Distributional Consequences of Policies for Electric Heat Conversion

NBER Proposal - Research Project on Distributional Consequences of New Energy Policies

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1. Motivation

Many states have adopted net-zero carbon emission goals. Towards this goal, a significant amount of renewable capacity has been added to the grid, reducing per-kWh emissions over the last 20 years (Holland et al., 2020). As the average carbon content of U.S. electricity has decreased, attention has turned in recent years to reducing carbon emissions by electrifying home heating, hot water heating, and cooking. Currently, fossil-fuel combustion from these activities accounts for more than 10% of all U.S. carbon emissions (RMI, 2021). To promote electrification, cities in California and elsewhere have implemented bans on new natural gas hookups, and California is poised to become the first state to ban natural gas use in new construction under the state's building code.

Efforts to electrify home heating have focused on electric heat pump technology, and many states have introduced policies to encourage or subsidize their use in residential settings (Nadel, 2020). See Berg and Cooper (2020) for a complete list of state-level policies. This technology—which works like an air conditioner in reverse, transferring heat from the outside the home to inside the home—has made marked gains in efficiency over the last 10 years. New developments in heat pumps have expanded the range of climates for which electric heat pumps are suitable for residential heating, increasing the viability of this new technology. More efficient heat pumps have lower operating costs and are effective in heating down to 5 degrees Fahrenheit. Heat pump technology has advanced to the point that the technology is nearly synonymous with home heating electrification policy as electric resistance (base-board) heating is largely uneconomical in most new applications. Furthermore, trends in electrification for home heating and home hot water heating indicate an increase in uptake, with electric heat pumps now comprising more than 50% of all residential heaters shipped by manufacturers (see figures 1, 2, and 3).

Little is understood about the decisions made by households to switch from fossil fuel to electricity for heating, or to switch heating technology to an electric heat pump.[1] Davis (2021) focuses on new construction and finds that the 40-year decline in real electricity prices explains the vast majority of new heat pumps installed in new construction, suggesting that households are sensitive to electricity prices. However, owners of existing homes face a different set of costs and policies relative to new construction. For example, their duct-work may be designed to accommodate a particular heating technology in a particular location, or their existing furnaces may have many years of life remaining. How sensitive are these households to the upfront cost of electrification via a heat pump? To changes in electricity vs. natural gas prices? Answering these questions will provide valuable insights into the efficiency, effectiveness, and distributional impacts of policies—such as adoption subsidies or carbon taxes or changes in electricity rate design—designed to relieve energy burdens, reduce carbon emissions, or both.

A variety of state-level policies influence the household decision to adopt heat pump technology for home heating. New York, Massachusetts, Vermont, California, Maine, and Connecticut all have mature programs to subsidize adoption of air-source heat pumps and comprise the bulk of the $108 million in annual budgetary

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[1] We use "heating fuel" to refer to the fuel source, and "heating technology" to refer to the heating mechanism. We refer to electrification as a policy, but acknowledge that the primary heating technology used in electrification is the heat pump.

spending in 2020. Combined, national programs issued over 79,000 rebates to over 23,000 customers that year (Nadel, 2020). Subsidies range from $500 per system in some parts of Vermont to $4,500 per system in the Sacramento Municipal Utilities District (SMUD). For many states, heat pump policies are part of a larger climate goal (e.g., in California and New York). Other states have implemented policy to improve energy efficiency and lower the heating cost burden on homes served by propane or fuel oil, such as Maine. In some states, policies are limited to pilot programs and planning. For instance, Michigan utilities have set shareholder goals to install cold-source heat pumps in low-income housing, targeting replacement of inefficient electric resistance heating in 500 units in 2020 (Nadel, 2020). The total number and aggressiveness of state-level policies is increasing as more states turn to electrification to meet climate goals. Yet policies are not uniformly supportive across the United States. Florida has high potential for switching to electricity (Davis, 2021) but has no policy in place. Meanwhile, some local utilities provide incentives to switch *away* from electricity to natural gas for water heating instead. Finally, many states, including Texas, Pennsylvania, and Minnesota, have statutes in place that prohibit fuel-switching programs or policies (Berg and Cooper, 2020).

Household heating fuel and heating technology decisions interact with documented distortions in retail electricity rates, which often result from policy decisions. These interactions have distributional consequences as well. The recovery of fixed costs via volumetric rates drives a wedge between prices and marginal social costs, which can result in welfare losses due to both over- and under-consumption, depending on the direction of the distortion. Inefficient pricing is present in many locations in both retail electricity (Borenstein and Bushnell, 2018) and natural gas (Davis and Muehlegger, 2010), but is unlikely to be present in residential propane markets (assuming these markets are relatively competitive). The interaction of these distortions with the household heating fuel and heating technology decisions may impose large losses in welfare for two reasons. First, electricity rates set above social marginal cost discourage households from switching to electricity from other fuels and technologies, generating deadweight loss. Second, because electricity prices have lower *volatility* relative to propane and fuel oil, distorted electricity prices hamper the adoption of a more stable, less volatile heating fuel and technology. This generates welfare losses for households who are sensitive to energy bill shocks. To illustrate, figure 4 shows weekly residential propane prices by state over time, while figure 5 shows the within-year residualized mean (plus and minus two standard deviations) by year for a select set of states.

By hampering the decision to switch heating fuels and technology, distortions in retail electricity rates have a distributional component as well. The households who are most affected by the interactions discussed here are households who (1) use propane or fuel oil, (2) would be "marginal" for adopting the new technology in the presence of non-distorted prices, and (3) have a higher willingness to pay to avoid price volatility. Low-income households are most likely to satisfy all three criteria. Propane is predominant in low-cost construction where natural gas infrastructure is not available, which is largely in rural and poor areas (see figure 6 for propane-dominated areas). Households that rely on propane and fuel oil tend to spend more on heating than households using natural gas (see figure 7, which shows the distribution of expenditures per heating degree day by fuel type for different climates). Meanwhile, households using electric baseboard heating and electric central furnaces generally spend more on heating than they would using heat pump technology (see figure 8), despite setting their thermostats to lower temperatures at night (see figure 9). Finally, low-income households are well-documented to suffer disproportionately from shocks to home heating expenditures, e.g. as documented in the heat-or-eat literature (Bhattacharya et al., 2003). Therefore, beyond the average welfare losses, we hypothesize a disproportionate impact of inefficient retail electricity pricing on low-income households.

2. Research questions

This paper seeks to answer three interrelated questions about policies to promote household adoption of electric heating via heat pumps.

Question 1: What is the distribution of the private benefits of electrification across income and geography?

We explore how the key determinants of the electrification decision—state policies and subsidies, energy prices, heating demand, and adoption costs—vary geographically and across the income distribution. By mapping and characterizing the regions and demographic characteristics that would most benefit from switching technologies, we illustrate the existing policy landscape and baseline distribution of relevant energy costs, as well as the likely change in heating expenditures that would occur under a 100% adoption (or $0 cost adoption) scenario. We specifically highlight the effect of electrification on high-income vs. low-income and urban vs. rural populations.

Question 2: What drives the switching decision?

Merely characterizing the distribution of financial benefits from electrification does not directly estimate the distributional impacts, since not all households will actually switch to new heating technology or use an offered incentive. Thus, we develop a dynamic discrete choice model of the household's switching decision to estimate how household preferences, adoption costs, policies, and (possibly distorted) energy prices drive the switching decision. To better understand the role of bill volatility, we allow heterogeneous preferences for bill volatility depending on household income. A model is presented below.

Question 3: What are the distributional impacts of new electrification policies, and how do they interact with retail electricity price distortions?

With model estimates in hand, we examine how the availability and incentives for electric heating options shifts the distribution of energy expenditures across household income, holding energy prices constant. That is, we estimate who switches to electric heat (mostly heat pumps) when adoption costs are subsidized, and how much they benefit. We also examine the distributional effect of electrification policy, focusing on subsidies under a variety of potential policy landscapes and reformed electricity rates, as well as a carbon tax. We hypothesize that electrification incentives provide larger benefits to lower-income households under a variety of policy landscapes, though the impacts of electricity rate reform vary geographically.

3. Research plan and data

In this section we outline our main methods to address the research questions identified above.

Benefits of electrification over income and geography

We answer the first question by calculating the energy consumption and expenditures for a variety of heating fuel and heating technologies across the United States. We merge data on electricity, natural gas, and propane rates ("fuel retail rates"), income distribution, state and local incentives, and Census population data. We also merge household heating survey data to paint a full picture of the landscape of U.S. heating. Combined with engineering estimates of the operating costs of various heating technologies and local climate variables (e.g. heating degree days), we calculate expected expenditures for each of the three main heating technologies—natural gas (when available), propane, and electric heat pumps. We take a numerical-engineering approach to identify correlations in household income, existing heating technology, demographics, and heating fuel retail rates.

The data assembled presents a comprehensive picture of U.S. heating. Current fuel retail rates are processed from the U.S. Utility Rate Database assembled by the National Renewable Energy Laboratory (NREL) and geolocated using the Department of Homeland Security's Infrastructure Foundation-level Geodatabase. Natural gas and weekly state-level propane retail rates are from the Energy Information Administration (EIA). Decennial U.S. Census data and American Community Survey 5-year estimates are used to calculate heating fuel technology prevalence by census tract as well as tract-level income and demographics. Data on appliance specifications, efficiency ratings, and sales of new heating and cooling appliances from 2010-2020 are from the Air-conditioning, Heating, and Refrigeration Institute (AHRI), an industry trade group

that represents over 90% of U.S. HVAC manufacturers and retailers. Preliminary explorations highlight the volatility of propane prices both within- and between-regions (see figure 4). Figure 5 shows the substantial within-year variation in residualized propane prices across years and selected states. Figure 6 shows the tract-level shares of heating fuel by census tract, and figure 10 shows the change in shares between 2013 and 2018.

Expected savings from electrification are positive for a large swath of the United States, but switching rates remain low everywhere (see figure 10). Potential explanations for the hesitancy of households to electrify home heating systems include cost of learning about options, access to contractors familiar with electric home heating systems like heat pumps, and fixed costs. We characterize these explanations as "switching costs" and investigate further in the following section.

Drivers of heating technology choices

Electrification rates in existing homes lag new-home rates, and likely lag the rate suggested by engineering estimates. A key determinant in electrification is the switching cost—both the cost imposed by the need to wait until an existing heating technology reaches the end of its service life, as well as the tangible and intangible investment cost. We address the second research question by building a structural model of adoption that leverages a national longitudinal sample of households that biennially reports heating fuel and heating technology, the American Housing Survey (AHS). The AHS surveys more than 45,000 households every two years and elicits responses on a range of household energy characteristics. In addition to heating fuel and heating technology, the AHS asks about interruptions in heating services due to equipment failure, energy bill burden and non-payment, home age and size, tenancy and tenure, supplemental heating fuel, and water heating technology. It also contains a range of household-specific demographic questions including age and presence of children, income, receipt of public assistance, and disability status. Geographic area reported is either one of 15 Core-based Statistical Areas (CBSA), or one of nine Census Divisions.

Notably for identification of our model, the AHS survey responses indicate that more than 2% of all homes experienced a change in heating fuel source between 2015 and 2019. Table 2 shows a transition matrix between aggregated heating fuel types. Note that 6% of households that started with electric heating switched to natural gas, while 6% of households that started with some other fuel switched to electricity. Figure 11 shows the fraction of households within each of the 15 Core-based Statistical Areas that report using electric heat pumps for space heating. Note the stark difference between Los Angeles and Phoenix (at bottom left). Despite the two cities having similar climates, Phoenix has a much higher share of heat pumps—perhaps because Phoenix historically has lower electricity prices, although household characteristics (e.g. home age) may confound this relationship. Meanwhile, figure 12 shows the prevalence of switching to heat pumps. Note that Los Angeles has a higher rate of switching during 2015–2019, which coincides with a 20% drop in electricity prices during that period vs. no change for Phoenix during this time period.[2] The variation in switching rates over electricity rates, incentives, and observable characteristics comprises the identifying variation in our model.

Model of heating technology choice and conversion

For illustration, consider a homeowner that chooses in each period whether to switch from the traditional heating source (indexed by 0) to an electric heat pump (indexed by 1). Utility flow in current period for the individual is given by:

$$u(x_t, d_t) = \begin{cases} \alpha_0 - b_0(x_t) + \epsilon_{0t} & \text{if } d_t = 0 \\ \alpha_1 - b_1(x_t) - k(x_t) + \epsilon_{1t} & \text{if } d_t = 1, \end{cases} \tag{1}$$

where: α_j is a technology-specific constant that reflects differences in the non-price attributes of different heating technologies (e.g., aesthetics); $b_j(\cdot)$ is the energy bill under fuel type j in the current period, which depends on a vector of state variables (x) including energy prices, climate, and home characteristics; $k(\cdot)$ is the cost of conversion to electric heating, inclusive of switching costs, which also depends on state variables like technology costs and home characteristics as well as state and local incentives; and ϵ_j is a utility shock observed by the homeowner but unobserved to the econometrician.

[2] See here for price trends: `https://www.bls.gov/regions/midwest/data/averageenergyprices_selectedareas_table.htm`.

Following Arcidiacono and Ellickson (2011), this leads to the conditional value function, which is defined as the present discounted value (net of the utility shock ϵ_t) of choosing d_t and behaving optimally from period $t+1$ onward:

$$v_t(x_t, d_t) \equiv u(x_t, d_t) + \beta \int \bar{V}_t(x_{t+1}) f(x_{t+1}|x_t, d_t) dx_{t+1}, \tag{2}$$

where: $u(\cdot)$ is the current period's payoff as defined above; $\beta \in (0,1)$ is the discount factor; $\bar{V}_{t+1}$ is a future continuation value term, which depends on next period's uncertain state variables; and where the integration is over transition probabilities $f(\cdot|\cdot)$ for the state variables, which are conditional on the current state variables and choices.[3]

The individual therefore chooses to convert to electric heating if and only if

$$v_t(x_t, 1) + \epsilon_{1t} > v_t(x_t, 0) + \epsilon_{0t}, \tag{3}$$

that is, if the expected payoff from switching at time t exceeds the expected payoff from keeping the current heating technology, accounting for how current choices affect future payoffs through the continuation value. Assuming that ϵ_{jt} is distributed iid extreme value then leads to the conventional logit form for the switching probability at time t:

$$p_t(d_t = 1|x_t) = \frac{e^{v_t(x_t,1)}}{e^{v_t(x_t,0)} + e^{v_t(x_t,1)}}. \tag{4}$$

Note that, for illustration, we have only modeled the one-directional switch from a conventional fuel source (like propane) to an electric heat pump. However, it would be straightforward conceptually to relax the model by allowing for (a) multiple conventional heating technologies, including propane, natural gas, and heating oil, (b) conversion costs from every heating source to every other source, and (c) the possibility that choices could be reversed in the future.

We suspect low-income households in particular will face higher disutility from bill shocks. We can accommodate this in the utility model by including both the heating bill and the bill scaled by income, which allows for differential bill sensitivity for low-income vs. high income households:

$$-b_j(x_t) - \theta_j b_j(x_t)/y, \tag{5}$$

where y is household income. When $\theta_j > 0$, this specification implies that low-income households are more sensitive to high bills and therefore would behave as if they are more averse to bill volatility. We plan to explore alternative specifications as well.

One potential challenge is that the AHS data on heating technology choices and fuel-switching do not report actual household energy consumption; rather, the AHS imputes these data based on household characteristics and home attributes (with coefficients estimated using EIA Residential Energy Consumption Survey or RECS data). Rather than use these imputed data or impute consumption ourselves, we propose an empirical approach that combines the AHS data with RECS while recognizing explicitly that energy demand is not observed in the AHS. For illustration, consider a simple linear model for the energy bill for household i that chooses heating source j at time t:

$$b_{ijt} = p_{jt} h_{ijt} \tag{6}$$

$$h_{ijt} = \gamma_0 + \gamma_1 hdd_{it} + \gamma_2 s_i + \xi_{ijt}, \tag{7}$$

where: the bill is the product of the energy price p_{jt} and the household's energy demand for home heating h_{ijt}; energy demand depends on heating degree days hdd_{it}, home size, and a household-specific random shock ξ_{ij}; and the coefficients $\gamma_0, \gamma_1, \gamma_2$ are parameters to be estimated. Note that ξ_{ij} is essentially a random parameter (an unobserved state variable) that multiplies price, while the other variables in heat consumption are observed. This model suggests an approach in which we (a) estimate the parameters $\gamma_0, \gamma_1, \gamma_2$ using RECS data, (b) use these estimates to impute household energy consumption conditional on home attributes for households in the AHS data net of the random coefficient ξ_{ijt}, (c) integrate over the distribution of ξ_{ijt} when calculating the choice probabilities in equation (4); identifying the distribution of ξ_{ijt} based on the errors from the estimation of equation 7.

[3] Note that the $\bar{V}_{t+1}$ implicitly integrates over the uncertain future utility shocks ϵ_{t+1}.

Distributional impacts of electrification policy and inefficient pricing

The third research question is answered through counterfactual simulations. With household demand estimates in hand, we calculate the baseline heating technology choices made by households under current retail energy rates and available technology, framing retail energy rates as constructed from market forces, as well as policy choices. We then calculate heating technology choices, energy expenditures, and welfare under two sets of counterfactuals. First, we fix policies that subsidize electric heat pump prices at a variety of subsidy levels (including zero) in states where subsidies are in place. We calculate impacts separately for low-income vs. high-income individuals, and for rural vs. urban customers (which roughly correspond to propane vs. piped natural gas customers). Second, we set electricity rates at the true social marginal cost for the region and calculate heating technology choices, expenditures, and welfare, again by income and urban vs. rural populations. We also propose allowing future electricity rates to increase or decrease, reflecting carbon taxes or cost declines. Heating decisions made under efficient retail rate pricing may vary significantly in parts of the country where retail rates are most distorted. Increases in welfare are hypothesized to accrue primarily to low-income and rural customers who, under current retail rates, are on the margin for electrification, but for whom distorted electricity rates present a barrier.

4. Contributions

We envision this research making four main contributions:

First, we compile an extensive set of national data to explore in detail the impacts of widespread electrification across the income distribution and across geography. This analysis will highlight the *potential* for electrification to lower energy bills and bill volatility. Low-income rural households, especially those living in the Midwest and relying on propane, may be more vulnerable to energy-price shocks than households in urban areas with access to price-regulated natural gas. These low-income rural households may benefit substantially from new policies for electrification (i.e., heat pumps) that make electric heating more feasible and affordable. Yet such households are relatively understudied in the literature.

Second, to better understand the benefits of electrification in practice, and potential barriers to their adoption, we estimate a micro model of heating fuel technology choice as a function of energy prices, technology costs, policies, and household characteristics. To estimate this model, we leverage panel data on heating technology choices and conversions from the American Housing Survey. We show how to combine these data with RECS data to infer benefits and costs of switching, as well as distributional impacts, across households. The model identifies the marginal adopters—those who would be most likely to adopt if electricity prices or up-front costs were altered by policy.

Third, we use this choice model to explore distributional impacts under several counterfactual scenarios, including a change in adoption costs for heat pumps, a move to marginal-cost pricing for electricity, and the combination of these two policies. These simulations allow us to characterize patterns of adoption and distributional impacts of falling technology costs under current price regime, as well as the patterns of adoption and distributional impacts under reformed prices. Thus, we are able to characterize if and how much current prices act as a barrier to adoption, and how this disproportionately affects households across income and geography.

Finally, we emphasize that this model could be used to analyze a variety of other policy counterfactuals, in addition to electricity price reforms. For example, we could use the model to study the distributional impacts of a carbon tax on natural gas and electricity generation, and how these distributional impacts are ameliorated (if at all) by fuel-switching. Incorporating estimates of marginal emission factors as in (Holland et al., 2020) would provide insight into the carbon emissions impacts of electrification. Likewise, we could explore the distributional impacts of various targeted and untargeted subsidy policies to promote the adoption of heat pumps.

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Figures and Tables

Table 1: Transition matrix of heating technology per 2-year interval from AHS. Each row indicates the probability of switching from the row technology to the three column technologies over a 2-year period. For example, 98.5% of all gas households use gas two years later, while 1.1% switch to electricity as the primary heating fuel.

	Gas	Electric	Other
Gas	0.985	0.011	0.004
Electric	0.059	0.937	0.004
Other	0.194	0.063	0.742

Table 2: Frequency of major fuel technologies by HDD bin

	Less Cold	Cold	More Cold
Electricity	2896	2217	897
Natural Gas	2138	2939	3616
PropaneLPG	101	289	338

Note: Using only the 3 major heat fuels.

HDD is binned by terciles.

Source: EIA RECS 2015 and 2009

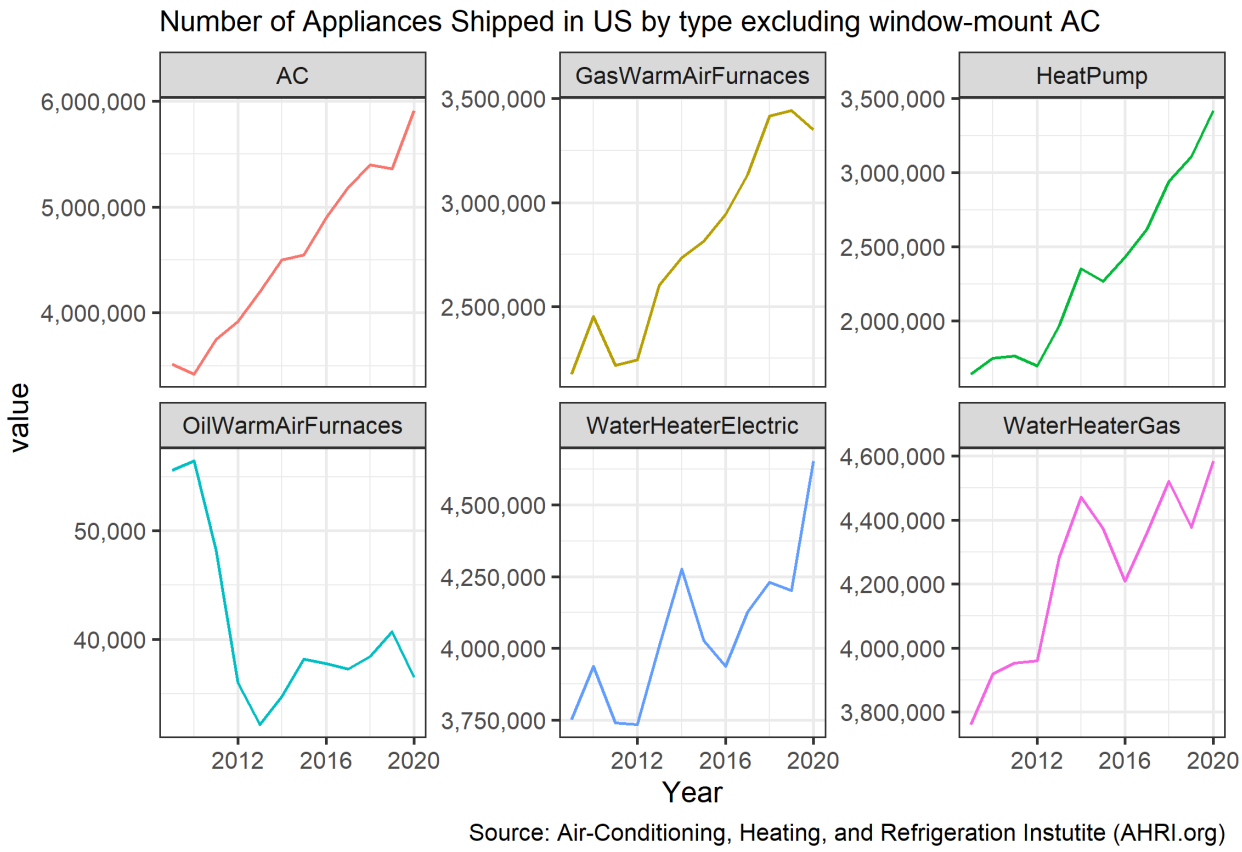


Figure 1: Number of appliances shipped in the United States by technology 2009-2020

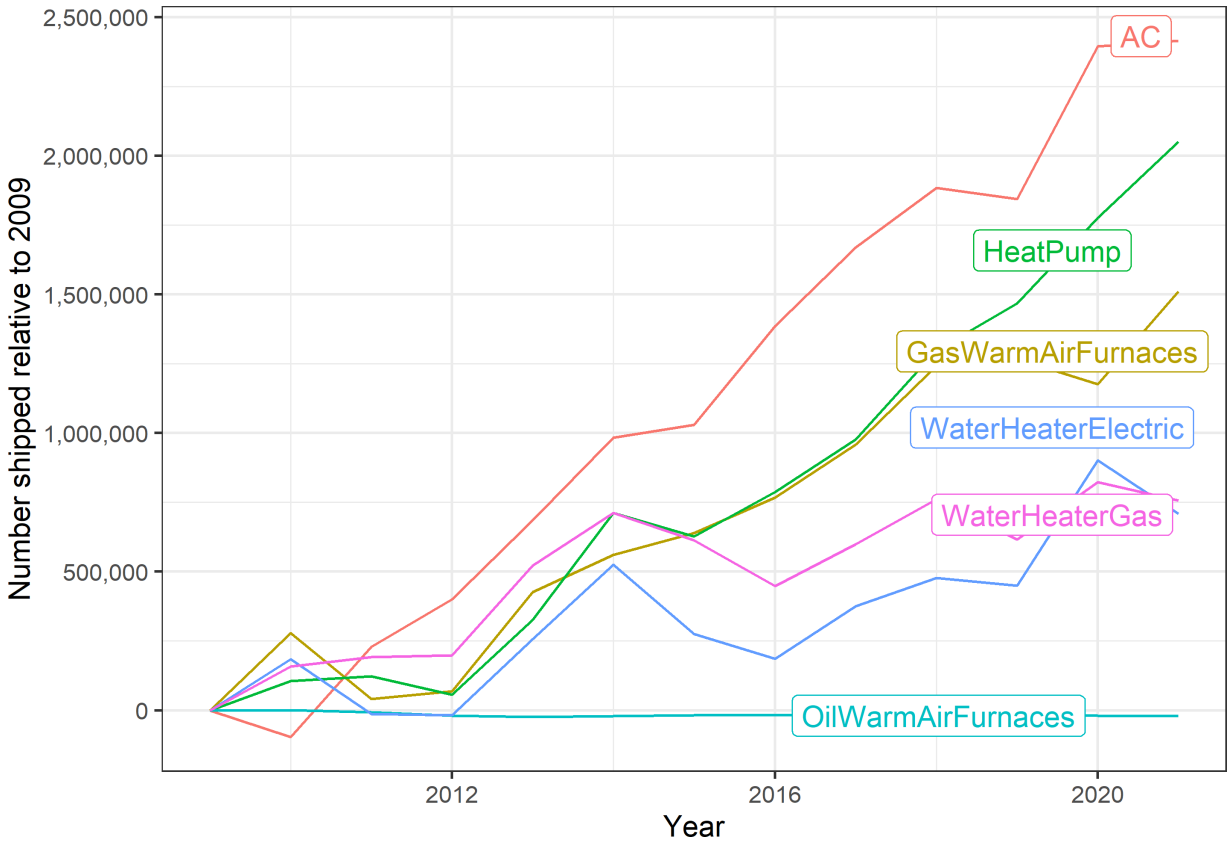


Figure 2: Number of appliances shipped in the United States by technology indexed to 2009

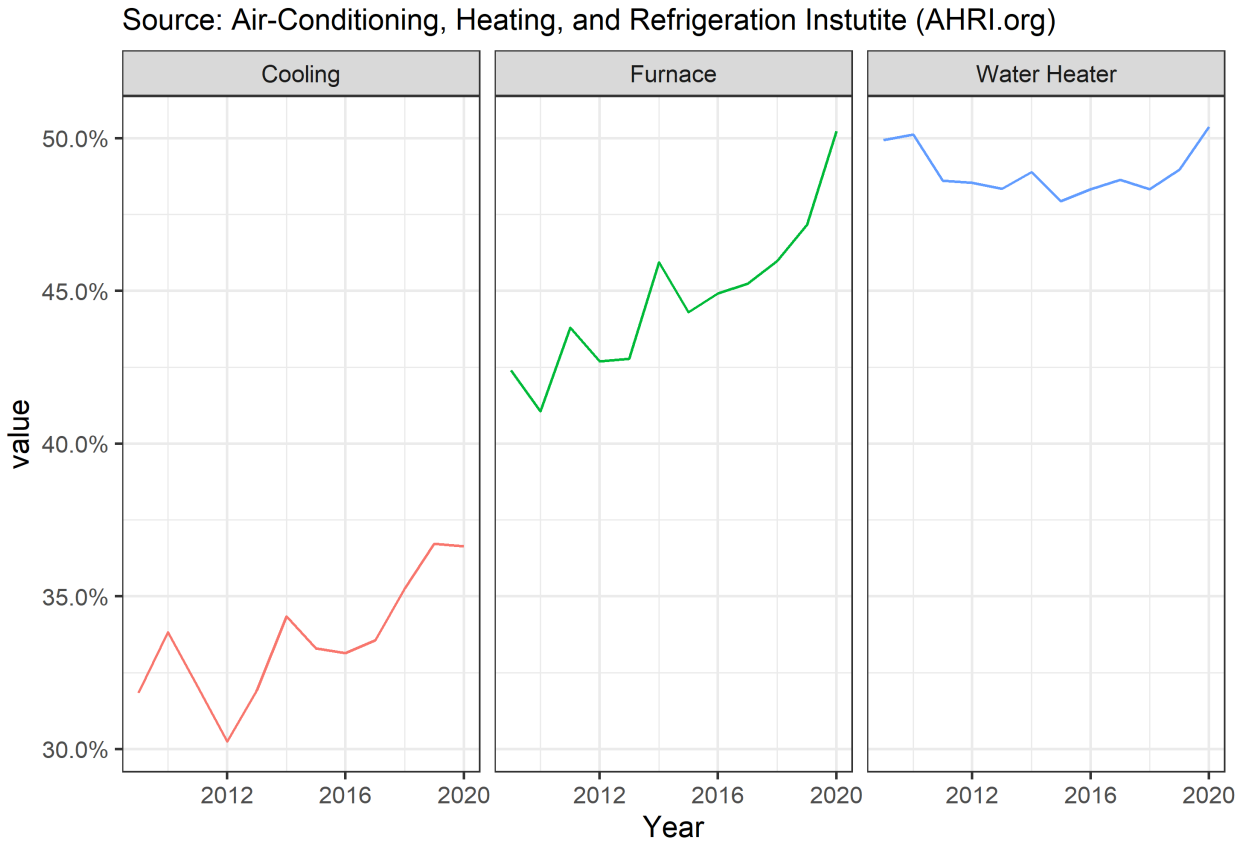


Figure 3: Heat pump share of HVAC appliances shipped in the United States 2009-2020. Left panel indicates the fraction of air conditioning units that used heat pump technology (heating and cooling) relative to all air conditioning units (excluding window units). Center panel indicates the fraction of all heating units (gas, oil, and electric) that used heat pump technology. Right panel indicates fraction of all hot water heaters using electricity (heat pump and resistance).

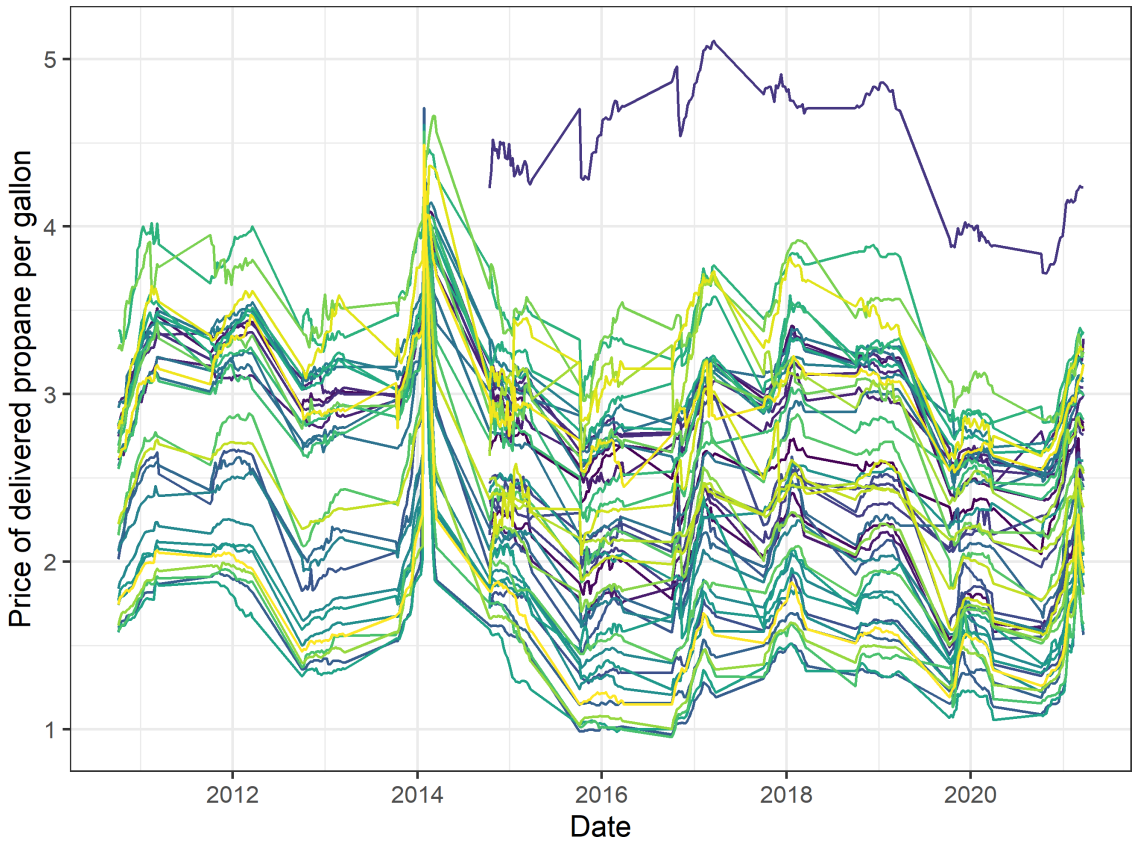


Figure 4: Residential delivery propane prices by state

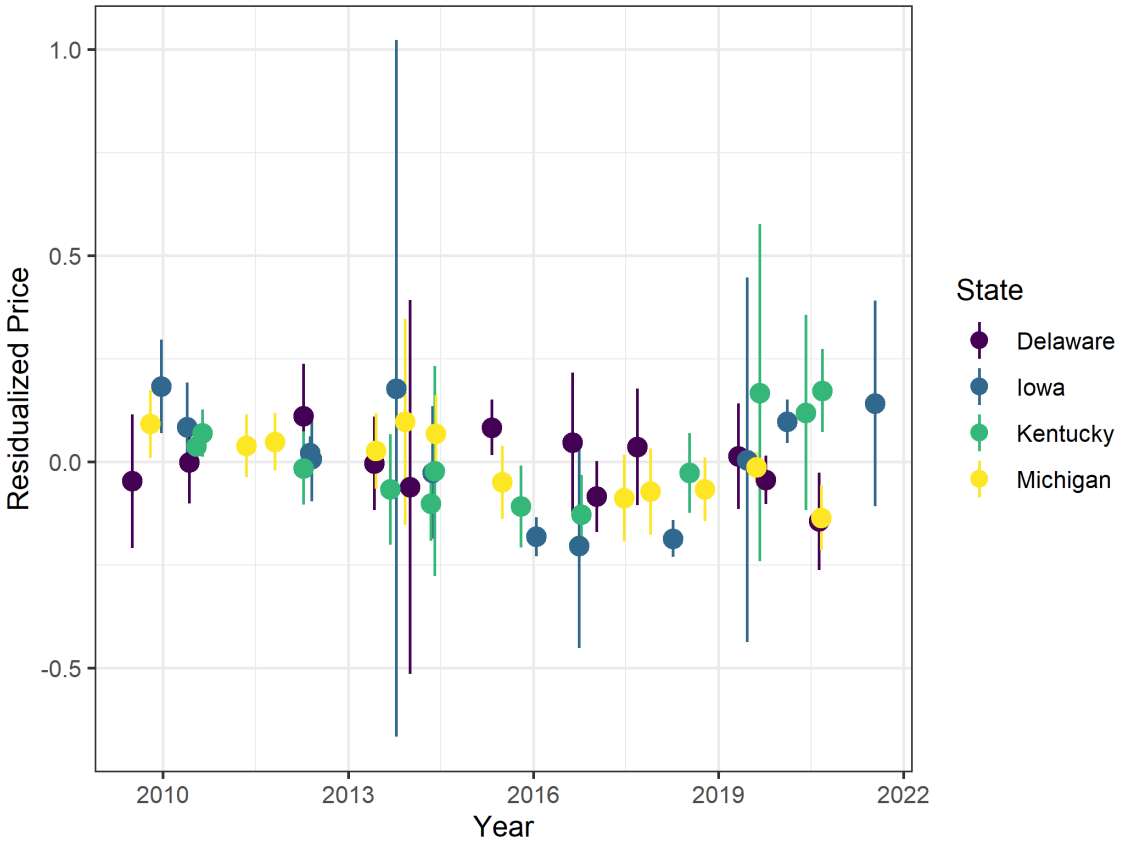


Figure 5: Mean residualized weekly propane prices over time in select states. Residualized price is taken as the residuals from a two-way fixed-effects regression on state and time fixed effects. Vertical bars are the sample means plus/minus two times the sample standard deviation.

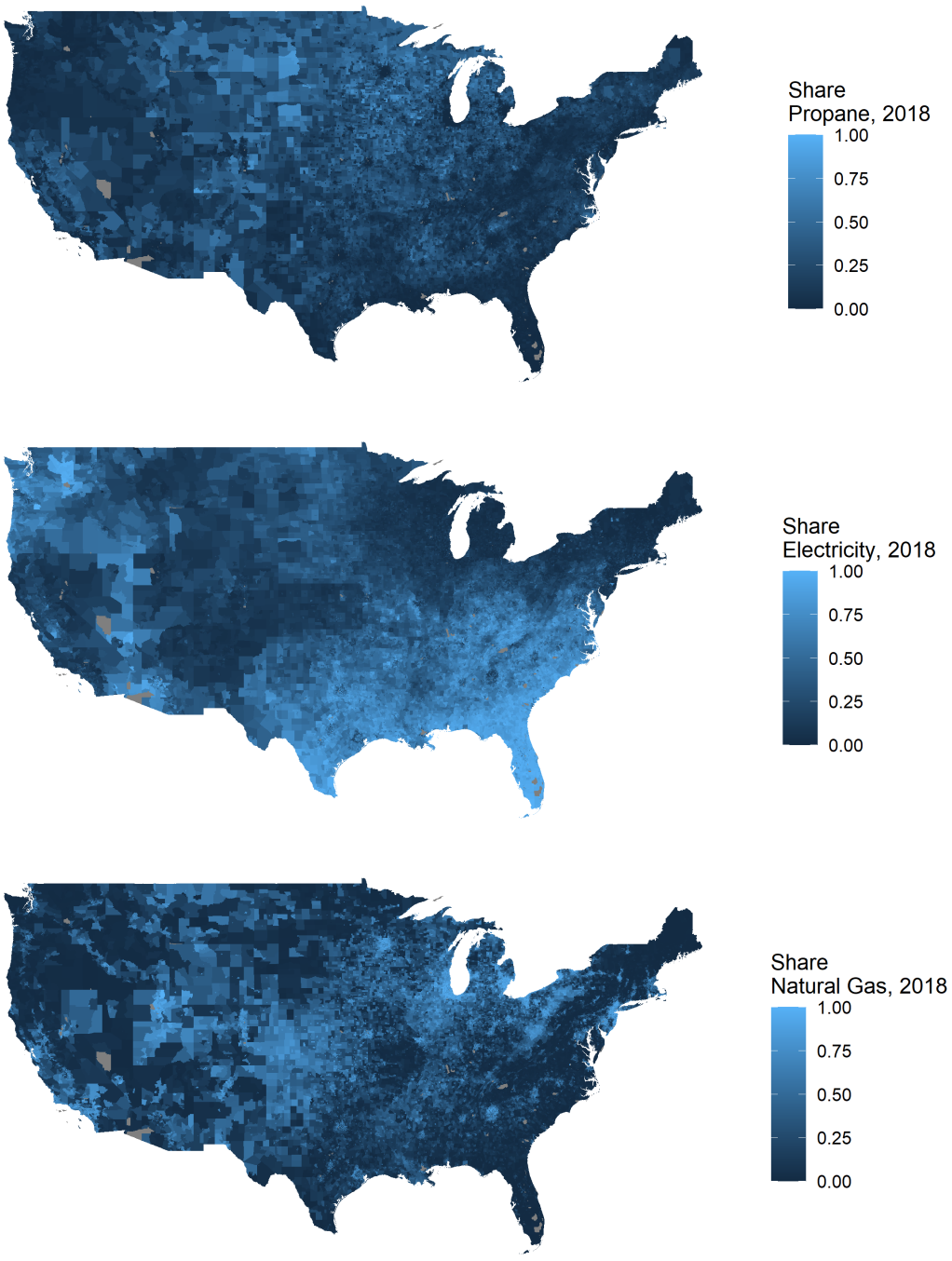


Figure 6: Share of households by heating fuel

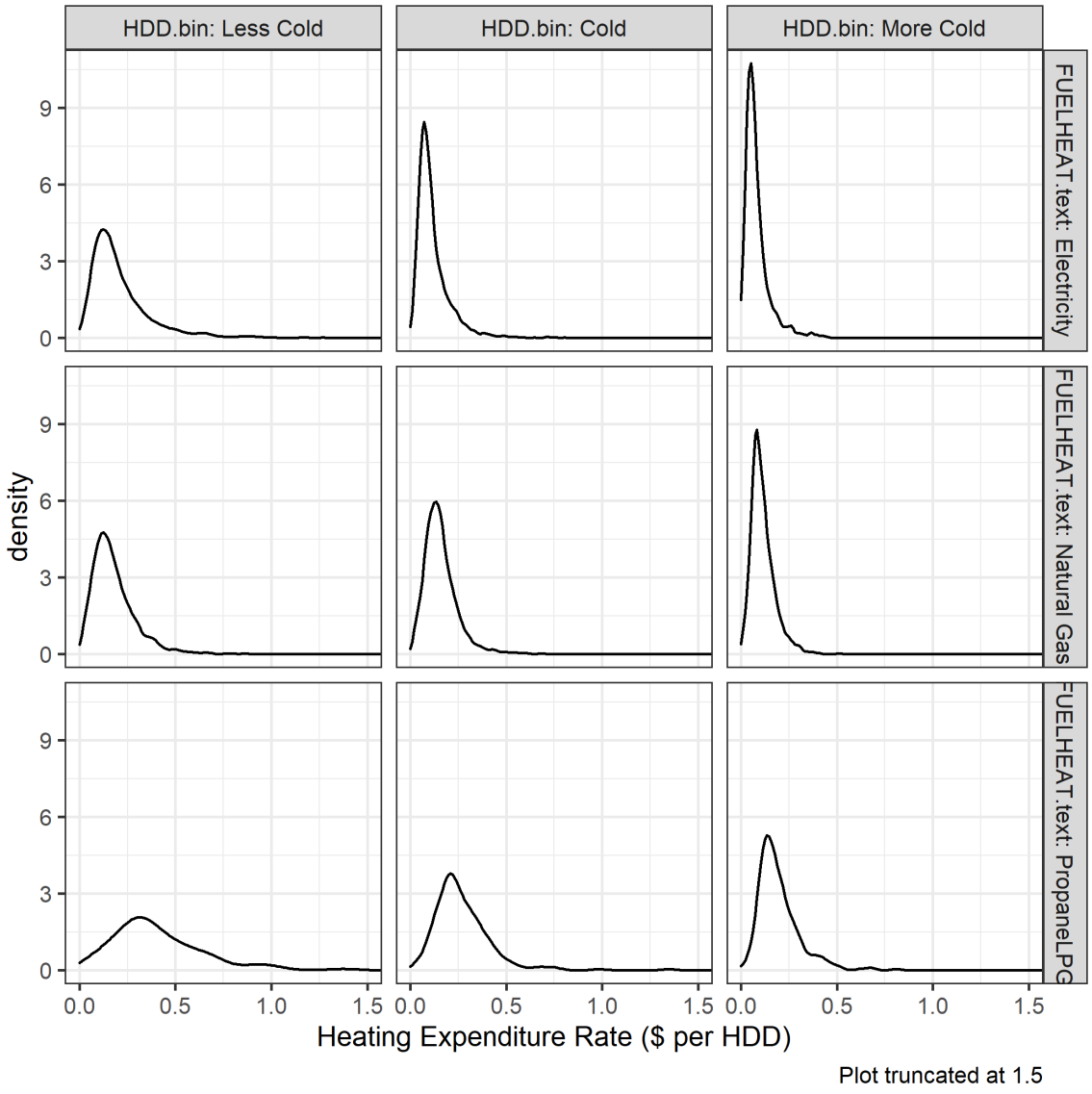


Figure 7: Heating expenditures by HDD bin and heating fuel from the RECS in 2009 and 2015

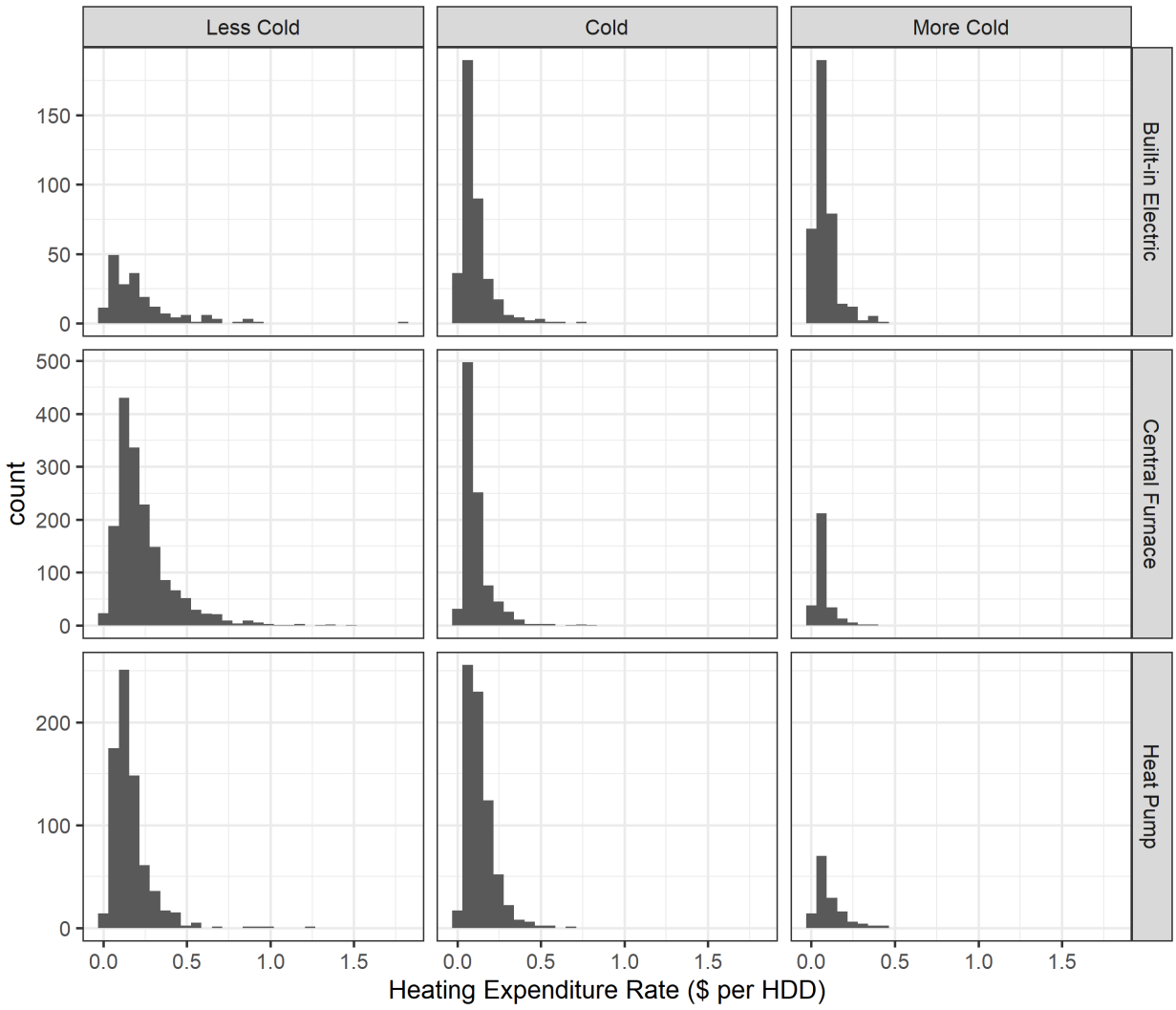


Figure 8: Heating expenditures by HDD bin and electric heating technology from the RECS in 2009 and 2015

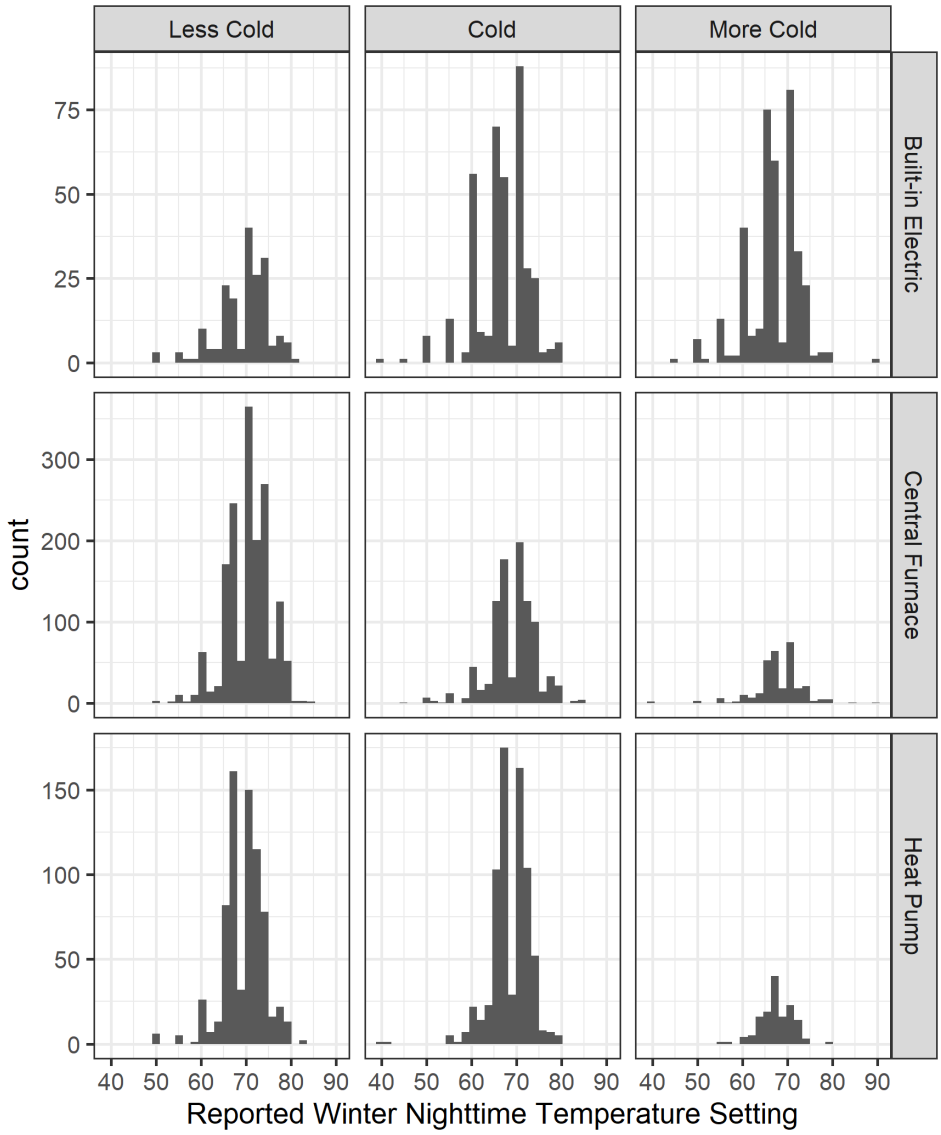


Figure 9: Reported winter nighttime temperature setting

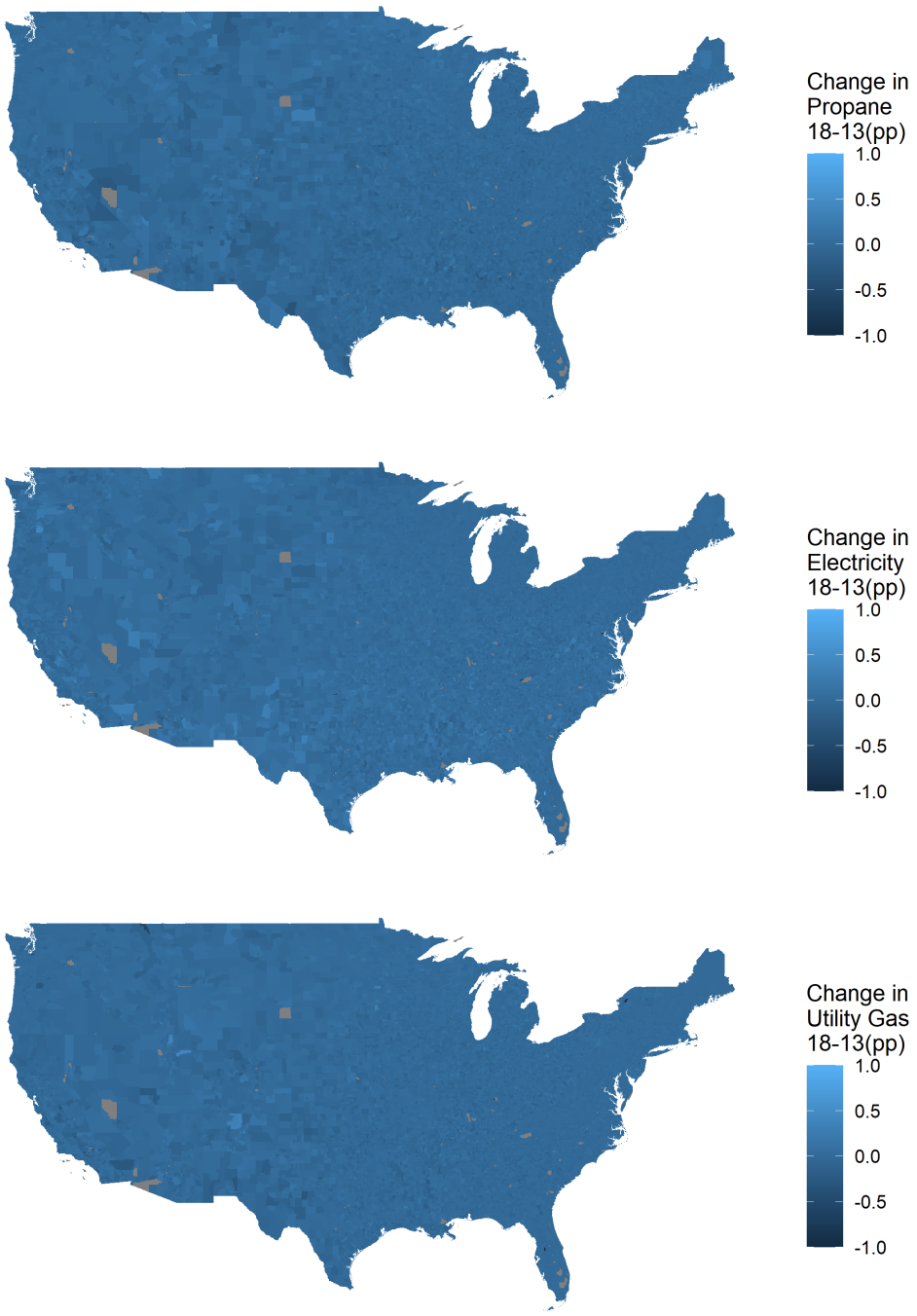


Figure 10: Change in share of households by heating fuel type 2013 to 2018

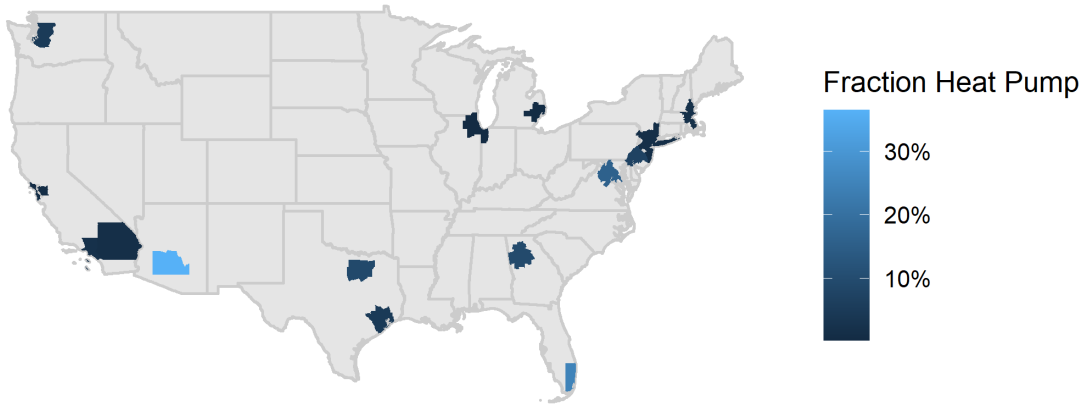


Figure 11: Fraction of homes using heat pump for primary space heating in AHS CBSA sample, 2015

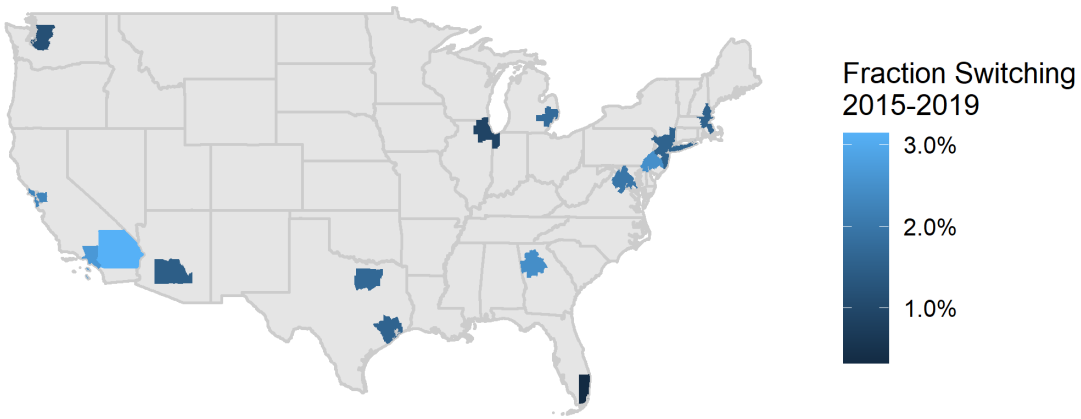


Figure 12: Fraction of homes switching to heat pump for primary space heating in AHS CBSA sample, 2015-2019.

Conflict of Interest Statement

Soren Anderson declares no financial or other interests that might bear on the proposed work.

Justin Kirkpatrick declares no financial or other interests that might bear on the proposed work.