75k) - which currently have a median energy burden of 2.6% – would experience a median change in energy burden of greater than 1 percentage point, indicating that energy burden could become a concern for households which are currently energy secure.

3.3 Time of use electricity rates

We examine the impact of two time-of-use rates available to all customers in the study region on the annual increased utility costs and energy burdens of the sample for a hypothetical conversion to heat humps. Switching to the standard time-of-use rate (DTE no. D1.11) ("DTE Electric Company Rate Book for Electric Service" 2023) reduces the mean cost increase for the sample by $120 per year from $1154 to $1034 (see Fig 3a-2) relative to a flat rate. Under this rate, the median utility cost change due to heat pumps is lower for every income category. The effect of this lower cost change is minimal for energy burden, reducing the rate by less than 1 percentage point for each category [Fig 3b-2].

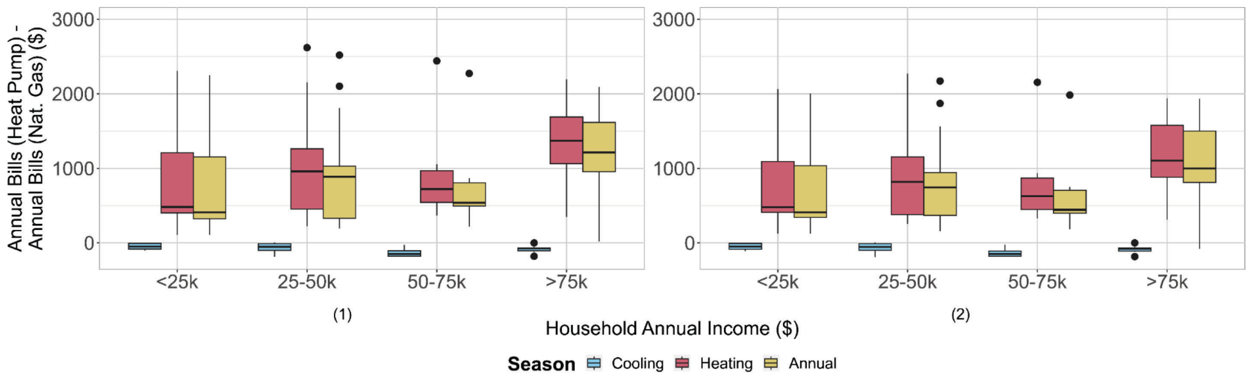


Fig 3a: **Change in annual energy bills for switching to a heat pump from natural gas heating by income.** The x-axis represents four income categories to which participants were assigned given the income range they provided. Dot represents outliers. Each box plot shows the median cost increase (middle line), first and third quantiles (lower and upper box bounds), and minima and maxima of change in utility cost change for (1) standard flat electricity rate and 2022 natural gas cost; (2) standard time-of-use electricity rate and 2022 natural gas cost.

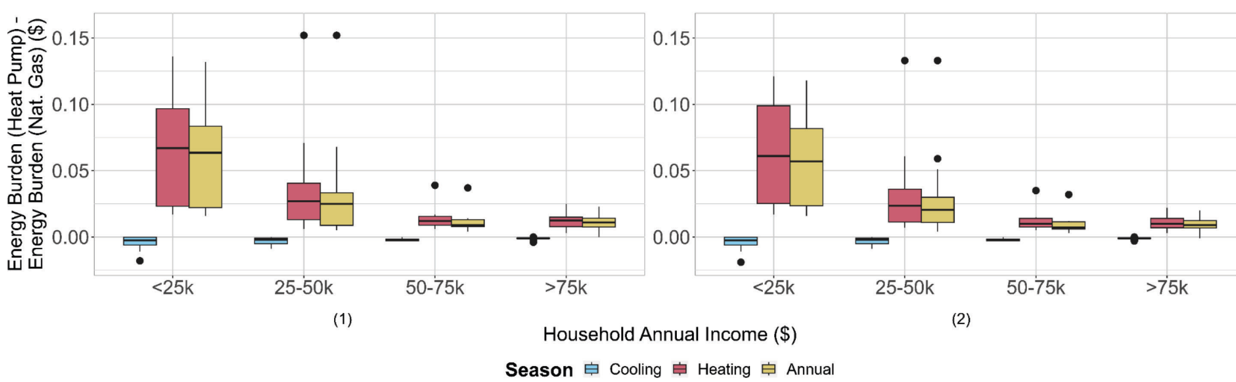


Fig 3b: **Change in energy burden for switching to a heat pump from natural gas heating by income.** The x-axis represents four income categories to which participants were assigned given the income range they provided. Dot represents outliers. Each box plot shows the median energy burden increase (middle line), first and third quantiles (lower and upper box bounds), and minima and maxima of change in energy burden change for (1) standard flat electricity rate and 2022 natural gas cost; (2) standard time-of-use electricity rate and 2022 natural gas cost.

By comparison, relative to a flat rate, the optional time-of-use rate (DTE no. D1.2) (DTE Electric Company Rate Book for Electric Service, 2023) would worsen the increase in annual utility cost for switching to a heat pump for all income groups. Switching to D1.2 increases the mean cost increase for the sample by $623 per year to $1777 (see Figure B.4). This rate nearly doubles the median energy burden changes for all income groups earning less than $75k (see Figure B.5). The D1.2 rate had a higher cost per kWh at peak times and a peak window two hours longer than the D1.11 rate. These rates impacted each household differently given the variety of occupants, schedules, housing vintage across the sample. For instance, those who saw the greatest cost increase with the standard time-of-use rate had the oldest, least efficient AC units in the sample and used their cooling systems during the peak window, whereas, in reality, the switch to a heat pump would include a new, more efficient AC.

While the gas commodity prices have risen dramatically from 2021-2023, the delivered price of natural gas for residential customers has in fact been modest and does not affect the results. See Figures B.4 and B.5 for a comparison of annual bill and energy burden changes with 2021 and 2023 gas rates. See

Table C.2 for a detailed comparison of all of the electricity and gas rates available to DTE customers as of 2023 and their impact on baseline household energy use.

3.4 Energy retrofit model

Energy retrofits are a possible strategy to mitigate this increase in bills. Since we do not have empirical estimates of cost savings potential of envelope improvements to mitigate the cost increase of heating electrification, we first model the corresponding energy uses using the NREL ResStock End Use Savings Shapes (E. Wilson et al. 2022). We randomly sample 400 Michigan homes heated with natural gas from the database and examine four scenarios: baseline envelope with natural gas heating, envelope upgrade, heat pump upgrade, and combined heat pump and envelope upgrade. To then convert the energy uses to cost, we apply the electricity and gas rates experienced by 41/51 of our study participants to the hourly electricity and gas loads to estimate the relative cost impact of retrofits for the natural gas scenario and the heat pump scenario.

We find that transitioning to a heat pump without energy retrofits results in a mean utility cost increase of 26% over the baseline. Adding a comprehensive envelope retrofit improvement mitigates this cost premium and drives utility costs back to what they were with natural gas heating with the existing envelope. Energy efficiency retrofits alone reduce bills by 11% compared to the baseline condition [Fig 4]. See Note D.1 for a comparison of the modeled results to the estimates calculated using observed data from the field study, including a breakdown of model findings by house vintage (Figure B.6).

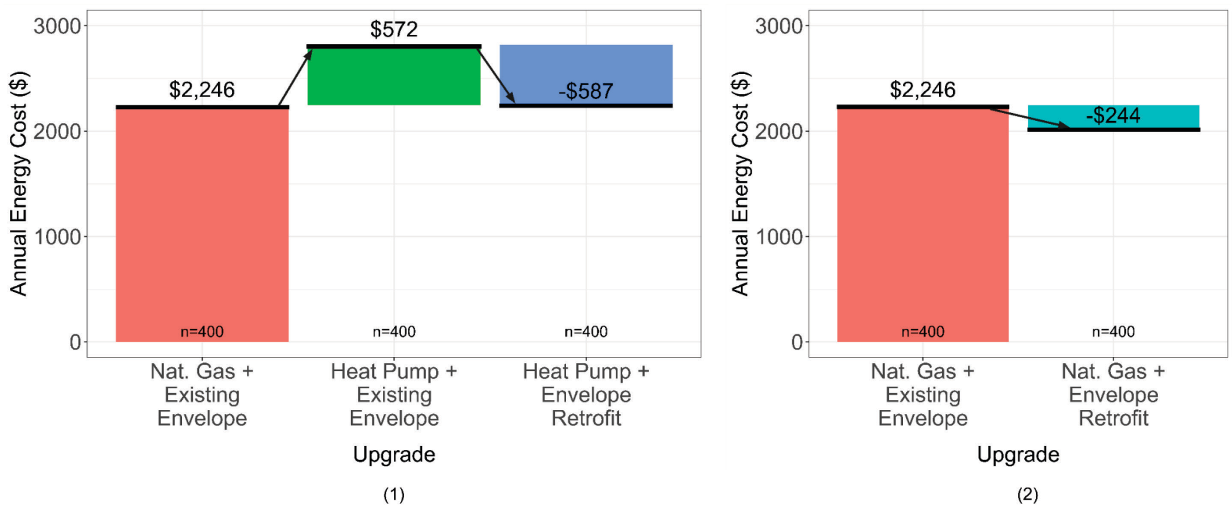


Fig 4: **Modeled mean annual energy cost impact of heating electrification and envelope improvements.** (1) The baseline case (natural gas heating with existing envelope) represented in red is compared to two upgrades: heat pump with efficient envelope retrofit (green) and heat pump without envelope improvements (blue). (2) The baseline case (natural gas heating with existing envelope) represented in red is compared natural gas heating with efficient envelope retrofit (teal). Means represent 400 randomly sampled homes from the ResStock end use load profile database that use natural gas in Michigan. Using a Kruskall-Wallace test, we find a significant difference between the medians of the utility costs in each upgrade category (p-value < 0.01). We test the null hypothesis that the medians were the same using a pairwise with the Bonferroni adjustment and similarly find significant differences for each comparison.

3.5 Contractor retrofit recommendations

Our results suggest that, with energy retrofits, most homes would not experience an increase in utility bills relative to the status quo if they shifted to heat pumps. Based on REM/Rate ("REM/Rate" 2024), commonly used software, our contractor recommended a different combination of ten individual retrofit measures for the homes in our sample and these upgrades are expensive with long payback periods. The most commonly recommended measure is air sealing, an intervention in which joints are sealed to reduce air infiltration. We classify building envelope upgrades as simple if they can be completed by one contractor (e.g., spraying cellulose in the attic) and complex otherwise (e.g., foam injection into drywall). Upgrades to the HVAC system are in a separate category, as are upgrades to other appliances (e.g., fridges) (see Figure B.8). The median retrofit package costs are about 10% of household income. ($3250 for <$25k; $4700 for $24-50k; $10,300 for $50-75k; $7,000 for >$75k) (see Figure B.9). 14 households in the lowest three income groups are faced with total package costs of more than 20% of their income. The median payback period across the sample is 24 years, with a large variance across the income groups (see Figure B.10).

Upfront cost and simple payback estimates for retrofits match previous studies. Fowlie et al. (Fowlie, Greenstone, and Wolfram 2018) use empirical estimates for actual energy savings across the Michigan WAP and find internal rates of return (IRR) at -10.6% (10 year), -2.3% (16 year), and 0.21% (20 year). We find even lower IRR for the recommended retrofits by the energy assessment contractor: -16.1% (10 year), -5.3% (16 year), and 2.2% (20 year). Less et al. (Less et al. 2021) estimate an archetypical retrofit package for a single family house that includes the most common retrofit recommendations in our sample (attic floor insulation, air sealing, foundation floor insulation) based on actual US construction costs at $7,825 (see Note D.2 for measure cost calculation). The mean upgrade package cost estimated by the energy audit contractor in our sample is $7,628 and the median is $5,900 (see Figure B.9). Since the package described by Less et al. excludes system or appliance measures, we surmise that it is likely our contractor's costs are underestimates. Realized project costs could be higher, and payback periods longer.

There is no clear pattern about what measures are most cost-effective. The results show a large range of annual cost savings available from the recommended retrofit packages, with annual utility bill savings ranging from $26 to $730 [Fig 5a]. We find that air sealing, which was recommended to all households, provides a payback range of 3.7 to 144 years [Fig 5b] and attic insulation alone provides a payback range of 20 to 259 years (see Note D.2 for measure cost calculation). The high-end estimates that reflect payback periods much higher than seen in the literature are due a sample-specific scenario in which 25% of the homes in the study received energy efficiency retrofits before the study period. For these homes, which were already high performing, the contractor recommended improvements to existing conditions (such as attic insulation and air sealing), which resulted in marginal energy savings and therefore long payback periods.

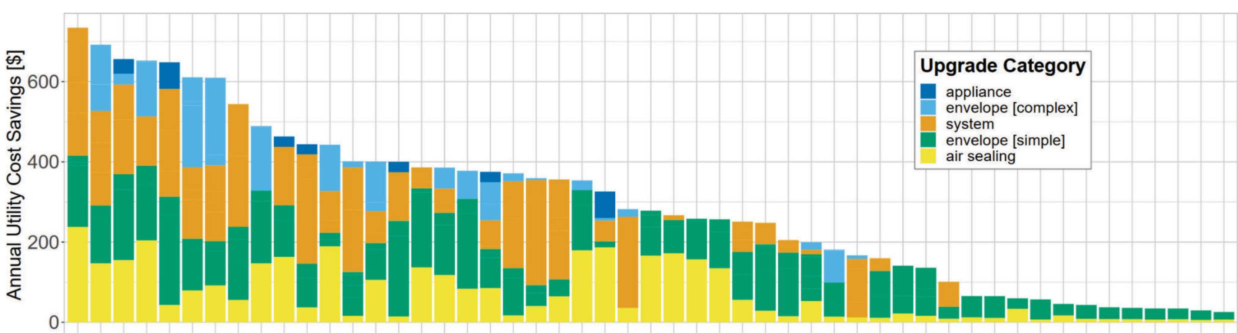


Fig 5a: **Annual utility cost savings for retrofit packages by household.** Colors represent categories we develop to indicate the relative cost and difficulty of adopting the recommendation. There is no clear pattern for which energy retrofits provide the best payback

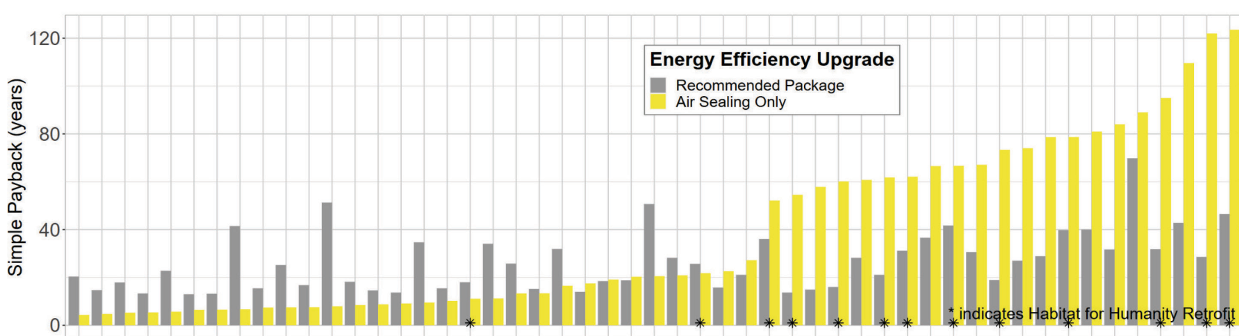


Fig 5b: **Simple payback for the recommended package and air sealing by household.** Gray bars represent the payback for the full retrofit package recommended for each home. Corresponding yellow bars represent the air sealing payback period for that home. Star indicates houses that have been retrofit by Habitat for Humanity.

4. Discussion

We explored the drivers of energy inefficiency, explored the economic impact of replacing natural gas furnaces with heat pumps by income, assessed a range of energy retrofit measures that could support utility cost reduction in the 51 Michigan households we studied, and compared this impact to estimates from a national model. Heat pumps raise energy cost and energy burden disproportionately for low-income households. The median utility cost increase for switching to a heat pump is lowest for low-income households because they use the least amount of energy. This finding is suggestive of an efficiency paradox (Goldstein, Reames, and Newell 2022) where the lowest consuming households live in the least efficient homes, indicating that they are likely not using enough energy to meet their health, safety, and comfort needs. Yet, the increase in energy burden is disproportionately higher for low-income groups because even though their cost increase is nominally the smallest, it is a greater percentage of their annual income. Our results show that adopting heat pumps results in a fmedian energy burden increase of 75% and 54% for both income groups earning below AMI (<$25k and $25-50k, respectively). Given that households below median income have a 6% median energy burden on their existing natural gas heating systems, such increases would severely worsen existing energy insecurity, for instance increasing risk of poor health (Tony G. Reames, Daley, and Pierce 2021) and coping behaviors like trading off paying utility for paying for rent or food (Hernández 2016), or the underconsumption of energy in household who struggle to pay their bills (Meyer et al. 2018; Barrella et al. 2022; Faiella and Lavecchia 2021; Antepara et al. 2020).

Policymakers should act to help lower the operating costs of heat pumps compared to natural gas for low-income households in cold climates. This can be done in three ways. First, government-sponsored initiatives to advance more efficient heat pump technology like the US Department of Energy Residential Cold Climate Heat Pump Challenge are essential to improve energy bill affordability of fuel switching. More efficient heat pumps reduce the utility cost premium over natural gas furnaces.

Second, state regulators should exercise a more robust scrutiny of utility company returns and create more opportunities to improve customer outcomes in the rate making process. For example, the Michigan Public Service Commission recently ruled in a disputed rate case in the study region that resulted in allocations for energy retrofits in historically underserved areas due to intervening efforts from customer groups not typically represented in rate making like community advocates and municipal governments (Hon. Daniel C. Scripps, Chair, Hon. Katherine L. Peterick, Commissioner, and Hon. Alessandra R. Carreon, Commissioner 2023). A high ratio of per-unit electricity to gas rates makes heat pumps less attractive than natural gas furnaces.

Third, states should consider implementing percentage of income payment plans (PIPP) that place a cap on energy expenditures relative to household income. These programs can be paired with federal- and state-funded retrofit programs to simultaneously improve the building stock and mitigate energy poverty. Capping household utility costs insulates low-income households from increase in bills.

Local factors exacerbate the economic penalty for household heating electrification described in this study and pose additional barriers to change not found in other regions. In our study sample, the average electricity cost is $0.18 per kWh and gas costs $0.8 per 100 cubic feet, or $0.03 per kWh. Per unit energy, electricity is therefore 5 times more expensive than gas, which is a large-enough difference that the higher efficiency of heat pumps is unable to compensate for it. (See Table C.4 for energy burden changes by income). Our results show that under these circumstances, energy cost increases for heating electrification could be disruptive even for households earning twice the median income.

Low-income households will need expanded and flexible financial assistance to retrofit their homes to prepare them for electrification. The subset (25%) of homes that received deep energy retrofits prior to the data collection period had consistently more efficient air sealing and attic insulation than the market-rate homes. Retrofits to improve the performance of these characteristics were the most frequently recommended to study participants by the contractor, but we found they had a large range in payback period. There was no clear best choice investment that would provide either the greatest utility savings or the best payback, making it difficult for policymakers to make broadly-applicable recommendations for energy efficiency retrofits.

The group of very low earners (<$25k) with low energy burdens living in highly efficient homes were the same households that experienced the lowest energy burden increase due to heat pumps. This demonstrates the value of energy efficiency improvements in buffering households from the impact of utility cost rise due to electrification. However, the retrofits that provide the remedy are expensive. Our findings suggest that actual upfront costs for recommended retrofits in homes that have not been renovated far exceeded the $7,700 cap for the Weatherization Assistance Program. Additionally, the payback periods in many cases were so high the projects would not qualify for the program, which requires a 1:1 saving-to-investment (SIR) ratio without consideration of discount rates. Current programs need to be expanded to cover the cost of expensive upgrades, and to be made available to more homes.

5. Conclusions

Policy action is needed to make heating electrification viable. The economics of electrification are adverse for the existing housing stock in cold climates. Our findings suggest that heat pumps are not a feasible economic alternative for households currently using natural gas, unless governments offset energy cost premiums through public funding. Some of the policy discussion around heat pumps does not acknowledge this (U.S. Department of Energy 2023; Rewiring America 2021; Fathollahzadeh et al. 2022). Such an investment can be justified on the basis of equity and by internalizing the social cost of carbon, current estimates of which are ~$180 per ton CO2 (U.S. Environmental Protection Agency 2022; Rennert et al. 2022).

Coupling heating electrification with retrofits in existing homes with natural gas heating can limit utility cost increases and reduce a key barrier to heat pump adoption. At the same time, our study shows that even after a visit from a home energy auditor, homeowners can be left without sufficient information to act. The reports they are provided could be more useful in supporting investment decisions by providing a marginal abatement curve specific to each house, where the payback period of each measure is plotted against the cumulative cost of all the recommended measures. The homeowner can decide the most they are willing to spend, and the curve would show them all the fastest-payback measures that can be implemented for that amount.

The impact of rate structures should be analyzed based on empirical data from the rate base. Time-of-use rate design for electricity determines the cost increase for switching to heat pumps. We estimate that one rate (D1.11) reduced the increase in bills by 10% compared to the flat rate (D1), while the other (D1.2) further elevated the average cost increase by 56%. Modeled results using ResStock show the opposite, where the D1.11 rate is usually no worse than the flat rate (see Figure B.7 for utility rate comparison). Using empirical energy use data in utility rate design to understand how proposed rates affect households across the income spectrum and across housing quality given future adoption of heat pumps could help mitigate energy insecurity and promote greater access to heat pump adoption among natural gas users.

While our focus on Michigan allows us to understand the cost dynamics for electrification in a cold climate with high prevalence of natural gas use, limitations of our study include the small sample size and the limited regional scope. Additionally, we were unable to incorporate homeowner attitudes regarding converting their natural gas heating systems to electric heat pump systems. Future work will investigate these perceptions, examining the factors that influence decision making for residential electrification and further examining potential barriers to equitable adoption of heat pumps across income.

Data Availability

Model inputs and aggregated data that support the findings of this study are available from the corresponding author upon reasonable request. Demographic information for participants and raw data is not available in accordance with the informed consent agreement signed by study participants.

Ethics Statement

The University of Michigan’s Institutional Review Board reviewed and approved this research based on informed consent by study participants.

Acknowledgements
We thank the University of Michigan Graham Institute for Sustainability and the U.S. Department of Energy Building Technologies Office Innovation in Buildings (IBUILD) graduate research fellowship for supporting this research. We also thank Shantonio Birch for feedback on this research.

Declaration of Interests
The authors declare no competing interests.

References

Abbasi, Mohammad Hosein, Badr Abdullah, Raúl Castaño-Rosa, Muhammad Waseem Ahmad, Ali Rostami, and Jeff Cullen. 2022. "Planning Energy Interventions in Buildings and Tackling Fuel Poverty: Can Two Birds Be Fed with One Scone?" *Energy Research & Social Science* 93 (November): 102841. https://doi.org/10.1016/j.erss.2022.102841.

Allcott, Hunt, and Michael Greenstone. 2017. "Measuring the Welfare Effects of Residential Energy Efficiency Programs with Self-Selection into Program Participation."

"An Act Creating a Next Generation Roadmap for Massachusetts Climate Policy, SB9." n.d. (Massachusetts senate - assembly. 2022. Regular Sessions.).

Antepara, Iñigo, Lefkothea Papada, João Pedro Gouveia, Nikolas Katsoulakos, and Dimitris Kaliampakos. 2020. "Improving Energy Poverty Measurement in Southern European Regions through Equivalization of Modeled Energy Costs." *Sustainability* 12 (14): 5721. https://doi.org/10.3390/su12145721.

Azariadis, Costas, and John Stachurski. 2005. "Chapter 5 Poverty Traps." In *Handbook of Economic Growth*, 1:295–384. Elsevier. https://doi.org/10.1016/S1574-0684(05)01005-1.

Barrella, Roberto, Irene Priego, José Ignacio Linares, Eva Arenas, José Carlos Romero, and Efraim Centeno. 2020. "Feasibility Study of a Centralised Electrically Driven Air Source Heat Pump Water Heater to Face Energy Poverty in Block Dwellings in Madrid (Spain)." *Energies* 13 (11): 2723. https://doi.org/10.3390/en13112723.

Barrella, Roberto, José Carlos Romero, José Ignacio Linares, Eva Arenas, María Asín, and Efraim Centeno. 2022. "The Dark Side of Energy Poverty: Who Is Underconsuming in Spain and Why?" *Energy Research & Social Science* 86 (April): 102428. https://doi.org/10.1016/j.erss.2021.102428.

Bednar, Dominic J., Tony Gerard Reames, and Gregory A. Keoleian. 2017. "The Intersection of Energy and Justice: Modeling the Spatial, Racial/Ethnic and Socioeconomic Patterns of Urban Residential Heating Consumption and Efficiency in Detroit, Michigan." *Energy and Buildings* 143 (May): 25–34. https://doi.org/10.1016/j.enbuild.2017.03.028.

Besagni, Giorgio, Marco Borgarello, Lidia Premoli Vilà, Behzad Najafi, and Fabio Rinaldi. 2020. "MOIRAE – Bottom-up MOdel to Compute the Energy Consumption of the Italian REsidential Sector: Model Design, Validation and Evaluation of Electrification Pathways." *Energy* 211 (November): 118674. https://doi.org/10.1016/j.energy.2020.118674.

Booth, A.T., and R. Choudhary. 2013. "Decision Making under Uncertainty in the Retrofit Analysis of the UK Housing Stock: Implications for the Green Deal." *Energy and Buildings* 64 (September): 292–308. https://doi.org/10.1016/j.enbuild.2013.05.014.

Bradshaw, Jonathan L., Elie Bou-Zeid, and Robert H. Harris. 2014. "Comparing the Effectiveness of Weatherization Treatments for Low-Income, American, Urban Housing Stocks in Different Climates." *Energy and Buildings* 69 (February): 535–43. https://doi.org/10.1016/j.enbuild.2013.11.035.

Calver, Philippa, Sarah Mander, and Dana Abi Ghanem. 2022. "Low Carbon System Innovation through an Energy Justice Lens: Exploring Domestic Heat Pump Adoption with Direct Load Control in the United Kingdom." *Energy Research & Social Science* 83 (January): 102299. https://doi.org/10.1016/j.erss.2021.102299.

Ceglia, Francesca, Elisa Marrasso, Samiran Samanta, and Maurizio Sasso. 2022. "Addressing Energy Poverty in the Energy Community: Assessment of Energy, Environmental, Economic, and Social Benefits for an Italian Residential Case Study." *Sustainability* 14 (22): 15077. https://doi.org/10.3390/su142215077.

"Climate Commitment Act (CCA) SB 5126." n.d. (WA senate - assembly. 2021-2022. Regular Sessions).

"Climate Leadership and Community Protection Act, S. 6599." n.d. (New York senate - assembly. 2019–2020. Regular Sessions).

Cong, Shuchen, Destenie Nock, Yueming Lucy Qiu, and Bo Xing. 2022. "Unveiling Hidden Energy Poverty Using the Energy Equity Gap." *Nature Communications* 13 (1): 2456. https://doi.org/10.1038/s41467-022-30146-5.

Deetjen, Thomas A, Liam Walsh, and Parth Vaishnav. 2021. "US Residential Heat Pumps: The Private Economic Potential and Its Emissions, Health, and Grid Impacts." *Environmental Research Letters* 16 (8): 084024. https://doi.org/10.1088/1748-9326/ac10dc.

Domínguez-Amarillo, Samuel, Jesica Fernández-Agüera, Andrew Peacock, and Ignacio Acosta. 2020. "Energy Related Practices in Mediterranean Low-Income Housing." *Building Research & Information* 48 (1): 34–52. https://doi.org/10.1080/09613218.2019.1661764.

Donaldson, Ross, and Richard Lord. 2018. “Can Brownfield Land Be Reused for Ground Source Heating to Alleviate Fuel Poverty?” *Renewable Energy* 116 (February): 344–55. https://doi.org/10.1016/j.renene.2017.09.037.

Drehobl, Ariel, Lauren Ross, and Roxana Ayala. 2020. “An Assessment of National and Metropolitan Energy Burden across the United States,” 80.

“DTE Electric Company Rate Book for Electric Service.” 2023. Michigan Public Service Commission. https://www.michigan.gov/mpsc/consumer/electricity/data-price/electric-rate-books/mpsc-approved-dte-electric-rate-books-and-cancelled-sheets.

Faiella, Ivan, and Luciano Lavecchia. 2021. “Energy Poverty. How Can You Fight It, If You Can’t Measure It?” *Energy and Buildings* 233 (February): 110692. https://doi.org/10.1016/j.enbuild.2020.110692.

Fathollahzadeh, Mohammad Hassan, Lacey Tan, Edie Taylor, Mike Henchen, and Talor Gruenwald. 2022. “The Economics of Electrifying Buildings.” RMI.

Fitó, J., N. Dimri, and J. Ramousse. 2021. “Competitiveness of Renewable Energies for Heat Production in Individual Housing: A Multicriteria Assessment in a Low-Carbon Energy Market.” *Energy and Buildings* 242 (July): 110971. https://doi.org/10.1016/j.enbuild.2021.110971.

Flower, Jack, Graeme Hawker, and Keith Bell. 2020. “Heterogeneity of UK Residential Heat Demand and Its Impact on the Value Case for Heat Pumps.” *Energy Policy* 144 (September): 111593. https://doi.org/10.1016/j.enpol.2020.111593.

Förster, Michael F. 1994. “Measurement of Low Incomes and Poverty in a Perspective of International Comparisons.” *OECD Labour Market and Social Policy Occasional Paper* No. 14. http://www.oecd.org/dataoecd/45/58/1895548.pdf.

Fowlie, Meredith, Michael Greenstone, and Catherine Wolfram. 2018. “Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program*.” *The Quarterly Journal of Economics* 133 (3): 1597–1644. https://doi.org/10.1093/qje/qjy005.

Gillingham, Kenneth, and Karen Palmer. 2014. “Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence.” *Review of Environmental Economics and Policy* 8 (1): 18–38. https://doi.org/10.1093/reep/ret021.

Goldstein, Benjamin, Tony G. Reames, and Joshua P. Newell. 2022. “Racial Inequity in Household Energy Efficiency and Carbon Emissions in the United States: An Emissions Paradox.” *Energy Research & Social Science* 84 (February): 102365. https://doi.org/10.1016/j.erss.2021.102365.

Graff, Michelle, Sanya Carley, David M. Konisky, and Trevor Memmott. 2021. “Which Households Are Energy Insecure? An Empirical Analysis of Race, Housing Conditions, and Energy Burdens in the United States.” *Energy Research & Social Science* 79 (September): 102144. https://doi.org/10.1016/j.erss.2021.102144.

Graff Zivin, Joshua, and Kevin Novan. 2016. “Upgrading Efficiency and Behavior: Electricity Savings fromResidential Weatherization Programs.” *The Energy Journal* 37 (4). https://doi.org/10.5547/01956574.37.4.jziv.

Hernández, Diana. 2016. “Understanding ‘Energy Insecurity’ and Why It Matters to Health.” *Social Science & Medicine* 167 (October): 1–10. https://doi.org/10.1016/j.socscimed.2016.08.029.

Hon. Daniel C. Scripps, Chair, Hon. Katherine L. Peterick, Commissioner, and Hon. Alessandra R. Carreon, Commissioner. 2023. Order Approving Settlement Agreement. Michigan Public Service Commission.

Huang, Luling, Destenie Nock, Shuchen Cong, and Yueming (Lucy) Qiu. 2023. “Inequalities across Cooling and Heating in Households: Energy Equity Gaps.” *Energy Policy* 182 (November): 113748. https://doi.org/10.1016/j.enpol.2023.113748.

Jones, A., D. Nock, C. Samaras, Y.L. Qiu, and B. Xing. 2023. “Climate Change Impacts on Future Residential Electricity Consumption and Energy Burden: A Case Study in Phoenix, Arizona.” *Energy Policy* 183. https://doi.org/10.1016/j.enpol.2023.113811.

Koasidis, Konstantinos, Vangelis Marinakis, Alexandros Nikas, Katerina Chira, Alexandros Flamos, and Haris Doukas. 2022. “Monetising Behavioural Change as a Policy Measure to Support Energy Management in the Residential Sector: A Case Study in Greece.” *Energy Policy* 161 (February): 112759. https://doi.org/10.1016/j.enpol.2021.112759.

Less, Brennan, Iain Walker, Núria Casquero-Modrego, and Leo Rainer. 2021. “The Cost of Decarbonization and Energy Upgrade Retrofits for US Homes.” None, 1834578, ark:/13030/qt0818n68p. https://doi.org/10.2172/1834578.

Lewis, Jamal, Diana Hernández, and Arline T. Geronimus. 2020. “Energy Efficiency as Energy Justice: Addressing Racial Inequities through Investments in People and Places.” *Energy Efficiency* 13 (3): 419–32. https://doi.org/10.1007/s12053-019-09820-z.

Liu, Zhijian, Yuanwei Liu, Di Wu, Guangya Jin, Hancheng Yu, and Wensheng Ma. 2020. “Performance and Feasibility Study of Solar-Air Source Pump Systems for Low-Energy Residential Buildings in Alpine Regions.” *Journal of Cleaner Production* 256 (May): 120735. https://doi.org/10.1016/j.jclepro.2020.120735.

Liu, Zhijian, Di Wu, Bao-Jie He, Yuanwei Liu, Xutao Zhang, Hancheng Yu, and Guangya Jin. 2018. “Using Solar House to Alleviate Energy Poverty of Rural Qinghai-Tibet Region, China: A Case Study of a Novel Hybrid Heating System.” *Energy and Buildings* 178 (November): 294–303. https://doi.org/10.1016/j.enbuild.2018.08.042.

Meyer, Sandrine, Holzemer Laurence, Delbeke Bart, Lucie Middlemiss, and Kevin Maréchal. 2018. “Capturing the Multifaceted Nature of Energy Poverty: Lessons from Belgium.” *Energy Research & Social Science* 40 (June): 273–83. https://doi.org/10.1016/j.erss.2018.01.017.

Palma, Pedro, João Pedro Gouveia, and Ricardo Barbosa. 2022. “How Much Will It Cost? An Energy Renovation Analysis for the Portuguese Dwelling Stock.” *Sustainable Cities and Society* 78 (March): 103607. https://doi.org/10.1016/j.scs.2021.103607.

Pastore, Lorenzo Mario, Gianluigi Lo Basso, and Livio de Santoli. 2022. “Towards a Dramatic Reduction in the European Natural Gas Consumption: Italy as a Case Study.” *Journal of Cleaner Production* 369 (October): 133377. https://doi.org/10.1016/j.jclepro.2022.133377.

Reames, Tony G., Dorothy M. Daley, and John C. Pierce. 2021. “Exploring the Nexus of Energy Burden, Social Capital, and Environmental Quality in Shaping Health in US Counties.” *International Journal of Environmental Research and Public Health* 18 (2): 620. https://doi.org/10.3390/ijerph18020620.

Reames, Tony Gerard. 2016. “Targeting Energy Justice: Exploring Spatial, Racial/Ethnic and Socioeconomic Disparities in Urban Residential Heating Energy Efficiency.” *Energy Policy* 97 (October): 549–58. https://doi.org/10.1016/j.enpol.2016.07.048.

“REM/Rate.” 2024. NORESCO. https://www.remrate.com/.

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, et al. 2022. “Comprehensive Evidence Implies a Higher Social Cost of CO2.” *Nature* 610 (7933): 687–92. https://doi.org/10.1038/s41586-022-05224-9.

Rewiring America. 2021. “Bringing Infrastructure Home: A 50-State Report on U.S. Home Electrification.” https://www.rewiringamerica.org/policy/bringing-infrastructure-home-report.

Savage, Thomas, Jethro Akroyd, Sebastian Mosbach, Michael Hillman, Franziska Sielker, and Markus Kraft. 2022. “Universal Digital Twin – the Impact of Heat Pumps on Social Inequality.” *Advances in Applied Energy* 5 (February): 100079. https://doi.org/10.1016/j.adapen.2021.100079.

Thomaßen, Georg, Konstantinos Kavvadias, and Juan Pablo Jiménez Navarro. 2021. “The Decarbonisation of the EU Heating Sector through Electrification: A Parametric Analysis.” *Energy Policy* 148 (January): 111929. https://doi.org/10.1016/j.enpol.2020.111929.

U.S. Department of Commerce. 2024. “U.S. Census.” https://data.census.gov/.

U.S. Department of Energy. 2023. “Pump Up Your Savings with Heat Pumps.” May 30, 2023. https://www.energy.gov/articles/pump-your-savings-heat-pumps.

“US Dept. of Energy Building Energy Codes Program.” 2024. 2024. www.energycodes.gov/status/states/michigan.

U.S. Energy Information Administration. 2021. “Price Elasticity for Energy Use in Buildings in the United States.” https://www.eia.gov/analysis/studies/buildings/energyuse/pdf/price_elasticities.pdf.

U.S. Energy Information Administration. 2023. “Residential Energy Consumption Survey.” https://www.eia.gov/consumption/residential/about.php.

U.S. Environmental Protection Agency. 2022. *Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources. EPA–HQ–OAR–2021–0317*. https://www.federalregister.gov/documents/2022/12/06/2022-24675/standards-of-performance-for-new-reconstructed-and-modified-sources-and-emissions-guidelines-for.

Vaishnav, Parth, and Adilla Mulia Fatimah. 2020. “The Environmental Consequences of Electrifying Space Heating.” *Environmental Science & Technology* 54 (16): 9814–23. https://doi.org/10.1021/acs.est.0c02705.

Walker, Iain S., Brennan D. Less, and Núria Casquero-Modrego. 2022. “Carbon and Energy Cost Impacts of Electrification of Space Heating with Heat Pumps in the US.” *Energy and Buildings* 259 (March): 111910. https://doi.org/10.1016/j.enbuild.2022.111910.

White, Lee V., and Nicole D. Sintov. 2020. “Health and Financial Impacts of Demand-Side Response Measures Differ across Sociodemographic Groups.” *Nature Energy* 5 (1): 50–60. https://doi.org/10.1038/s41560-019-0507-y.

Willand, Nicola, Trivess Moore, Ralph Horne, and Sarah Robertson. 2020. “Retrofit Poverty: Socioeconomic Spatial Disparities in Retrofit Subsidies Uptake.” *Buildings and Cities* 1 (1): 14–35. https://doi.org/10.5334/bc.13.

Wilson, Eric J.H., Chioke B. Harris, Joseph J. Robertson, and John Agan. 2019. “Evaluating Energy Efficiency Potential in Low-Income Households: A Flexible and Granular Approach.” *Energy Policy* 129 (June): 710–37. https://doi.org/10.1016/j.enpol.2019.01.054.

Wilson, Eric, Andrew Parker, Anthony Fontanini, Elaina Present, Janet Reyna, Rajendra Adhikari, Carlo Bianchi, et al. 2022. “End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration, Validation, and Uncertainty Quantification.” NREL/TP-5500-80889, 1854582, MainId:78667. https://doi.org/10.2172/1854582.

Wilson, Eric, Parker, Andrew, Fontanini, Anthony, Present, Elaina, Reyna, Janet, Adhikari, Rajendra, Bianchi, Carlo, CaraDonna, Christopher, Dahlhausen, Matthew, Kim, Janghyun, LeBar, Amy, Liu, Lixi, Praprost, Marlena, White, Philip, Zhang, Liang, DeWitt, Peter, Merket, Noel, Speake, Andrew, Hong, Tianzhen, Li, Han, Mims Frick, Natalie, Wang, Zhe, Blair, Aileen, Horsey, Henry, Roberts, David, Trenbath, Kim, Adekanye, Oluwatobi, Bonnema, Eric, El Kontar, Rawad, Gonzalez, Jonathan, Horowitz, Scott, Jones, Dalton, Muehleisen, Ralph, Platthotam, Siby, Reynolds, Matthew, Robertson, Joseph, Sayers, Kevin, and Li, Qu. 2021. "End-Use Load Profiles for the U.S. Building Stock". United States. https://dx.doi.org/10.25984/1876417. https://data.openei.org/submissions/4520.

Appendix A. Supplementary Methods

1. Data collection.

We obtained one year of utility data for each household, including hourly metered electricity use and daily metered gas use where available. We conducted one visit to each home, during which we installed a smart thermostat where the heating and cooling system could accommodate the product (Ecobee 3 lite) (n = 40). For homes that could not receive the smart thermostat, we set up a wi-fi connected thermo-hygrometer (Govee H5179). Both devices record data at 15-minute intervals.

Comprehensive energy assessment. An accredited energy audit contractor accompanied the research team to each site visit. He performed and energy audit and collecting the following data at each house:

- A blower door test to measure the air infiltration ACH at 50 Pa
- Thermal imaging to identify cold spots on wall surfaces (audits were conducted in the winter, producing thermal gradients at uninsulated areas)
- Indoor and outdoor visual inspection of the house.

All characteristics that impact energy performance were recorded in the audit. Air infiltration rate derived from blower door test results, equipment efficiencies and fuel, roof insulation value, vintage and house area were used in this paper. See Note D.4 for more detail on data collected during the energy audit.

The contractor then recommended energy efficiency measures for each home and provided first cost and utility cost savings estimates for the recommended work. The houses were modeled using the National Energy Audit Tool (NEAT), developed by Oak Ridge National Laboratory (ORNL) and designed for use for evaluations performed as part of the Weatherization Assistance Program (WAP).

During the field work, we discovered that 13 of the 51 participants were Habitat for Humanity homebuyers. Habitat for Humanity of the Huron Valley serves a significant portion of our region of study (Washtenaw County). Although Habitat for Humanity most commonly builds new homes for affordable homeownership, the local chapter has been renovating homes for the last 14 years, since the economic pressure of the 2008 housing crisis rendered retrofits a greater value for those they serve over new homes. The homes we visited had been renovated between 2010 and 2020.

Energy burden. Participants provided income ranges, so we estimate energy burden based on the arithmetic midpoint , i.e. if a participant reports their income to $25k-50k, the energy cost burden for that household was calculated at the proportion of their actual annual utility bills to $37.5k. Household energy expenditure and income are analyzed as observed. No equivalization scales were applied to energy expenditure and income because we observed occupancy in some homes to which the published equivalence scales (Förster 1994) would not readily apply, for example, households with adult children that may live at home for periods of time varying duration and frequency throughout the year. Devising an appropriate scale is beyond the scope of this study. See

2. Housing quality analysis.

We considered the homes retrofit by Habitat for Humanity (H4H) separately from the rest of the sample, since the H4H homes had undergone extensive efficiency retrofits already. We assess whether energy use intensity (EUI) and housing characteristics vary systematically by income. We treat self-reported income categories as an ordered set (<$25k, $25-50k, $50-75k, and >$75k) and fit a linear regression model to EUIper occupant and infiltration on these income groups.

To assess participant behavior, we estimate indoor temperature setpoints in two ways. First, we estimate the heating inflection temperature (HIT) (ambient temperature at which a household begins heating) for each home using a splitwise regression of metered daily gas use on hourly average ambient air temperature (obtained from NOAA Local Climatological Data (LCD) for the data collection period). Second, we evaluate the observed heating and cooling setpoints and the observed indoor temperature for the heating and cooling season for a subgroup that received a smart thermostat (n = 40). Both data points are recorded on 15-minute intervals and accessed with participants' permission. We calculate cooling and heating season means for setpoint temperature as well as the standard deviation for setpoint and indoor temperature using this interval data.

3. Heat pump cost analysis.

Our energy cost analysis for switching to all-electric heat pumps from natural gas-based heating consists of three steps: determining hourly heating load from metered natural gas consumption data (consisting of (A) calculating existing gas use and (B) deriving heat load by multiply it by equipment efficiency), deriving hourly operating efficiency for a cold climate heat pump that is commonly used on the market today, and calculating electricity use and cost if the households were to switch to heat pumps. We also assessed whole home energy costs for the heat pump scenario compared with the current condition of the homes, and test a sensitivity for three electricity utility rates and two gas utility rates.

Heat load.

(A) Existing furnace gas use. To determine heating natural gas use, we first estimated the inflection point for temperature dependent gas use using a split-wise regression of heating degree hours (a measure of the intensity of the space heating needed for a given time and place) on daily total gas use. We assumed this point indicates the minimum amount (ccf) of gas used in the home after which gas is used for space heating in addition to domestic hot water and cooking. **We assumed that the slope of the piecewise linear function (found with the segmented() function in R) past this inflection point indicates heating related natural gas usage. From that, we derived the slope which is the natural gas usage per heating degree hour.** We then obtained the amount of gas used during each hourly time step for heating by multiplying the **slope** by the difference between the outside ambient air temperature departure from the indoor heating setpoint gathered during the initial data collection period when the energy audit took place.

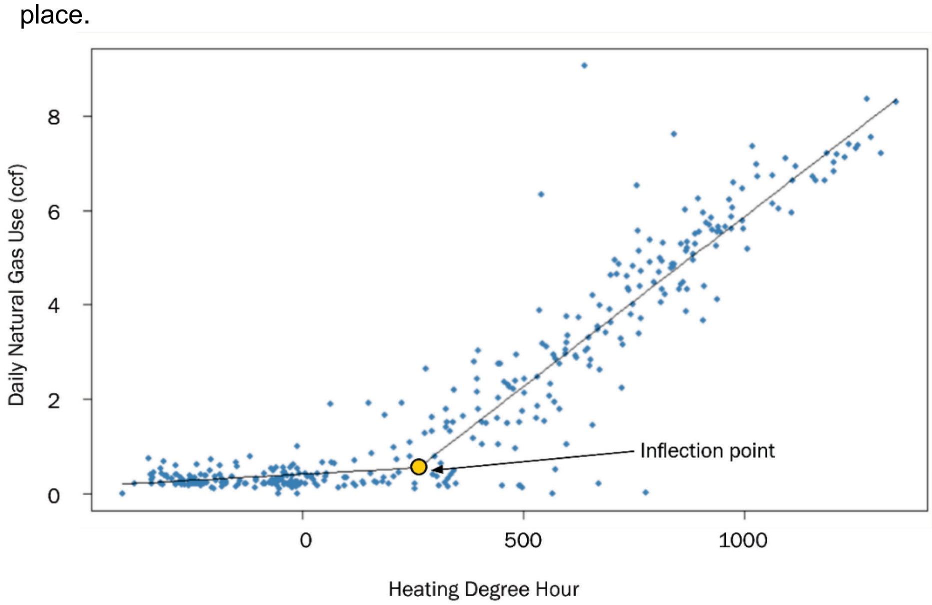


Fig A1: Example split-wise regression of metered natural gas use on heating degree hour. Blue points indicate one day for a single house in the sample, line indicated best fit line calculated using segmented() function in R. Inflection point indicates point beyond which home use of natural gas is for heating

(B) Deriving head load. We multiplied the hourly gas use by the furnace efficiency to obtain the hourly heating load for each house. We obtained the hourly ambient temperatures for each home during the window of time the utility data was provided by the utility (e.g. 11/10/2020 to 11/11/2021) using the NOAA Local Climatological Data (LCD) Tool for the closest available weather station.

$$y_1 = \beta_{A0} + \beta_{A1} \cdot x_1 \qquad y_2 = \beta_{B0} + \beta_{B1} \cdot x_2$$
$$x_1 = x_2 \text{ and } y_1 = y_2$$

$$\beta_{B1} \cdot \sum_{1}^{8760} T_O - T_{SH} = E_g$$

$$Q_h = E_g \cdot \eta$$

Where:

a. (x_1) and (x_2) define the temperatures;
b. (y_1) and (y_2) define the heating load;
c. The inflection temperature is the point at which the lines y1 and y2 intersect.
d. **β_{A0} defines the y-intercept for *temperature independent segment* of splitwise regression** of heating degree hours on hourly total gas use (segment A)**;**
e. **β_{A1} defines the slope for *temperature independent segment* of splitwise regression** of heating degree hours on hourly total gas use (segment A)**;**
f. **β_{B0} defines the y-intercept for *temperature dependent segment of* splitwise regression** of heating degree hours on hourly total gas use (segment B)**;**
g. **β_{B1} defines the slope for *temperature dependent segment* of splitwise regression** of heating degree hours on hourly total gas use (segment B)**;**
h. **T_O = outdoor air temperature (F)** using the NOAA LCD weather data for the same period for which had metered natural gas data for each home;
i. **T_{SH} = setpoint heating temperature (F)** obtained from smart thermostat data for each home;
j. **E_g = annual gas energy use (kWh);**
k. **η = heating furnace efficiency (%)** obtained from home energy audits**;**
l. **Q_h = annual heating load (kW).**

Heat pump model. We calculated the heat pump hourly temperature-dependent coefficient of performance (COP) using the following equation:

Eq. A1: Heat pump hourly temperature-dependent coefficient of performance (COP) for heating season

$$COP'_i \times (1 - l(t_i)) = COP_i \qquad Tmin < t, i \in 8760$$
$$COP_i = 1 \quad t < Tmin$$

Where

- ***i indexes hour;***
- ***COP' = manufacturer reported coefficient of performance*** *using the efficiency curve (ambient temperature vs. COP) of the Mitsubishi M2i cold climate ASHP for heating;*
- ***l() = defrost efficiency loss for give temperature , t (%)*** A 2017 analysis of field operation of heat pumps in Minnesota identifies the duration and operating efficiency impact of the defrost cycle across a range of temperatures. Our calculation includes 11.3% total efficiency loss between 10 and 20°F DB, 10.1% loss between 21 and 30°F DB, and 5.81% loss between 31 and 40°F DB;
- ***t = hourly dry bulb temperature (F)*** *using the NOAA LCD weather data for the same period for which had metered natural gas data for each home;*
- ***COP = observable coefficient of performance;***
- **T_{min} = 10°F** reflecting the change over point noted in Shoenbauer et al., 2018. Recent case studies for cold climate heat pump applications (Shoenbauer et al., 2018; Lopez et al., 2019; Williamson and Aldrich, 2015) demonstrate that field operation reflects more conservative settings for change over point (the point at which the heat pump system switches to backup heating with electric resistance coil) than manufacturer specifications. Mitsubishi specifies heating with the heat pump down to -22°F WB ambient with thermal lockout (heat pump no longer delivering heating) at -31°F WB ambient.
- **Below T_{min} COP = 1** reflecting the heating efficiency of an electric heating coil used to ensure that heating setpoints are met below the change over point. Resistance backup heating is designed to supplement the refrigeration cycle when defrost is needed on the outdoor coils to remove frozen evaporant and enable use of the heat pump in cold temperatures (Williamson and Aldrich, 2015).

We calculated percentage improvement in cooling energy by dividing the Mitsubishi H2i SEER rating (SEER = 17) by the on-label AC efficiency obtained from the energy audits for each home. We then applied this factor to the mean cooling energy percentage (20%) obtained from the Resstock End Use Savings Shapes (Wilson et al., 2021) to determine the annual energy savings.

We find that 20% is a reasonable estimate of the proportion of electricity used for AC according to the following method:

- Using smart thermostat data for the sample, median household size is 1,255 square feet;
- According the smart thermostat, that home uses AC system for a total of 210 hours;
- Assuming industry standard metric for cooling capacity required (1 ton (3.52 kW) per 600 square feet), peak cooling power use is 2 tons (7.034 kW):

$$Cc = A \; x \; Cr$$

Where
A = house area in square feet;
C_r = cooling ratio;
C_c = cooling capacity in tons to the closest ton;

E_c for the median home size is 1477kWh:

$$Ec = Cc \; x \; T$$

Where
E_c = total annual electricity used for cooling in kWh; T = total time AC was on in hours.

P_c for the median home size is 23%:

$$Pc = Ec \div Et$$

Where
P_c = percentage of total annual electricity using for cooling; E_t= total annual electricity consumption in kWh

Electricity cost. We calculated electricity for a hypothetical all-electric heat pump operating in each home by multiplying the hourly heat load derived from the metered gas use by the hourly COP derived using the process described above. We then calculated the hourly energy cost using an hourly model developed in R that simulates the rate schedules published by Detroit Edison Company (DTE) (DTE Electric Company Rate Book for Electric Service, 2023). Our model allows us to calculate the total electricity cost in the manner calculated by the utilities. For instance, there is a flat rate service charge per month, capacity and non-capacity energy charges assessed per kWh, as well as surcharges and credits.

Gas cost. We calculated gas use if the home were to switch to a heat pump by subtracting the sum of temperature-dependent gas use from the total metered gas use for each home, and applying the customer's DTE gas rate. We calculated the total annual energy cost if the home were to switch to a heat pump by adding the electricity cost and gas cost as described above.

Rate sensitivity cases. We examined 6 utility rate sensitivity cases to provide a range of expected energy cost change due to heat pumps. Utility rate details are provided in Note D.5.

To test the sensitivity of the cost change to natural gas price, we calculated the annual cost of the gas furnace baseline and heat pump intervention using the new rate for gas in both conditions. Due to changes in the cost recovery mechanisms effective January 2023 (DTE Electric Company Rate Book for Electric Service, 2023), applying the new rate to the metered gas use of the participants results in an average increase of 20% (SD = 1.29) across the sample.

4. Resstock.

We analyzed the potential for energy efficiency to mitigate cost increase due to heat pumps in single family homes that use natural gas heating by calculating energy costs derived from four modeled house retrofit scenarios included in the NREL Resstock End Use Savings Shapes database (Wilson et al., 2021). This database provides hourly electricity and gas use by appliance for a representative sample of homes in each U.S. city. Hourly load profiles are available for a baseline case (i.e., the housing stock as it is, and various "upgrades" including full electrification with or without deep efficiency retrofits, and deep efficiency retrofits with no change to the current heating and cooling system). To these scenarios, we applied the utility rates for all sensitivity cases as described above. We then calculated the mean incremental annual energy cost change resulting from a series of these changes across a random sample of 400 homes in the database. Starting with the baseline housing stock as captured in the database (Natural Gas + Existing Envelope), we calculated the cost increase associated with adding a heat pump without improving the envelope (Heat Pump + Existing Envelope), the cost savings associated with keeping the heat pump and improving the envelope efficiency (Heat Pump + Envelope Retrofit), and finally the cost savings associated with keeping the original natural gas system and improving the envelope efficiency (Natural Gas + Envelope Retrofit). These scenarios refer to ResStock measure packages 1, 4, 10, and 2 respectively.

We used a Kruskall-Wallace test to test the significance of the difference between the medians of the utility costs in each upgrade category (p-value < 0.01). We tested the null hypothesis that the medians were the same using a pairwise with the Bonferroni adjustment and similarly found significant differences for each comparison.

5. Retrofit Cost Analysis.

The contractor recommended energy efficiency measures and provided first cost and utility cost savings estimates for the recommended work. We used the "Return on Investment and Rebate Report" prepared for each study participant to summarize the recommended energy efficiency upgrades to code the unique efficiency measures recommended across the sample. Of the ten measures recommended by the contractor, we categorized them into five upgrade categories, which included appliances, HVAC system, and two building envelope retrofit categories: simple weatherization upgrades, which consist of services that can be completed by one contractor, require fewer labor hours, and require less invasive techniques than complex upgrades.

Appendix B. Supplementary Figures

Figure B.1
The distribution of energy burden across households

The households provided an income range. We calculate three possible energy burdens for each household using the actual annual utility cost and the high, low and midpoint of the reported income bracket. The energy burden range is shown for each household, and the midpoint is shown as a dot. Large ranges represent utility costs that are a high proportion of income. The below median income group includes households earning less than $50k, the median income group includes households earning $50-75k and the above median income group includes households earning more than $75k.

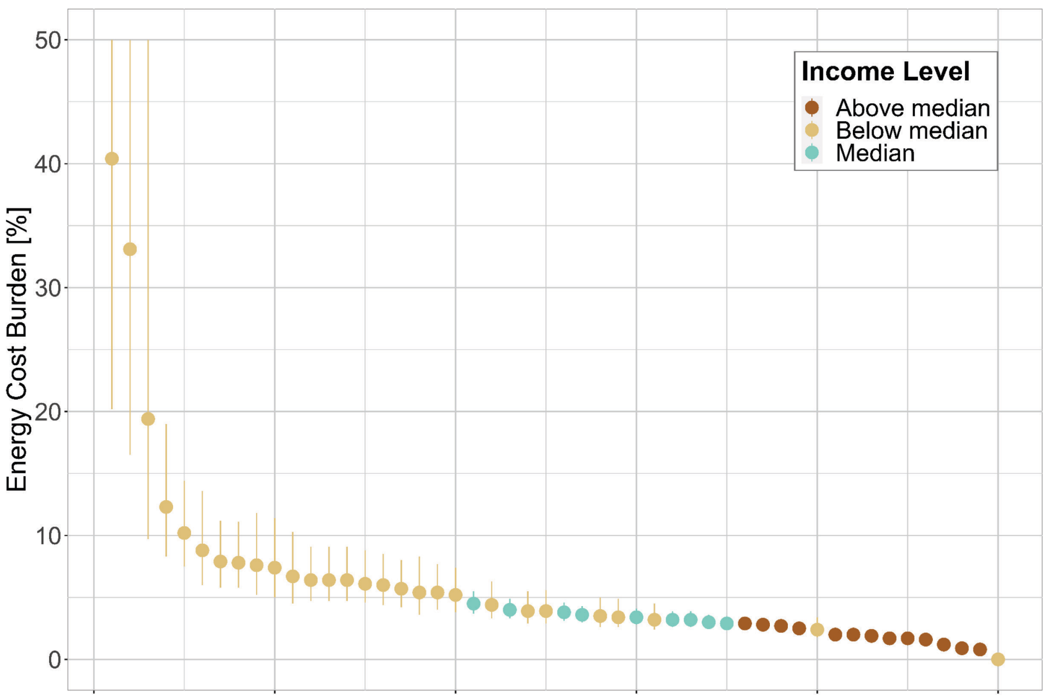


Figure B.2
Heating inflection temperature demonstrate no significant pattern across income

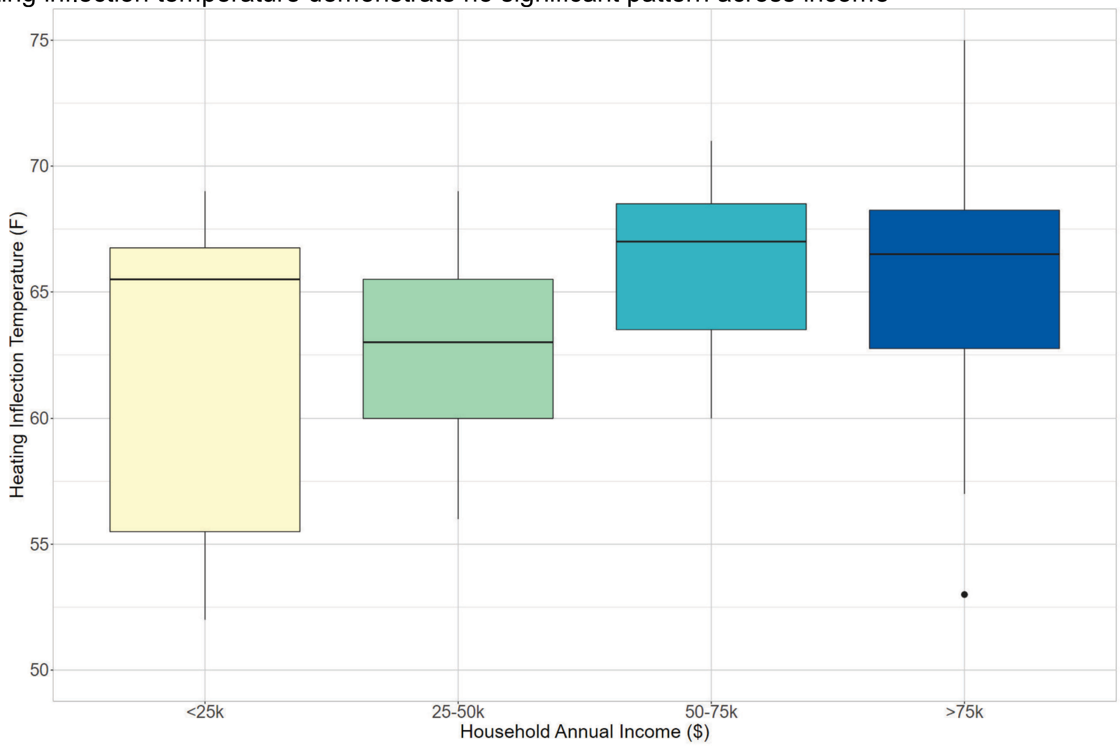


Figure B.3
Air infiltration by income
Air infiltration rates measured by a blower door test are shown here. Each dot represents one household. The green dots represent homes that have been retrofit by Habitat for Humanity and yellow dots represent market rate homes in the sample. Using a non-linear least squares regression, we find a significant downward trend (p-value=0.023) among market rate homes, indicating that wealthier people live in more efficient homes.

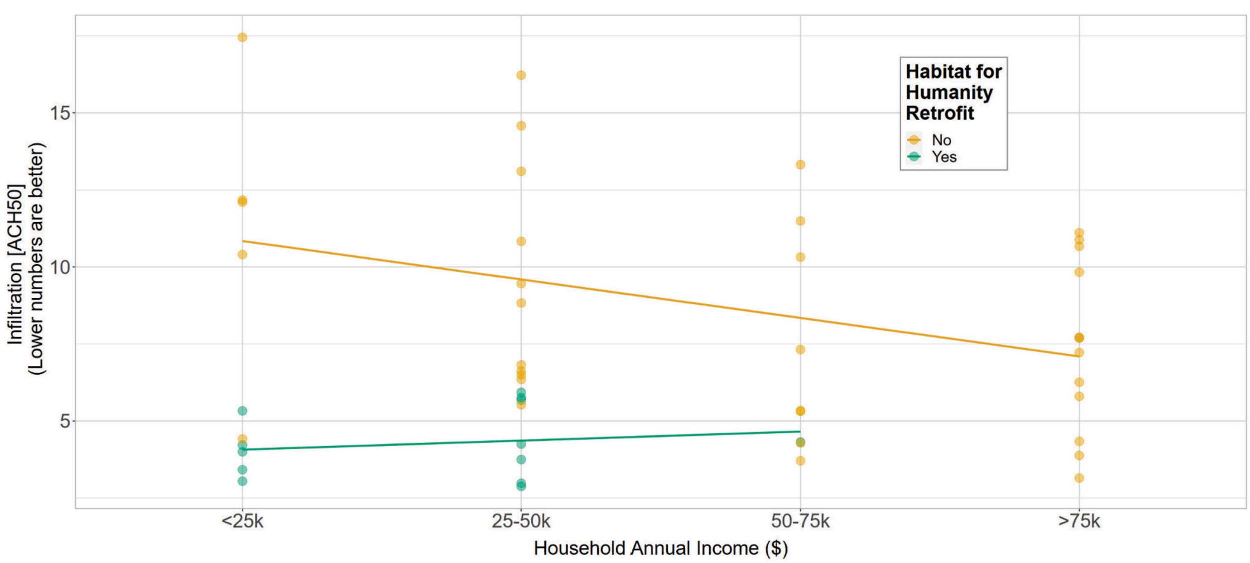


Figure B.4

Change in annual energy bills for switching to a heat pump from natural gas heating by income. The x-axis represents four income categories to which participants were assigned given the income range they provided. Dot represents outliers. Each box plot shows the median cost increase (middle line), first and third quantiles (lower and upper box bounds), and minima and maxima of change in energy burden change for (1) optional time of use rate (DTE D1.2) and 2022 natural gas cost; (2) standard flat electricity rate (DTE D1) and 2023 natural gas cost; (3) standard time of use electricity rate (DTE D1.11) and 2023 natural gas cost; (4) optional time of use rate (DTE D1.2) and 2023 natural gas cost.

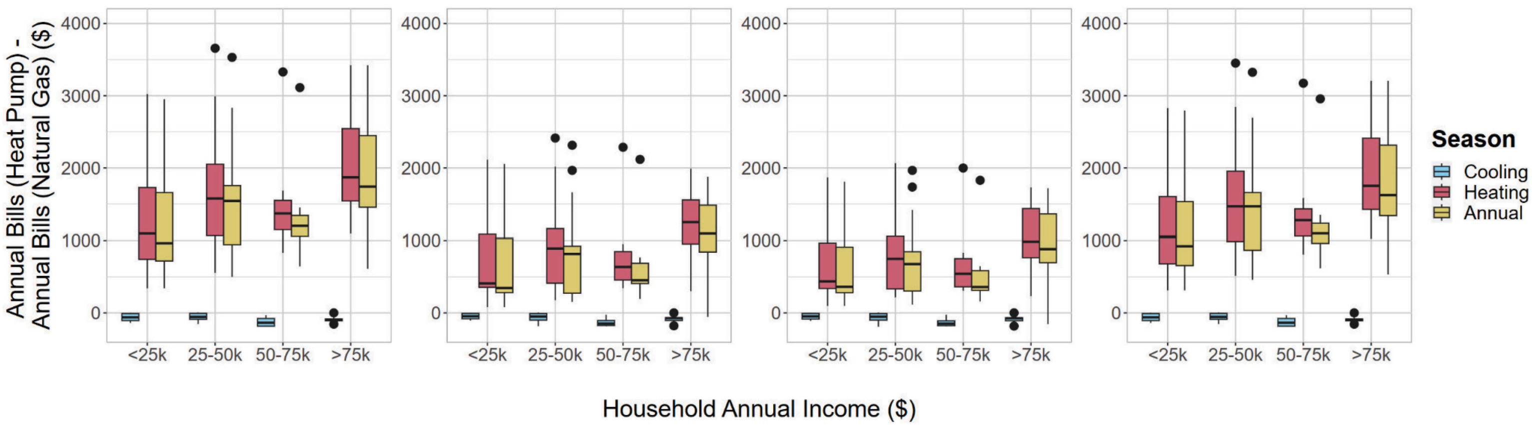


Figure B.5

Change in energy burden for switching to a heat pump from natural gas heating by income. The x-axis represents four income categories to which participants were assigned given the income range they provided. Dot represents outliers. Each box plot shows the median cost increase (middle line), first and third quantiles (lower and upper box bounds), and minima and maxima of change in energy burden change for (1) optional time of use rate (DTE D1.2) and 2022 natural gas cost; (2) standard flat electricity rate (DTE D1) and 2023 natural gas cost; (3) standard time of use electricity rate (DTE D1.11) and 2023 natural gas cost; (4) optional time of use rate (DTE D1.2) and 2023 natural gas cost.

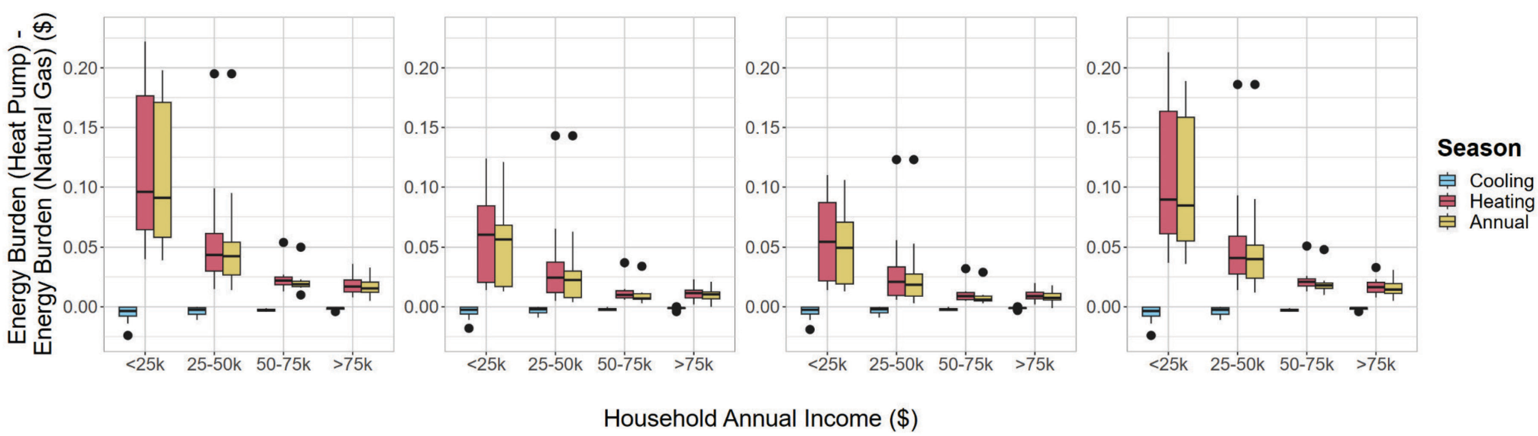


Figure B.6
Resstock energy retrofit and heat pump utility cost change by vintage

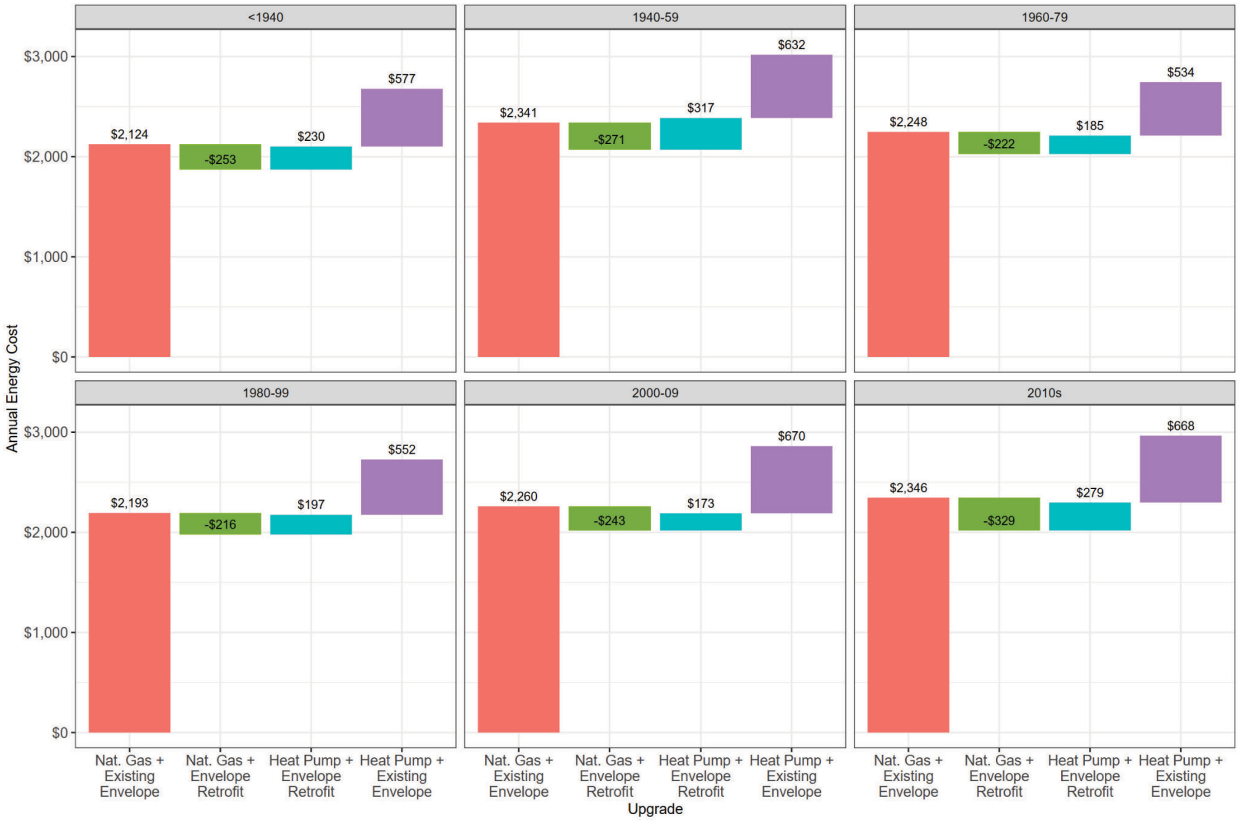
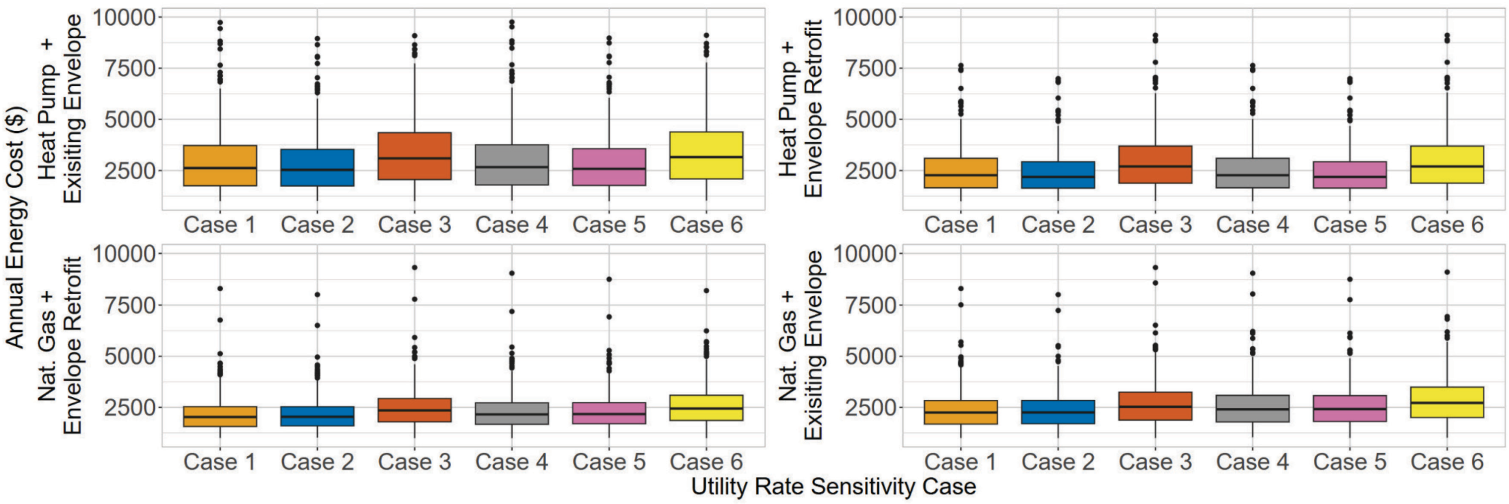


Figure B.7
Resstock Energy retrofit and heat pump utility cost comparison.



	Electricity Rate	Gas Rate
Case 1	Standard flat rate (expires May 2023) (D1)	2021 residential rate
Case 2	Standard time of use rate (D1.11)	2021 residential rate
Case 3	Optional time of use rate (D1.2)	2021 residential rate
Case 4	Standard flat rate (expires May 2023) (D1)	2023 residential rate
Case 5	Standard time of use rate (D1.11)	2023 residential rate
Case 6	Optional time of use rate (D1.2)	2023 residential rate

Figure B.8

Frequency of energy retrofit measures recommended for homes

The x-axis represents each unique recommendation made by the energy audit contractor, and the y-axis represents the frequency of that recommendation across the sample. Colors represent categories we develop to indicate the relative cost and difficulty of adopting the recommendation. There are three envelope categories: complex, simple. and air sealing, which was recommended for every house. A dense pack cellulose attic insulation (a simple retrofit) was recommended in 92% of homes. See Table C.5 for more details on the extent of work required under each recommendation.

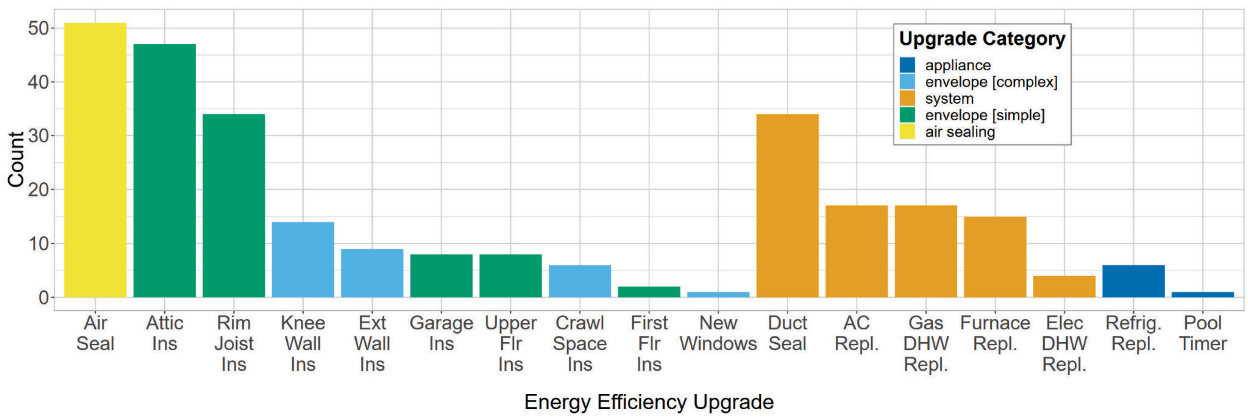


Figure B.9

Energy retrofit upfront cost by income

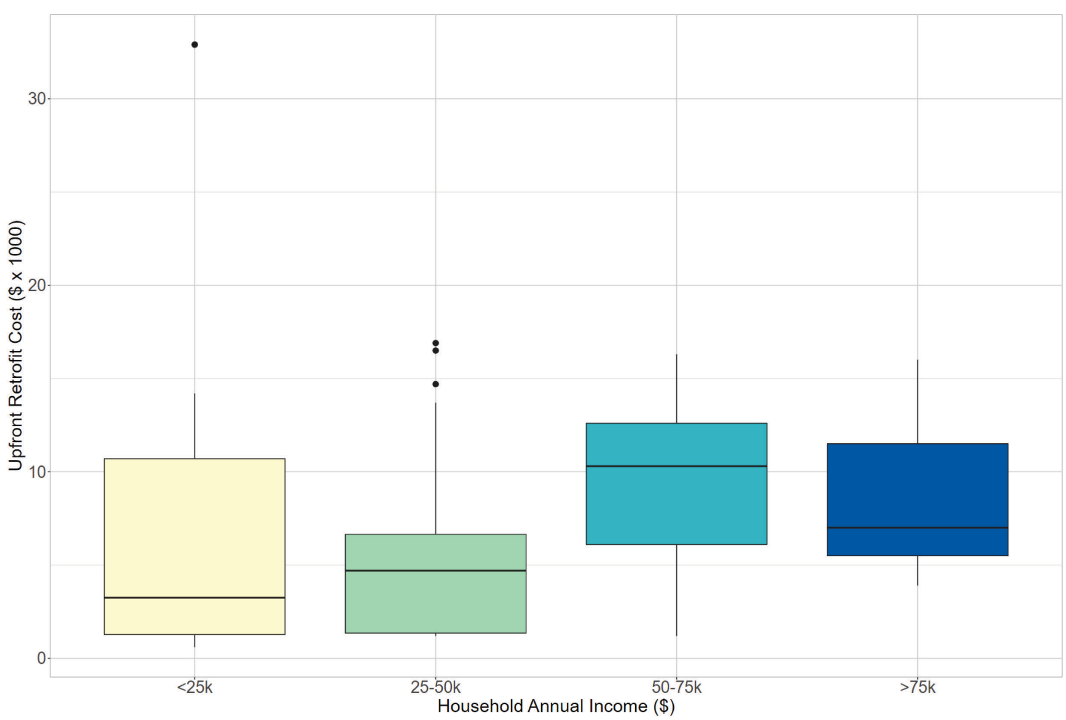
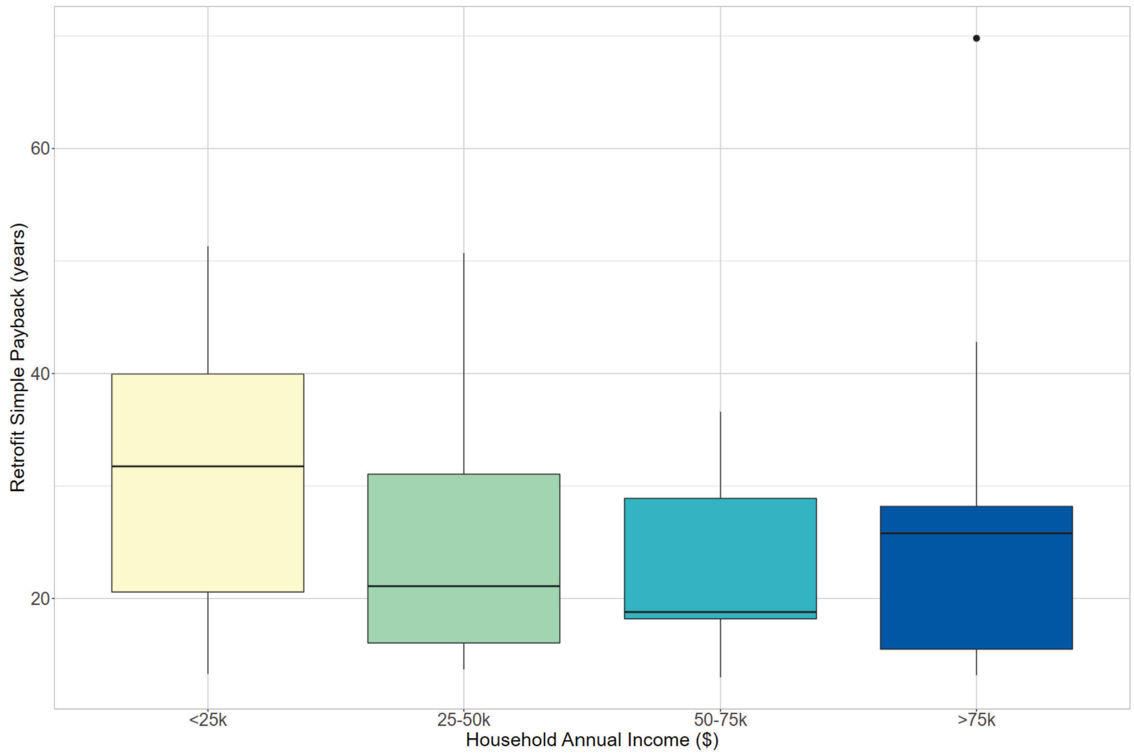


Figure B.10
Energy retrofit simple payback by income



Appendix C. Supplementary Tables

Table C.1

Descriptive statistics

	all	<25k	25-50k	50-75k	>75k
Energy Cost/SF/Occupant mean	0.54	0.5	0.61	0.54	0.47
Energy Cost/SF/Occupant median	0.47	0.45	0.59	0.51	0.34
Energy Cost/SF/Occupant min	0.18	0.2	0.25	0.26	0.18
Energy Cost/SF/Occupant max	1.56	0.88	1.22	0.95	1.56
Energy Cost/SF/Occupant SD	0.31	0.26	0.32	0.24	0.38
Energy Cost Burden mean	0.06	0.16	0.05	0.04	0.02
Energy Cost Burden median	0.04	0.11	0.06	0.03	0.02
Energy Cost Burden min	0.01	0.05	0.02	0.03	0.01
Energy Cost Burden max	0.41	0.41	0.10	0.05	0.03
Energy Cost Burden SD	0.07	0.12	0.02	0.01	0.01
Actual Utility Cost [$] mean	1976	1522	2004	2190	2141
Actual Utility Cost [$] median	2013	1400	2048	2048	2290
Actual Utility Cost [$] min	878	912	878	1807	1021
Actual Utility Cost [$] max	3874	2381	3758	2804	3874
Actual Utility Cost [$] SD	654	502	695	312	757

Table C.2
Comparison of electricity time of use rates available to study participants on utility bills

Detroit Edison Company (DTE) provides electricity service to 48 households and gas to 3 households, Consumers Energy provides electricity to 1 household and gas to 2 households. 1 household was served electricity by a municipal utility and 1 household was not connected to gas service.

	all	<25k	25-50k	50-75k	<75k
Actual Utility Bills - Electric and Gas mean	1977	1425	2015	2171	2170
Actual Utility Bills - Electric and Gas median	1976	1297	2046	2088	2288
Actual Utility Bills - Electric and Gas min	878	911	878	1806	1021
Actual Utility Bills - Electric and Gas max	3872	2085	3756	2802	3872
Actual Utility Bills - Electric and Gas SD	682	426	723	329	792
Actual Utility Bills - Electric and Gas IQR	894	519	923	360	862
Actual Utility Bills - Electric and Gas range	2994	1174	2879	996	2851
Cost D1A - Electric and Gas mean	1931	1430	2003	2110	2107
Cost D1A - Electric and Gas median	1995	1373	2042	2055	2182
Cost D1A - Electric and Gas min	860	902	860	1779	1025
Cost D1A - Electric and Gas max	3697	2126	3697	2652	3621
Cost D1A - Electric and Gas SD	634	424	700	319	670
Cost D1A - Electric and Gas IQR	792	490	806	359	455
Cost D1A - Electric and Gas range	2836	1224	2836	873	2596
Cost D1.11 - Electric and Gas mean	2011	1488	2087	2198	2191
Cost D1.11 - Electric and Gas median	2086	1437	2133	2136	2265
Cost D1.11 - Electric and Gas min	894	938	894	1836	1069
Cost D1.11 - Electric and Gas max	3780	2242	3780	2780	3762
Cost D1.11 - Electric and Gas SD	660	452	723	343	700
Cost D1.11 - Electric and Gas IQR	828	513	868	372	474
Cost D1.11 - Electric and Gas range	2886	1304	2886	944	2693
Cost D1.2 - Electric and Gas mean	2339	1710	2450	2566	2531
Cost D1.2 - Electric and Gas median	2431	1657	2536	2499	2593
Cost D1.2 - Electric and Gas min	997	1039	997	2038	1241
Cost D1.2 - Electric and Gas max	4408	2715	4176	3349	4408
Cost D1.2 - Electric and Gas SD	796	579	857	452	839
Cost D1.2 - Electric and Gas IQR	1008	608	1044	429	522
Cost D1.2 - Electric and Gas range	3411	1676	3179	1311	3168

Table C.3
Annual utility cost change sensitivity analysis for heat pump adoption

	all	<25k	25-50k	50-75k	<75k
Heat Pump Cost Change - D1 mean	1154	887	1334	937	1338
Heat Pump Cost Change - D1 median	921	482	960	723	1372
Heat Pump Cost Change - D1 min	109	109	225	367	416
Heat Pump Cost Change - D1 max	5624	2309	5624	2442	2197
Heat Pump Cost Change - D1 SD	1013	777	1404	703	565
Heat Pump Cost Change - D1 IQR	996	807	1260	425	570
Heat Pump Cost Change - D1.11 mean	1020	822	1186	823	1127
Heat Pump Cost Change - D1.11 median	812	478	818	628	1104
Heat Pump Cost Change - D1.11 min	124	124	258	332	309
Heat Pump Cost Change - D1.11 max	4906	2064	4906	2155	1939
Heat Pump Cost Change - D1.11 SD	878	675	1215	625	507
Heat Pump Cost Change - D1.11 IQR	783	679	1135	422	482
Heat Pump Cost Change - D1.2 mean	1777	1401	2037	1561	1946
Heat Pump Cost Change - D1.2 median	1433	1093	1576	1370	1838
Heat Pump Cost Change - D1.2 min	341	341	555	832	1101
Heat Pump Cost Change - D1.2 max	7217	3024	7217	3330	3113
Heat Pump Cost Change - D1.2 SD	1224	925	1698	826	682
Heat Pump Cost Change - D1.2 IQR	1000	987	1404	404	750
Heat Pump Cost Change - 2023 Gas Cost mean	1048	801	1225	839	1208
Heat Pump Cost Change - 2023 Gas Cost median	817	408	890	637	1250
Heat Pump Cost Change - 2023 Gas Cost min	81	81	176	342	339
Heat Pump Cost Change - 2023 Gas Cost max	5277	2114	5277	2286	1990
Heat Pump Cost Change - 2023 Gas Cost SD	955	728	1325	671	522
Heat Pump Cost Change - 2023 Gas Cost IQR	961	730	1180	393	540

Table C.4

Annual utility energy burden sensitivity analysis for heat pump adoption

	all	<25k	25-50k	50-75k	<75k
Heat Pump Energy Burden Change - D1 mean	0.04	0.07	0.04	0.02	0.01
Heat Pump Energy Burden Change - D1 median	0.02	0.07	0.03	0.01	0.01
Heat Pump Energy Burden Change - D1 min	0.00	0.02	0.01	0.01	0.00
Heat Pump Energy Burden Change - D1 max	0.15	0.14	0.15	0.04	0.03
Heat Pump Energy Burden Change - D1 SD	0.04	0.04	0.04	0.01	0.01
Heat Pump Energy Burden Change - D1 IQR	0.03	0.07	0.03	0.01	0.01
Heat Pump Energy Burden Change - D1.11 mean	0.03	0.06	0.03	0.01	0.01
Heat Pump Energy Burden Change - D1.11 median	0.02	0.06	0.02	0.01	0.01
Heat Pump Energy Burden Change - D1.11 min	0.00	0.02	0.01	0.00	0.00
Heat Pump Energy Burden Change - D1.11 max	0.13	0.12	0.13	0.04	0.02
Heat Pump Energy Burden Change - D1.11 SD	0.03	0.04	0.03	0.01	0.01
Heat Pump Energy Burden Change - D1.11 IQR	0.03	0.07	0.03	0.01	0.01
Heat Pump Energy Burden Change - D1.2 mean	0.06	0.12	0.06	0.03	0.02
Heat Pump Energy Burden Change - D1.2 median	0.04	0.10	0.04	0.02	0.02
Heat Pump Energy Burden Change - D1.2 min	0.01	0.04	0.01	0.01	0.01
Heat Pump Energy Burden Change - D1.2 max	0.22	0.22	0.20	0.05	0.04
Heat Pump Energy Burden Change - D1.2 SD	0.06	0.07	0.05	0.01	0.01
Heat Pump Energy Burden Change - D1.2 IQR	0.05	0.11	0.04	0.01	0.01
Heat Pump Energy Burden Change - 2023 Gas Cost mean	0.03	0.06	0.03	0.01	0.01
eat Pump Energy Burden Change - 2023 Gas Cost median	0.02	0.06	0.02	0.01	0.01
Heat Pump Energy Burden Change - 2023 Gas Cost min	0.00	0.01	0.00	0.01	0.00
Heat Pump Energy Burden Change - 2023 Gas Cost max	0.14	0.12	0.14	0.04	0.02
Heat Pump Energy Burden Change - 2023 Gas Cost SD	0.03	0.04	0.04	0.01	0.01
Heat Pump Energy Burden Change - 2023 Gas Cost IQR	0.03	0.06	0.03	0.01	0.01

Table C.5
Energy retrofit measure categories

Envelope Upgrades

Code	Description	Upgrade intensity
Air Seal	Spray foam air sealing	simple
Attic Ins	Dense pack cellulose insulation in attic	simple
Rim Joist Ins	High density spray insulation at rim joist	simple
Knee Wall Ins	High density spray foam insulation on knee walls and vertical attic walls	complex
Ext Wall Ins	Dense pack cellulose insulation in exterior walls	complex
Garage Ins	High density spray foam insulation on ceiling over garage	simple
Upper Flr Ins	High density spray foam insulation on upper floor cantilever	simple
Crawl Space Ins	Seal and insulate crawl space with high density foam	complex
First Flr Ins	High density spray foam insulation on first floor cantilever	simple
New Windows	Install double pane windows	complex

System Upgrades

Code	Description
Duct Seal	Duct system sealing
AC Replace	Replace central air conditioner with 16 SEER
Gas DHW Replace	Replace water heater with 0.96 UEF gas storage
Furnace Replace	Replace furnace with 97 AFUE
Elec DHW Replace	Replace water heater with 3.55 UEF heat pump hot water heater

Appliance Upgrades

Code	Description
Refrig. Replace	Refrigerator replacement with Energy Start appliance
Pool Timer	Install pool timer

Table C.6
AMI sourced from US Census 2020

Household	Zipcode	Self Reported Income	AMI
1	48101	More than $125,000	$69,331
2	48103	Prefer not to answer	$64,994
3	48103	$0-$9,999	$64,994
4	48103	More than $125,000	$64,994
5	48103	$25,000 to $49,999	$64,994
6	48103	More than $125,000	$64,994
7	48104	$10,000 to $24,999	$64,994
8	48105	$25,000 to $49,999	$80,437
9	48108	$100,000 to $124,999	$68,160
10	48108	$50,000 to $74,999	$68,160
11	48118	$100,000 to $124,999	$85,529
12	48118	$50,000 to $74,999	$85,529
13	48146	$50,000 to $74,999	$47,084
14	48150	$50,000 to $74,999	$81,011
15	48169	$25,000 to $49,999	$86,534
16	48170	$0-$9,999	$89,850
17	48187	$10,000 to $24,999	$95,133
18	48197	$100,000 to $124,999	$62,138
19	48197	$100,000 to $124,999	$62,138
20	48197	$100,000 to $124,999	$62,138
21	48197	$25,000 to $49,999	$62,138
22	48197	$100,000 to $124,999	$62,138
23	48197	$25,000 to $49,999	$62,138
24	48197	$0-$9,999	$62,138
25	48197	$50,000 to $74,999	$62,138
26	48197	$10,000 to $24,999	$62,138
27	48197	$25,000 to $49,999	$62,138
28	48197	$100,000 to $124,999	$62,138
29	48197	$75,000 to $99,999	$62,138
30	48197	$25,000 to $49,999	$62,138
31	48198	$25,000 to $49,999	$51,825
32	48198	$50,000 to $74,999	$51,825
33	48198	$50,000 to $74,999	$51,825
34	48198	$25,000 to $49,999	$51,825
35	48198	$10,000 to $24,999	$51,825
36	48198	$25,000 to $49,999	$51,825
37	48198	$25,000 to $49,999	$51,825
38	48198	More than $125,000	$51,825
39	48198	$25,000 to $49,999	$51,825
40	48198	$50,000 to $74,999	$51,825
41	48198	$10,000 to $24,999	$51,825
42	48198	$25,000 to $49,999	$51,825
43	48198	$50,000 to $74,999	$51,825
44	48202	$75,000 to $99,999	$28,768
45	48203	$10,000 to $24,999	$26,744
46	48203	$10,000 to $24,999	$26,744
47	48208	$25,000 to $49,999	$20,185
48	48221	$25,000 to $49,999	$43,833
49	48221	$25,000 to $49,999	$43,833
50	48227	$25,000 to $49,999	$28,769
51	48487	$25,000 to $49,999	$69,717

Table C.7

Literature Review

Contribution	**Empirical work**	**Demographic distribution of housing quality**	**Household impact of heating electrification**	**Energy equity**	**Energy efficiency retrofits**	**Dynamic electricity pricing**
This paper	n = 51 households in Michigan	Provides direct evidence of high energy use intensity per occupant in low income homes due to housing characteristics.	Quantifies energy cost and energy burden changes associated with a switch from natural gas heating to an air source heat pump.	Compares energy burden of heating electrification across income. Discusses barriers to energy retrofits, such as lack of information in investment decision making.	Uses contractor recommendations to provide. Quantifies bill savings potential of energy retrofits using contractor recommendations and NREL Resstock database.	Provides sensitivity analysis for two time of use rates available in the region alongside flat rate and two gas rates.
P. Vaishnav and A. M. Fatimah, 2020			Quantifies household annual bill change for heating electrification from existing condition in 883 US locations.			
D. J. Bednar, T. G. Reames, and G. A. Keoleian, 2017		Provides evidence of spatial, economic, and racial disparities in household energy use intensity.				
T. A. Deetjen, L. Walsh, and P. Vaishnav, 2021			Quantifies household net present value of switching to a heat pump from existing condition for 400 homes in 55 cities using NREL Resstock simulations.			
M. Graff, S. Carley, D. M. Konisky, and T. Memmott, 2021	n = 2,000 adults in Indiana			Provides evidence that low-income Black and Hispanic households are most likely suffer energy insecurity across three metrics: ability to pay an energy bill, receive a disconnection notice, be		

Contribution	**Empirical work**	**Demographic distribution of housing quality**	**Household impact of heating electrification**	**Energy equity**	**Energy efficiency retrofits**	**Dynamic electricity pricing**
				disconnected. Provides evidence that race, housing conditions, and energy burdens are associated with household energy security.		
B. Goldstein, T. G. Reames, and J. P. Newell, 2022		Provides evidence that EUI increases with building age due to poor weatherization, and that homes in African-American neighborhoods are on average a decade older than those of other groups.		Discusses barriers to weatherization and clean technology access, such as financing, split incentives, and program design.		
S. Cong, D. Nock, Y. L. Qiu, and B. Xing, 2022	n = 4,577 households in Arizona			Proposes new energy poverty metric. Provides evidence that vulnerable households start cooling their homes at higher temperatures, exposing them to greater health risks than their counterparts.		
J. L. Bradshaw, E. Bou-Zeid, and R. H. Harris, 2014.					Provides evidence of energy savings potential for six residential retrofit treatments, and identifies greater potential in cold climates.	
E. J. H. Wilson, C. B. Harris, J. J. Robertson,					Links housing characteristics to income and models energy savings of retrofit	

Contribution	**Empirical work**	**Demographic distribution of housing quality**	**Household impact of heating electrification**	**Energy equity**	**Energy efficiency retrofits**	**Dynamic electricity pricing**
and J. Agan, 2019.					packages using 350,000 representative house archetypes in NREL Resstock.	
H. Allcott and M. Greenstone, 2017.	n = 100,000 households in Wisconsin				Provides evidence that realized savings from WAP investments fall short of predictions, and that there is a wide dispersion in benefits and costs of weatherization beyond monetary factors.	
Zivin, J.G. and K. Novan, 2016.	n = 275 households				Provides evidence that electricity savings due to WAP projects are overstated, and that there is a substantial heterogeneity in the effectiveness of retrofits.	
M. Fowlie, M. Greenstone, and C. Wolfram, 2018	n = 30,000 households in Michigan				Provides evidence that the upfront project costs of energy retrofits conducted by Michigan WAP are about twice the cost of realized savings, and that poor return on investment can be attributed to the rebound effect, where household demand for energy increases as a result of greater efficiency.	
I. S. Walker, B. D. Less, and N. Casquero-Modrego, 2022			Quantifies heat pump performance compared with natural gas heating performance to achieve			

Contribution	**Empirical work**	**Demographic distribution of housing quality**	**Household impact of heating electrification**	**Energy equity**	**Energy efficiency retrofits**	**Dynamic electricity pricing**
			household energy cost neutrality in 50 states.			
L. V. White and N. D. Sintov, 2020	n = 7,487 households in southwest US			Examines impact of dynamic electricity pricing on vulnerable households and their counterparts.		Provides evidence that (compared to counterparts) time-of-use electricity rates raise bills more for elderly and disabled households is associated with greater AC curtailment in low-income, young children, Hispanic and African American households.
E. Wilson et al., 2022			Provides database for end-use load profiles for US residential building stock, including scenarios for heat pumps.		Provides database for end-use load profiles for US residential building stock, including scenarios for energy retrofits	
B. Less, I. Walker, N. Casquero-Modrego, and L. Rainer, 2021					Provides benchmark for residential energy retrofit costs by compiling and analyzing contractor estimates for 1,739 projects in 15 states.	
Huang et al., 2023	n = 418,255 households for cooling, n = 22,628 households for cooling in Northern Illinois, US			Provides evidence that low-income households start cooling their homes at higher temperatures, than their higher-income counterparts. Provides evidence that vulnerable households with electrical heating start heating their homes earlier in the winter and for more months than their higher-income counterparts.		

Contribution	**Empirical work**	**Demographic distribution of housing quality**	**Household impact of heating electrification**	**Energy equity**	**Energy efficiency retrofits**	**Dynamic electricity pricing**
Liu et al., 2020	n = 1119 households			Compares household energy saving behavior across income	Includes investment in energy efficient appliances in application of theory of planned behavior	

Appendix D. Supplementary Notes

Note D.1

These modeled results are about half of our empirical estimate of utility cost increase for switching to a heat pump without energy efficiency. (See Figure B.5 for a sensitivity analysis of these findings on housing vintage). When comparing ResStock electricity load profiles to metered utility data for the homes in the sample, we note a possible explanation for this discrepancy. The model may overestimate electrical plug loads, resulting in higher energy costs across all modeled cases than is evident in the sample and a lower difference between retrofit scenarios.

Note D.2

In their 2021 report on US residential retrofit costs, Less et al. estimate costs for the most common retrofit recommendations in our sample (attic floor insulation, air sealing, foundation floor insulation) in an archetypal house. We convert these costs, which were estimated in 2019, to 2022 dollars using a 5.9% inflation rate. Since total package costs were given by the contractor and not individual measure costs, we use these estimated costs in our calculations for air sealing and attic insulation payback in [Fig 8b].

Note D.3

Demographic questions sent to 883 respondents to a study interest form. Qualtrics was used to distribute the survey. We used email, text messages, and phone calls to reach out to 90 respondents of the survey.

- How much total combined money did all members of your household earn last year?
- Do you consider yourself White, Black or African-American, American Indian or Alaskan Native, Asian, Native Hawaiian or other Pacific islander, or some other race?
- In the last year, how many months did your household reduce or forego expenses for basic household necessities, such as medicine or food, in order to pay an energy bill?
- How many children aged 17 or younger live in your household?
- Do you use air conditioning to help out someone in your household who has a disability or medical condition? This could include asthma, allergies, heart problems, or other medical conditions.
- Do you keep your daytime temperature at or above 68°F in the winter to help out someone in your household who has a disability or medical condition?
- Does anyone in your household use medical equipment (CPAP, nebulizer, Rascal scooter, or other device) that must be plugged in or charged OR does anyone in your household need to refrigerate medications?

Note D.4

Special attention was paid to common problem areas for energy efficiency, including uninsulated rim joist (in the basement, where the floor joist meets the concrete or stone basement wall), attic air sealing, and commonly uninsulated outdoor surfaces, including the floor between an upstairs room and the garage.

All characteristics that impact energy performance were recorded in the audit, including HVAC and equipment efficiencies and fuel, insulation of walls and roof, foundation type, vintage, house area, structure type, house dimensions, window material, and window to wall ratio.

Note D.5

DTE, the electric utility serving 49 out of 51 of study participants, is implementing a residential electric utility rate change that goes into effect immediately following the data collection period. In March 2023, DTE customers on the Residential Standard Rate schedule (No. D1) will be automatically changed to the Residential Standard Time of Use Rate schedule (No. D1.11).

- DTE rate schedule No. D1.11 (Residential Standard Time of Use) charges $0.210/kWh for peak hours June-September and $0.168/kWh for peak hours October-May, and $0.155/kWh year-round for off-peak hours. The peak window is 3:00PM - 7:00PM, Monday - Friday.
- Residential Enhanced Time of Use Rate schedule (DTE no. D1.2) charges $0.221/kWh for peak hours June-September and $0.197/kWh for peak hours November-May, and $0.120/kWh for off-peak hours June-October and $0.117/kWh for peak hours October-May. The peak window is 11:00AM - 5:00PM, Monday - Friday.