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What Matters for Electrification?
Evidence from 70 Years of U.S. Home Heating Choices

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Abstract

The percentage of U.S. homes heated with electricity has increased steadily from 1% in 1950, to 8% in 1970, to 26% in 1990, to 40% in 2020. This paper investigates the key determinants of this increase in electrification using data on heating choices from millions of U.S. households over a 70-year period. Energy prices, geography, climate, housing characteristics, and household income are shown to collectively explain 90% of the increase, with changing energy prices by far the most important single factor. This framework is then used to calculate the economic cost of an electrification mandate for new homes. Households in warm states tend to prefer electricity anyway, so would be made worse off by less than $350 annually on average. Households in cold states, however, tend to strongly prefer natural gas so would be made worse off by more than $1000 annually. These findings are directly relevant to a growing number of policies aimed at reducing carbon dioxide emissions through electrification.

Key Words: Electrification Mandates, Natural Gas Bans, Electric-Preferred Building Codes
JEL: H23, L51, Q41, Q42, Q48, Q54

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1 Introduction

U.S. households burn vast amounts of fossil fuels on-site for space heating: 2.7 trillion cubic feet of natural gas, 2.9 billion gallons of heating oil, and 2.5 billion gallons of propane annually.[1] This fossil fuel consumption is the carbon dioxide equivalent of having 40 million cars on the road.[2] Burning fossil fuels also contributes to local particulate pollution and ozone, as well as to upstream externalities including water contamination and methane leakage.

Policymakers are increasingly turning to electrification in an effort to reduce these externalities. The "electrify everything" movement recently gained attention when Berkeley became the first city in the United States to ban natural gas on all new residential construction.[3] More than forty cities in California have now enacted measures limiting or prohibiting natural gas in new homes, and cities in Washington, New York, Massachusetts, and Rhode Island have introduced "electric-preferred" building codes.[4]

Proponents argue that electrification is critical if the United States is to sharply reduce carbon dioxide emissions from the building sector. U.S. electricity gener-

[1] U.S. Department of Energy, Energy Information Administration, "Energy Consumption and Expenditure Tables from Residential Energy Consumption Survey", "Table CE4.1 Annual Household Site End-Use Consumption by Fuel in the U.S.—Totals", released May 2018.

[2] U.S. Department of Energy, Energy Information Administration, "Carbon Dioxide Emissions Coefficients" and U.S. Department of Transportation, "Highway Statistics", "Annual Vehicle Distance Traveled in Miles and Related Data by Highway Category and Vehicle Type, Table VM-1.

[3] See, e.g., "All-Electric Movement Picks Up Speed, Catching Some Off Guard," *New York Times*, Jane Morgolies, February 4, 2020.

[4] "To Cut Carbon Emissions, a Movement Grows to 'Electrify Everything' ", *PBS News Hour*, April 17, 2020. "Banning Natural Gas is Out; Electrifying Buildings Is In", *S&P Global*, Tom DiChristopher, July 8, 2020.

ation has become much less carbon-intensive, making this a more viable path to decarbonization than even just a few years ago (Holland et al., 2016, 2020, 2021). Critics argue that electric heating costs more than natural gas per unit of heating, so electrification mandates can be expensive and regressive.[5]

Mostly missing from this discussion, however, is that home electrification is already happening. As this paper documents, the percentage of U.S. homes heated with electricity has increased steadily from 1% in 1950, to 8% in 1970, to 26% in 1990, to 40% in 2020. This paper uses data on heating choices from millions of U.S. households over a 70-year period to investigate the key determinants of this increase. The paper proposes five hypotheses, collects data on all five, and then designs an empirical framework aimed at testing and quantifying each factor.

Overall, the five factors are shown to explain 90%+ of the increase in electrification since 1950. By far, the single most important single factor is energy prices. Average U.S. residential electricity prices have fallen 59% in real terms since 1950, while average residential prices for natural gas and heating oil have increased 22% and 41%, respectively. Heating choices are shown to be highly sensitive to energy prices such that the change in energy prices can explain over two-thirds of the increase in electrification.

Geography and climate matter too. Electric heating tends to have lower capital costs but higher operating costs than other forms of heating, so is preferred by households

[5] "Towns Trying to Ban Natural Gas Face Resistance in Their Push for All-Electric Homes" *Wall Street Journal*, July 31, 2021. "Should Cities Phase Out Gas Appliances and Require New Buildings to Be All Electric?" *Wall Street Journal*, November 19, 2019. "Natural Gas Bans Will Worsen California's Poverty Problem" *Real Clear Energy*, Robert Bryce, August 9, 2020.

in warmer climates. Over this 70-year period, there has been a pronounced shift in new housing construction toward warmer states, and this changing geography can explain 7% of the increase in electrification. In addition, climate change is making all parts of the United States more conducive to electric heating, and can explain 4% of the increase in electrification.

Other factors have only a modest impact. Multi-unit homes are more likely to use electric heating, so the increased prevalence of multi-unit homes and other changes in housing characteristics since 1950 can explain 4% of the increase in electrification. Finally, higher income households are found to be slightly less likely to choose electric heating, but the effect is so small in magnitude that rising incomes since 1950 have essentially zero effect on electrification.

These data and framework are then used to calculate the economic cost of an electrification mandate for new homes. A discrete choice model is used to describe household heating system choices and to estimate how much households would be willing-to-pay per year to avoid an electrification mandate. Households in warm states tend to prefer electricity anyway, so would be made worse off by less than $350 annually on average. Households in cold states, however, tend to strongly prefer natural gas so would be made worse off by $1000+ annually.

These findings are directly relevant to a growing number of policies aimed at building electrification. Several recent interdisciplinary studies consider pathways to decarbonize the U.S. economy by mid-century (Larson et al., 2020; National Academies, 2021; Williams et al., 2021). Rapid electrification of residential heating plays a prominent role in virtually all considered pathways, so understanding the cost of such a transition is of critical policy importance.

There are very few existing economic analyses of building electrification. This paper is the first to document or attempt to understand this 70-year increase in U.S. home electrification, and the first to calculate the economic cost of an electrification mandate. Most previous economic analyses of home heating were written well before this recent policy interest in electrification, and with quite different research objectives.[6]

There are also parallels which can be drawn from a substantial existing literature on energy-efficiency. See, e.g. Allcott and Greenstone (2012), Gillingham and Palmer (2014), Gerarden et al. (2017), and references therein. Electrification and energy-efficiency are similar in that both are motivated by reducing externalities from fossil fuels, and both are impacted by building codes.[7]

Finally, the finding that household heating choices are highly sensitive to energy prices points to the critical importance of pricing energy efficiently, a long-standing theme in economic analyses of energy markets and utility rate design. See, e.g., Feldstein (1972); Sherman and Visscher (1982); Naughton (1986); Borenstein and

[6]For example, Dubin and McFadden (1984) estimates a model of space and water heating to test for correlation between adoption and usage decisions. Dubin (1985) describes residential heating and cooling demand models and shows how these models can be used to forecast energy consumption. Mansur et al. (2008) estimates a fuel choice model to predict how U.S. energy consumption will change with climate change. Davis and Kilian (2011) estimates a heating system choice model to measure the allocative cost of price ceilings in the U.S. natural gas market.

[7]The existing literature on building codes has mostly focused on measuring energy savings. See, e.g., Aroonruengsawat et al. (2012); Jacobsen and Kotchen (2013); Levinson (2016); Kotchen (2017).

Bushnell (2022, forthcoming).

The paper proceeds as follows. Section 2 describes the data and presents descriptive statistics. Section 3 describes regression and decomposition analyses. Section 4 introduces the discrete choice model and calculates willingness-to-pay to avoid an electrification mandate. Section 5 concludes.

2 Data

2.1 Heating Choices

The core dataset for this analysis was compiled using five waves of the U.S. decennial census: 1960, 1970, 1980, 1990, and 2000, along with 21 waves of the U.S. American Community Survey (ACS): 2000-2020. Both the census and ACS ask respondents about their primary form of home heating. The key question asks *"Which fuel is used most for heating this home?"*.[8] These data also provide information on the age of the home, household income, housing characteristics, and the state of residence. Census and ACS sampling weights are used throughout the analysis. See Ruggles et al. (2022) for details.

Figure 1 shows the growth in electric heating 1950-2020. Only 1% of U.S. households in 1950 used electricity as their primary heating fuel.[9] By 1960, this had increased

[8]The home heating question is not asked to respondents in group quarters (e.g. correctional facilities, nursing homes, college dormitories) so these individuals are excluded from all analyses.

[9]The 1950 map is constructed somewhat differently from the map for subsequent years. The home heating question was introduced with the 1960 census. Therefore, the 1950 map was constructed using homes in the 1960 census which were at least ten years old. This is a bit less accurate as it misses homes that were retrofitted with a new form of primary heating between 1950 and 1960.

to 2%, led by Washington, Oregon, Nevada, and Tennessee, four states that had access to cheap Federal electricity via the Bonneville Power Administration and the Tennessee Valley Authority. By 1970, 8% of U.S. households used electricity as their primary form of heating. Electric heating became more common in southern states like Mississippi, Alabama, Georgia, and North Carolina, as well as in Western states like Nevada, Arizona, Idaho, and Oregon.

Electric heating reached 18% in 1980, 26% in 1990, 30% in 2000, 35% in 2010, and 40% in 2020. There is a clear geographic pattern. Perhaps most strikingly, the maps show how electricity has grown to become the dominant form of heating in the Southeast, 50%+ throughout the region and 90%+ in Florida. Electric heating is also prevalent throughout the West and Midwest, particularly in the Pacific Northwest where rich hydroelectric resources contribute to lower than average residential electricity prices.

These heating choices have significant implications for energy consumption and carbon dioxide. The United States is a relatively cold country, so heating is by far the most important component of residential energy consumption. Across all fuel types, U.S. households use annually an estimated 3.9 quadrillion Btus for space heating, compared to 1.7 quadrillion Btus for water heating, 0.7 quadrillion Btus for air conditioning, and 0.3 quadrillion Btus for refrigerators.[10] Overall, space heating is responsible for 43% of U.S. residential energy consumption.[11]

[10] U.S. Department of Energy, Energy Information Administration, "Energy Consumption and Expenditure Tables from Residential Energy Consumption Survey", "Table CE3.1 Annual Household Site End-Use Consumption in the U.S.—Totals", released May 2018.

[11] Ibid.

2.2 Energy Prices

Residential prices for electricity, natural gas, and heating oil by state and year were compiled from various sources. Prices from 1950-1969 come from Edison Electric Institute (1950-1969), American Gas Association (1950-1969), and Platts Oil (1950-1969). Data from after 1970 come from EIA (1970-2020). Prices include all relevant taxes and, where appropriate, delivery charges, and reflect the average price per unit paid by residential customers. All prices and other dollar values throughout the paper have been normalized to reflect year 2020 dollars.

Figure 2 plots residential energy prices by state. Data series are labeled for the four most populous U.S. states. As mentioned earlier, average residential electricity prices have fallen 59% in real terms since 1950, while average residential prices for natural gas and heating oil have increased 22% and 41%, respectively.

There is considerable variation in electricity and natural gas prices, both over time and across states. For heating oil, there is considerable variation over time, but little variation across states. The model is identified using both time-series and cross-sectional variation. Results are reported from specifications with and without region- and division- fixed effects and with and without year fixed effects to assess how parameter estimates differ using alternative sources of identifying variation.

On an energy-equivalent basis, electricity has tended to be more expensive than natural gas and heating oil throughout this period. For example, per MMBTU, the average U.S. residential prices for electricity, natural gas, and heating oil in 2020 were \$39, \$12, and \$18, respectively.[12] This higher price per unit of heating is offset by lower capital costs. For example, recent estimates of installed costs for electric resistance and natural gas furnaces are \$1,200 and \$2,600, respectively.[13] Electric heating thus tends to be preferred by households in warmer climates, where the operating costs matter less.

2.3 Climate

Climate is measured at the state-by-year level using heating degree days (HDDs) from NOAA (2022). HDDs are often used as a summary measure for heating demand as they reflect both the number of cold days as well as the intensity of cold on those days. HDDs are calculated as the sum of daily mean temperatures in Fahrenheit below 65°F. For example, a day with an average temperature of 55°F has ten HDDs, whereas a day with an average temperature of 75°F has zero HDDs.

The HDDs from NOAA are population weighted to reflect the within-state distribution of where people live, and adjusted to account for artificial effects introduced into the climate record by instrument changes, station relocation, and other factors. Heating system choices are made based on expected long-run climatological condi-

[12] This back-of-the-envelope calculation is based on average residential prices of 13.3 cents per kWh, \$10.6 per MMBTU for natural gas and \$2.20 per gallon for heating oil. One kWh is equivalent to 3,412 Btu, or 0.003412 MMBTU, and one gallon of heating oil is equivalent to 0.138500 MMBTU. Furnace efficiencies were assumed to be 100% for electricity and 90% for natural gas and heating oil.

[13] U.S. Department of Energy, "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies", June 2018. These values reflect equipment and installation costs for 2020, but the cost premium for natural gas is similar in other years. Electric resistance unit heaters have even lower capital costs, e.g. \$125-\$275. Electric heat pumps tend to cost much more, but have other significant advantages as will be discussed later in the paper.

tions, not year-to-year variation in HDDs. Therefore, rather than use these raw data, the analyses which follow use fitted values from a linear time trend estimated separately by state.[14]

Figure 3 describes the change in annual HDDs between 1950 and 2020. For example, Minnesota had 9,300 HDDs in 1950 and 8,400 HDDs in 2020, for a decrease of 900 HDDs. Florida, in contrast, had 800 HDDs in 1950 and 600 HDDs in 2020, for a decrease of 200 HDDs. On average, HDDs decreased by 11% between 1950 and 2020.

2.4 Estimation Sample

The merged dataset is restructured to describe heating system choices at the time each home was constructed. The rationale for the focus on new homes is that there is considerable inertia in heating system choices. When a new home is built, a choice must be made as to whether the home is heated with electricity or some other heating fuel. Later on a home can be retrofitted, for example, from heating oil to natural gas, but the timing of any such retrofit is not observed in these data. Most of the policy interventions currently being discussed are primarily focused at new homes, providing further motivation for the focus on choices at the time of construction.

In particular, the sample is restricted to homes built in the last 10 years as of the time of each survey. For example, from the 1960 census, the sample is restricted to homes

[14] In all 48 regressions the dependent variable is HDDs and the only independent variable is the year. All regressions have 71 annual observations (1950-2020) and two coefficients, an intercept and a slope. All 48 estimated slopes are negative and the mean R^2 is 0.23.

built during the 1950s. While the 1970 census and later surveys also include homes built during the 1950s, these observations are excluded because these homes are more likely to have been retrofitted. Focusing on these initial heating system choices makes it possible to to confidently match each home to energy prices, climate, and other factors at the time the choice was made.

Recent waves of the ACS provide the exact age for newer homes. However, early waves of the ACS and all waves of the census instead provide an approximate range. For homes built in the last 10 years, there are typically three categories: 0-1 year, 2-5 years, and 6-10 years. These homes are assigned to specific construction years based approximately on the midpoint of each age range. Specifically, homes 0-1 years old are assumed to be 1 year old, homes 2-5 years old are assumed to be 4 years old, and homes 6-10 years old are assumed to be 8 years old.

2.5 Descriptive Statistics

Table 1 reports descriptive statistics. The estimation sample includes 5.5 million total observations. Panel (A) describes the dramatic increase in electric heating over this time period. The overall pattern is similar to Figure 1, though the table describes the "flow" (i.e. new homes built in each decade) rather than the "stock" (i.e. all homes as of a particular year). The percentage of new homes heated with electricity increases from 4% during the 1950s to 54% during the 2010s.

Panels (B) and (C) show residential energy prices and HDDs. Changes over time in these averages reflect both time-series variation and changes in where new homes are being constructed. For example, HDDs in Panel (C) decrease more rapidly than in Figure 3 because they reflect climate change as well as a relative increase in new home construction in warmer states. Panel (D) illustrates the shift in the composition of new homes toward southern states. Finally, Panel (E) shows changes in household demographics and housing characteristics. Perhaps most notably this shows the large increase in average household income since the 1950s.

All five hypotheses are at least partly visible in Table 1: (1) changing energy prices, (2) changing geography toward warmer states, (3) climate change, (4) changing housing characteristics, and (5) rising household incomes. What descriptive statistics cannot reveal however, is the relative contribution of these different factors to U.S. home electrification. The following section therefore turns to regression and decomposition analyses to quantify the relative magnitudes.

3 The Determinants of Electric Heating

3.1 Energy Prices

Table 2 reports coefficient estimates and standard errors from six separate least squares regressions. In all six regressions the dependent variable is an indicator variable for homes for which electricity is the primary form of heating. Estimates are reported for specifications with and without year fixed effects, and with and without fixed effects for the four census regions and the nine census divisions.

The most striking feature of Table 2 is the pronounced negative relationship between electricity prices and electrification. In column (6), for example, a 10% increase in electricity prices decreases electric heating by 4.2 percentage points. This is a large effect. In 2020, residential electricity prices ranged from 9.7 cents in Louisiana to 22.6 cents in Connecticut, a difference of 0.85 log points. The model implies that, everything else equal, an increase in electricity prices of this magnitude would decrease electric heating by 36 percentage points.[15] The estimated coefficients on electricity prices are similar across columns and statistically significant at the 1% level throughout.

Natural gas and heating oil prices matter too. These cross-price effects are expected to be positive and the point estimates are indeed positive in most cases. In column (6), for example, 10% increases in natural gas and heating oil prices increase electric heating by 2.1 and 0.7 percentage points, respectively. The estimated coefficients on natural gas prices are consistently positive and statistically significant at the 1% level, ranging from 0.15 to 0.29. The estimated coefficients on heating oil prices are smaller in magnitude and mostly not statistically significant.

3.2 Other Covariates

There are several other notable estimates in Table 2. First, income has only a very small impact on adoption of electric heating. Higher income households are slightly

[15]These estimates shed light on the long-run price elasticity of demand for electricity. In contrast, most previous studies of electricity demand focus on the short-run. See, e.g., Reiss and White (2005), Reiss and White (2008) and Ito (2014). The short-run price elasticity of demand primarily reflects changes in the intensity of usage, not changes in technology. Other studies have looked explicitly at technology changes. For example, Sahari (2019) finds that when electricity prices rose in Finland 2006-2011, households substituted away from electric heating and toward wood heating and ground source heat pumps.

less likely to choose electric heating. Across all eight specifications the point estimate is negative and statistically significant, but in all cases very small in magnitude. For example, in column (6) an additional $100,000 in annual household income decreases electric heating by only 2 percentage points.

Second, heating degree days have a strong negative impact. In column (6) an additional 1000 HDDs annually decreases electric heating by 5 percentage points. This is a large effect. For example, current HDDs in Minnesota and Florida are 8,400 and 600, respectively. Thus the coefficient on HDDs imply that, everything else equal, households in Minnesota are 39 percentage points less likely to choose electric heating than households in Florida. Households in cold climates tend not to choose electricity because of the high price per unit of heating.

Third, housing characteristics have the expected effects. Homes with 4- and 5-bedrooms are considerably less likely to be electric, whereas mobile homes, attached homes, and, multi-unit homes are more likely to be electric. This pattern makes sense because of economies-of-scale in forced air heating. Many new multi-unit buildings use electricity because it less capital-intensive and because shared walls imply lower overall heating demand.

Finally, rented homes are more likely to have electric heat. This is consistent with the "landlord-tenant problem". See, e.g. Gillingham et al. (2012). In particular, landlords have an incentive to buy inexpensive inefficient appliances when their tenants pay the utility bill. Although investments in more expensive technologies could, in theory, be passed on in the form of higher rents, it may be difficult for landlords to effectively convey this information to prospective tenants.

3.3 Decomposition Analysis

How much of the increase in electrification since 1950 can be explained by the five hypotheses? As documented earlier, there has been a steady increase in the percentage of new homes heated with electricity. This section uses the estimates from the linear probability model to perform a decomposition analysis. The estimates from the last column of Table 2 are used as the baseline specification, with results from alternative specifications reported for robustness.

The decomposition is performed as follows: (1) Choose one hypothesis and set the corresponding variables equal to 1950s levels. (2) Allow all other variables to evolve as they actually did over the period 1950-2020. (3) Use the model to predict electrification over the entire time period. (4) Compare predicted outcomes to actual outcomes. (5) Repeat the process for the other hypotheses.[16]

Figure 5 plots the results of this decomposition. There are five panels, one for each hypothesis. The darker line is the same in each panel, in each case plotting actual outcomes, i.e. the percentage of new homes in each year heated with electricity. The lighter line differs across panels, in each case plotting predicted outcomes, holding

[16] A Blinder-Oaxaca decomposition probably does not make sense in this context. With Blinder-Oaxaca, the difference in means between two groups is decomposed into the parts that are due to differences in the mean values of the covariates, group differences in the effects of the covariates, and an unexplained component. This approach is less well-suited to explaining electrification because the groups are time periods so it would be necessary to somewhat arbitrarily select a "beginning" and "end" rather then attempting to explain the entire 70-year trajectory. In addition, with Blinder-Oaxaca the regressions are estimated separately by group, whereas for identification purposes it makes more sense in the electrification context to estimate a single integrated regression.

fixed a different set of variables. For both the actual and predicted outcomes, a modest amount of smoothing has been applied to emphasize the overall pattern rather than idiosyncratic year-to-year fluctuations.

The single most important factor is energy prices. As the first panel illustrates, when energy prices are held fixed at 1950s levels, there is dramatically less adoption of electric heating during this 70-year period. Residential electricity prices fell sharply in real terms over this period, while residential natural gas and heating oil prices increased significantly. Had these changes not occurred, the model predicts that there would have been dramatically less electrification over this period.

Geography matters too, though not nearly as much as energy prices. As shown earlier, there has been a pronounced shift in new housing construction toward warmer states. Holding fixed the geography of new home construction as it was in the 1950s, the model predicts considerably less electrification over this time period.

Housing characteristics, climate, and income all have smaller impacts. The increased prevalence of multi-unit homes has worked to increase electrification, while the trend toward larger homes works against electrification. Climate change as measured by heating degree days has increased electrification, but the magnitude of the effect is modest. Finally, the large increase in average household income over this period has essentially zero effect.

3.4 Baseline and Alternative Specifications

Table 3 reports the results of the decomposition analysis for the baseline and alternative specifications. The first row describes the baseline specification. Energy prices play a dominant role, explaining 82% of the increase in electrification since 1950.[17] The changing geographic distribution of new home construction explains 7% of the increase. Housing characteristics (4%) and climate change (4%) both have modest impacts, while household income has essentially zero effect.

Results are quite similar in alternative specifications, with energy prices explaining over two-thirds of the increase in electrification throughout. A couple of alternative specifications merit additional discussion. Rows (6) and (7) include cooling degree days (CDDs) in addition to and instead of HDDs, respectively. Whereas HDDs are a summary measure of annual heating demand, CDDs are a summary measure of annual cooling demand. HDDs and CDDs are strongly negatively correlated, and results from the decomposition analysis are similar with either measure or both.

Row (12) includes a one-year lag and a one-year lead for electricity prices. This specification is aimed at relaxing the assumption that choices are made only on the basis of current prices. This is a reasonable assumption in many contexts (Anderson et al., 2013), although a case could be made that the steady decreases in real electricity prices during the 1950s and 1960s could have been anticipated. Nonetheless, results are similar after including a lag and a lead.

The instrumental variables specifications in rows (13) and (14) are motivated by po-

[17] When this effect is further decomposed, it can be shown that electricity, natural gas, and heating oil prices explain 59%, 19%, and 4% of the increase in electrification over this period, respectively.

tential concerns about residential prices being correlated with local demand shocks.[18] Results are quite similar, suggesting that the baseline results are not unduly influenced by price endogeneity. This is reassuring, but not entirely unexpected. Much of the variation in energy prices can be explained by supply-side factors.[19] In addition, to the extent there are demand shocks to heating system choices, only a small fraction of households make a heating system choice in a given year, so such shocks would be unlikely to meaningfully impact total energy demand or market prices. Also, electricity and natural gas are delivered by regulated utilities so residential prices are determined using rate-of-return regulation and only partly depend on the underlying commodity prices.

Rows (15) and (16) exclude households from the Northeast and from the ten states with the highest proportion of rural households, respectively. These specifications are motivated by potential concerns about the availability of natural gas. For example, previous work has shown that natural gas shortages from price controls were heavily concentrated in the Northeast (Davis and Kilian, 2011). Between 1974 and 1978, for example, shortages precluded some households in Massachusetts from installing natural gas heating systems (Myers, 2019). Results are similar in both alternative specifications, suggesting that the results are not unduly affected by natural gas availability.

[18] It is not clear which direction this bias would go. In typical competitive markets, a positive demand shock pushes up prices. However, with electric and natural gas distribution utilities it could also go the other way, with a demand shock leading to lower retail prices as fixed costs get spread over a larger number of customers.

[19] For example, several of the states with lower electricity prices have natural advantages in the form of access to hydroelectric power. Moreover, the time-series variation in prices clearly reflects broader supply-side factors including natural gas price regulation and deregulation, and technological advances in oil and natural gas production like hydraulic fracturing.

4 The Cost of an Electrification Mandate

4.1 Background

These data and framework are next used to calculate the economic cost of an electrification mandate for new homes. As mentioned in the introduction, many U.S. cities have introduced natural gas bans, "electric-preferred" building codes, and other mandates requiring or strongly encouraging households to use electric heat.

The analysis in this section uses a discrete choice model to measure the expected annual change in utility from requiring households to choose electric heating. The key variables and structure of the model are similar to the linear probability model described earlier. However, the discrete choice model makes a functional form assumption about the error term and other additional assumptions which make it possible to calculate willingness-to-pay to avoid an electrification mandate.[20]

Another key difference with the willingness-to-pay analysis is that the model is estimated using data from the ACS samples 2000-2020, but not the older census data. This emphasis on more recent data makes sense because whereas the previous analyses look to the past, this willingness-to-pay analysis looks to the future, and these relatively recent choices are more likely to be representative of future behavior.

[20]The modeling choices in this section are informed by a long history of economists using discrete choice models to describe household energy decisions, whether it be for air conditioning (Hausman, 1979), space heating (Dubin and McFadden, 1984; Dubin, 1985), or vehicles (Bento et al., 2009).

4.2 Modeling Assumptions

Households are assumed to choose which heating system to purchase by evaluating the following indirect utility function:

$$u_{ij} = \alpha_{0j} + \alpha_1 x_{ij} + \alpha_{2j} z_i + \epsilon_{ij}, \tag{1}$$

where u_{ij} is the utility for household i of heating system j.

Since 1990, 90% of new U.S. homes use electricity or natural gas as their primary source of heating. Accordingly, the choice set is restricted to those two choices, $j \in \{e, g\}$ where e and g denote electric and natural gas heating systems, respectively. Homes heated with heating oil, propane, and other less common heating fuels are excluded when estimating the discrete choice model and from the calculations of willingness-to-pay.

Preferences for heating system j depend on annual heating expenditures in dollars x_{ij}, and household characteristics z_i. Households choose electric heating if $u_{ie} > u_{ig}$. Only differences in utility matter, so α_{0g} and α_{2g} are normalized to zero. Natural gas is thus selected as the baseline category and coefficients α_{0e} and α_{2e} are interpreted relative to natural gas. Thus the indirect utility functions for electricity and natural gas can be expressed as follows:

$$u_{ie} = \alpha_{0e} + \alpha_1 x_{ie} + \alpha_{2e} z_i + \epsilon_{ie}, \tag{2}$$

$$u_{ig} = \alpha_1 x_{ig} + \epsilon_{ig}. \tag{3}$$

Annual heating expenditures, x_{ij}, are calculated using building energy model simulations from U.S. Department of Energy (2021). These simulations report electricity and natural gas consumption by end use for homes heated with electricity and natural gas, respectively, for eight climate zones and three moisture zones, based on a particular building code and other assumptions.[21] These consumption measures were matched to the predominant climate and moisture zones in each U.S. county, aggregated to the state level using county-level populations, and multiplied by electricity and natural gas prices in that state as of the year each home was constructed.[22]

The parameter α_{0e} reflects the relative desirability of electric heating systems, incorporating heating-system specific factors such as purchase and installation costs that are common across households. The model thus implicitly assumes that the relative purchase and installation costs for natural gas and electric heating systems are constant over time. The parameter α_1 reflects households' willingness to trade off heating expenditures against other heating system characteristics, and the parameter vector α_{2e} describes interactions between household characteristics and heating sys-

[21] These simulations were performed by Pacific Northwest National Laboratory using the EnergyPlus model, a widely-used energy simulation program. At the heart of the EnergyPlus model is a set of assumptions about heat balance, i.e. how heat flows within the building shell as well as between the inside and outside of the building. The model takes into account weather, building characteristics, heating system energy-efficiency, and other factors. As part of the process for developing new building codes and standards, the Department of Energy uses this model to simulate energy consumption for a set of residential building prototypes. Predictions for heating energy consumption were taken for single- and multi-unit homes, weighted 70% and 30% respectively, for homes with a crawl space built to the 2018 International Energy Conservation Code (IECC) standard. See `https://www.energycodes.gov/prototype-building-models#IECC` for details. Alternative results are reported later in the paper for the 2015 IECC as well as for alternative assumptions about the proportion of homes that are multi-unit.

[22] Variation in annual heating expenditures thus comes from both climate differences and energy prices. In practice, the former tends to be more important quantitatively. For example, a regression of annual electricity expenditures on heating degree days yields an r^2 of 0.57, while a regression of annual electricity expenditures on electricity prices yields an r^2 of 0.20.

tem alternatives. This specification allows households in multi-unit homes to prefer electric heating systems, for example.

The error terms, ϵ_{ie} and ϵ_{ig}, capture unobserved differences across households in preferences for particular heating systems. The error terms are assumed to be identically and independently distributed across households and heating systems with a type 1 extreme value distribution. Under this assumption, the probability that household i selects electricity e takes the well-known conditional logit form,

$$\frac{e^{\alpha_{0e}+\alpha_1 x_{ie}+\alpha_{2e} z_i}}{e^{\alpha_{0e}+\alpha_1 x_{ie}+\alpha_{2e} z_i}+e^{\alpha_1 x_{ig}}} \tag{4}$$

and the heating-system choice model can be estimated using maximum likelihood.

As mentioned earlier, a potential concern is the lack of availability of natural gas. Heating systems are being modeled as a "choice", but in some, mostly rural areas, natural gas is simply not available. As a consequence, the observed fraction of households with natural gas is lower than it would be otherwise, biasing upward the estimates of α_{0e} and α_{2e}, and understating household preferences for natural gas. The ACS data are poorly suited for further evaluating this issue, but this provides further rationale for excluding households with heating oil, propane, and other less common heating fuels, as these other fuels tend to be used mostly in areas where natural gas is not available (Mansur et al., 2008; Myers, 2019).

4.3 Heating System Choice Estimates

Table 4 reports coefficient estimates and standard errors from the heating system choice model. To aid interpretation, the table also reports implied marginal effects, evaluated at the mean for all variables. The overall tenor of the estimates is similar to the results from the linear probability model.

As expected, the coefficient estimate on annual energy expenditures is negative. That is, higher expected expenditures on either electricity or natural gas make that alternative less desirable. The implied marginal effect is -0.33, so a $1000 increase in annual expenditures decreases the probability that a household selects that alternative by 33 percentage points. This is a large effect. For example, annual electricity expenditures for homes built in 2020 in Minnesota and Florida are 1,900 and 700, respectively. Thus the coefficient implies that, everything else equal, households in Minnesota are 40 percentage points less likely to choose electric heating than households in Florida.

Household income continues to have only a modest impact. The implied marginal effect is -0.04, so a $100,000 increase in annual household income decreases the probability a household chooses electric heat by 4 percentage points. Homes that experience more heating degree days and homes with more bedrooms are less likely to be heated with electricity, while rental homes, mobile homes, and multi-unit homes are more likely to be heated with electricity.

Figure 6 confirms that the predictions from the discrete choice model match closely the geographic pattern of electric heating. Panels (A) and (B) plot the actual and predicted proportions of households in each state selecting electric heating. There is close correspondence between the two maps with low proportions of electric heating throughout the Midwest and Northeast, somewhat higher proportions throughout the West, and considerably higher proportions in the Southeast and, in particular, in Florida.

The estimates from the heating system choice model are used to calculate the average annual willingness-to-pay to avoid an electrification mandate. Willingness-to-pay is calculated as the expected difference in utility between the status quo in which households may choose either heating fuel and an electrification mandate which requires all households to use electric heating. Under the logit assumptions, this difference in expected utility takes the following well-known closed form solution (Small and Rosen, 1981),

$$WTP_i = \frac{1}{|\alpha_1|}[\ln(e^{\alpha_{0e}+\alpha_1 x_{ie}+\alpha_{2e}z_i} + e^{\alpha_1 x_{ig}}) - \ln(e^{\alpha_{0e}+\alpha_1 x_{ie}+\alpha_{2e}z_i})]. \tag{5}$$

Dividing by the marginal utility of income α_1 translates utility into dollars. In addition, willingness-to-pay depends on energy expenditures (x_{ij}), household characteristics (z_i), and the other model parameters α_{0e} and α_{2e}. Households who strongly prefer natural gas have a high willingness-to-pay while households who strongly prefer electricity have willingness-to-pay near zero.

4.4 Estimates of Willingness-to-Pay

Figure 7 plots annual willingness-to-pay by state. Households in warm states tend to prefer electric heating anyway, so are willing-to-pay less than \$350 annually on average to avoid an electrification mandate. Households in Florida, for example, already overwhelmingly choose electric heating so the average willingness-to-pay is only \$177 annually. In Texas the average willingness-to-pay is \$338 annually.

The West Coast is more temperate, with annual willingness-to-pay \$537 in California, \$545 in Oregon, and \$575 in Washington. California is considerably warmer than Oregon and Washington, but has similar willingness-to-pay, in part, because of the state's higher than average electricity prices. By the same argument, annual willingness-to-pay tends to be lower in states with below average electricity prices including North Carolina (\$449), Tennessee (\$456), and Kentucky (\$482).

Households in cold states tend to strongly prefer natural gas so are willing-to-pay over \$1000 annually on average to avoid an electrification mandate. This includes populous states like Ohio (\$1,119), Pennsylvania (\$1,204), Illinois (\$1,365), and New York (\$1,467). Finally, willingness-to-pay is above \$1500 annually in particularly cold states like Minnesota (\$1,679), Maine (\$1,736), New Hampshire (\$1,866), and Vermont (\$1,900).

Table 5 reports results for the baseline model and alternative specifications. Adding census division fixed effects in row (2) has little effect on average national willingness-to-pay, but changes the estimates for some states, most notably resulting in a higher willingness-to-pay for California. Rows (3), (4), and (5) are based on alternative measures of annual energy consumption for heating from U.S. Department of Energy (2021). In row (3), annual willingness-to-pay increases when new homes are assumed to be built to a less stringent building code, i.e. electrification mandates are more expensive when homes use more energy. Rows (4) and (5) show that electrification mandates are cheaper when there are more multi-unit homes, and more expensive when there are fewer.

4.5 Limitations of the Analysis

Before proceeding, it is important to note several important caveats. First, this model is estimated using historical data, and thus cannot speak to how these tradeoffs will be affected in the future by technological change. Over this time period, there has been little technological innovation in natural gas furnaces or conventional electric resistance heating. The more significant innovations occurred instead for electric heat pumps, which have become more energy-efficient along with other compressor-based appliances. Whereas electric resistance heating converts electricity into heat, a heat pump uses electricity to move heat from one space to another, and thus can be used for both heating and cooling, and can deliver more than one kWh of heat using one kWh of electricity.

The data used in this analysis does not distinguish heat pumps from other forms of electric heating. From other data sources, it is known that about 10% of U.S. households have heat pumps, with three-quarters of those households located in the Southeast where winter temperatures are mild and heat pumps are more effective.[23]

[23] U.S. Department of Energy, Energy Information Administration, "U.S. Households' Heating

The growing popularity of heat pumps in the Southeast is reflected in Figure 1 and is part of the reason the willingness-to-pay estimates tend to be lower in that region. Heat pump performance degrades at lower temperatures and thus far there has been relatively little heat pump adoption in the Northeast or Midwest.

What is less clear is whether additional technological innovation should be expected for heat pumps. Kaufman et al. (2019) find that heat pumps are not the least-cost alternative for home heating and cooling in any of the locations modeled. However, when they simulate a 30% increase in heat pump energy-efficiency between now and the mid 2030s, heat pumps become cheaper than alternative technologies in most regions. To the extent that these energy-efficiency gains are realized, this would significantly decrease willingness-to-pay to avoid an electrification mandate.

Second, no attempt has been made to explicitly model household demand for cooking, hot water heating, or other end uses. In part, this reflects data limitations. Since 1980, neither the census nor ACS collect data on fuels used for cooking or water heating. That said, the focus on electrification of space heating makes sense given that this is by far the largest component of on-site fossil fuel consumption. Moreover, many households view these as bundled choices, for example, selecting natural gas for both space and water heating.[24] To the extent that these decisions are bundled or at least highly correlated choices then the model and estimates of willingness-to-pay can be viewed as measuring willingness-to-pay for the entire bundle.

Equipment Choices are Diverse and Vary by Climate Region", April 6, 2017, https://www.eia.gov/todayinenergy/detail.php?id=30672#.

[24]In the 2015 Residential Energy Consumption Survey, among households who heat with natural gas, 86% also use natural gas for water heating. Moreover, among households who heat with electricity, 82% also use electricity for water heating.

Third, the estimates of willingness-to-pay do not capture some potentially important additional margins of adjustment. In addition to inducing households to switch to electricity, an electrification mandate could also affect where people choose to live, for example, leading households to substitute to nearby cities without the mandate. A mandate might also lead households to choose smaller and more energy-efficient homes, for which electric heating costs would be lower. Examining these other margins of adjustment goes beyond the scope of the study, but they will tend to reduce the overall economic costs of an electrification mandate.

Fourth, it is important to emphasize that these estimates of willingness-to-pay are for newly constructed homes and should not be generically applied to the entire existing building stock. This focus on new homes makes sense given current policy discussions but, of course, it is the stock of homes that matters for carbon dioxide emissions, and homes are long-lived. This analysis provides no evidence on the economic cost of electrifying existing buildings but related evidence from research on energy efficiency suggests that there may be significant additional challenges with retrofitting older buildings (Fowlie et al., 2015, 2018).

4.6 Considerations for Cost-Benefit Analysis

Performing a cost-benefit analysis of electrification mandates would require estimates of both costs and benefits. These estimates of willingness-to-pay provide an estimate of costs, but provide no information about benefits. While the full cost-benefit analysis goes beyond the scope of the paper, this section discusses some of the considerations involved in quantifying benefits.

As mentioned in the introduction, natural gas bans and other policies aimed at increasing building electrification are viewed as a way to decrease fossil fuel consumption, and thus to reduce environmental externalities. These benefits include not only reduced carbon dioxide emissions, but also reduced local pollutants, as well as reduced methane leaks from natural gas production.

Of course, the degree to which building electrification reduces environmental externalities depends on how electricity is generated. One of the valuable lessons from a series of papers by Stephen Holland and coauthors is that the U.S. electricity system is changing rapidly and with complex and divergent patterns for average versus marginal emissions (Holland et al., 2016, 2020, 2022).

Quantifying benefits is further complicated by the long-lived nature of heating system choices. What matters is not just what the electricity system looks like today, but also what it will look like in the future. This longer time horizon is probably even more important for buildings than for electric vehicles, given how few new buildings are built each year and how difficult and expensive it is to retrofit heating systems in existing buildings.

In measuring benefits, there is also considerable uncertainty about the magnitude of economic damages per ton of emissions. The existing literature reports a wide range of estimates, not only for the social cost of carbon, but also for the social cost of local pollutants. In addition, there is a lack of consensus about how much methane is released during natural gas production.

Despite these challenges, it would be very interesting in future research to quantify these different categories of benefits, along with appropriate caveats and sensitivity analysis. Total benefits could then be compared to the costs estimated here to determine where and when electrification mandates pass a cost-benefit test.

5 Conclusion

Policymakers are increasingly turning to electrification to reduce carbon dioxide emissions and other negative externalities from fossil fuels. Largely missing from this discussion, however, is that electrification has already been happening in some sectors. This paper focuses on an important sector where electrification has increased dramatically over the last 70 years, mostly without any policy intervention.

Using household-level energy choices from millions of U.S. households, the paper documents the growth in electric heating from only 1% of homes in 1950, to 8% in 1970, to 26% in 1990, to 40% in 2020. The paper asks two research questions: (1) What explains this large increase in electrification? and (2) How much would U.S. households be willing-to-pay to avoid an electrification mandate for new homes?

The paper proposes and tests five hypotheses. Energy prices turn out to be by far the most important factor, explaining over two-thirds of the increase in electrification over this period. This finding underscores the importance of pricing energy efficiently, a central theme in the broader literature in energy economics.

Geography, climate change, and housing characteristics are also shown to matter, collectively explaining about 15% of the increase. Household income growth, in contrast, has almost zero effect. This last finding suggests that it will not be harder, nor will it be easier, for policies to encourage electrification in lower-income communities.

Finally, a discrete choice model is estimated to measure the economic cost of an electrification mandate for new homes. Households in warm states tend to prefer electricity anyway, so would be made worse off by less than \$350 annually on average. Households in cold states, however, tend to strongly prefer natural gas so would be made worse off by \$1000 or more annually.

These measures of willingness-to-pay are directly relevant for evaluating electrification mandates and also shed light on how large a subsidy would be required to induce households to choose electric heating. In general, much smaller subsidies would be necessary in warmer states. In addition, the analysis highlights smaller homes and multi-unit homes as considerable opportunities for relatively lower-cost electrification.

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Figure 1: Growth in Electric Heating

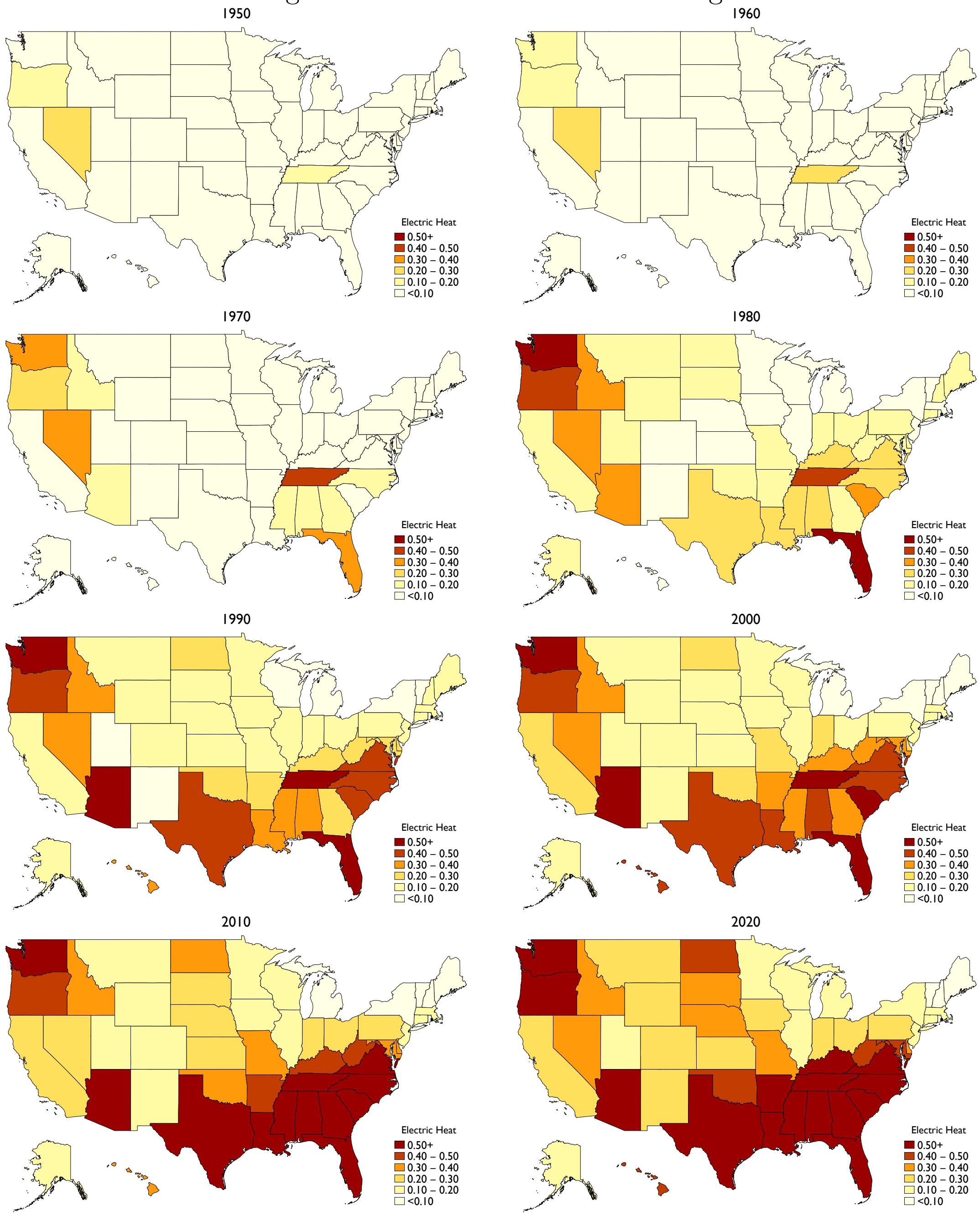
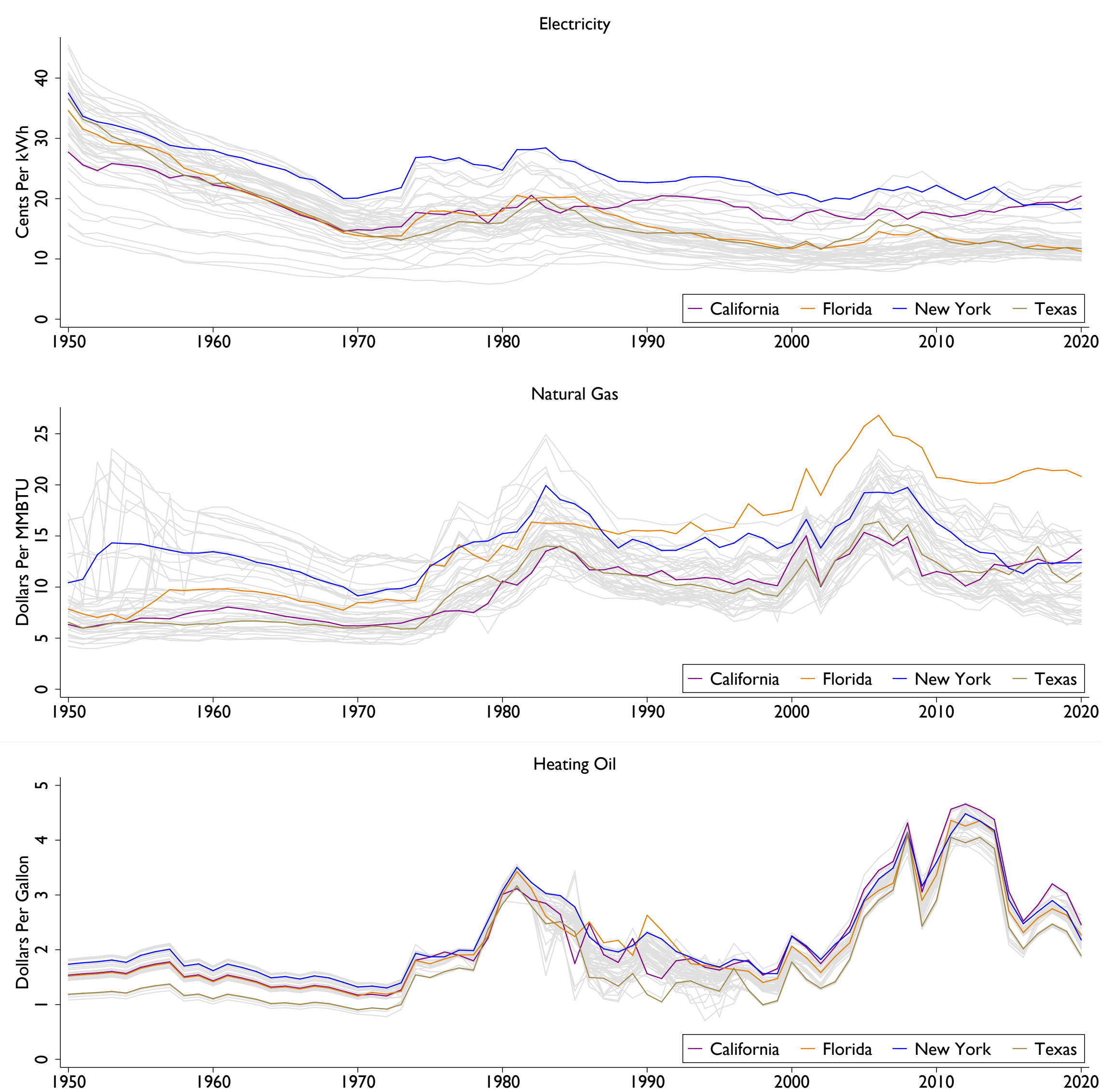


Figure 2: U.S. Residential Energy Prices By State Since 1950



Notes: This figure plots average residential prices by state for electricity, natural gas, and heating oil. Prices are calculated as average annual revenue from residential sales and are plotted for all U.S. states except Alaska and Hawaii. Data series are labeled for the four largest U.S. states by population. Data before 1970 come from Edison Electric Institute (1950-1969), American Gas Association (1950-1969), and Platts Oil (1950-1969), respectively. Data after 1970 come from U.S. Department of Energy, Energy Information Administration (EIA). Prices have been normalized to reflect year 2020 dollars.

Figure 3: Decrease in Heating Degree Days Since 1950

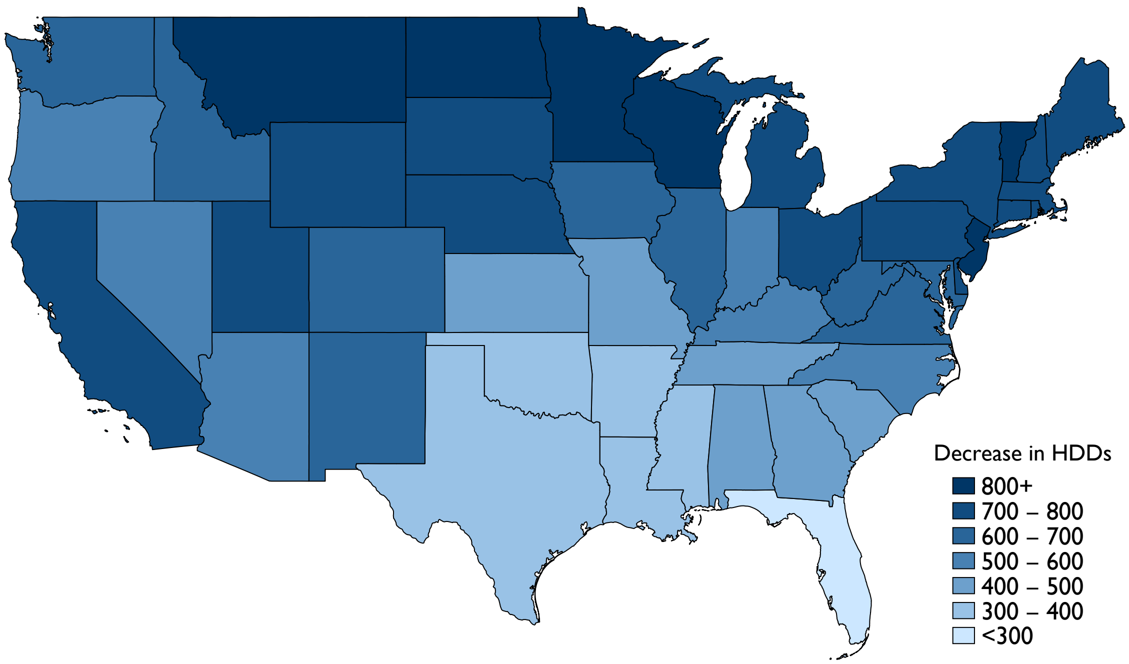
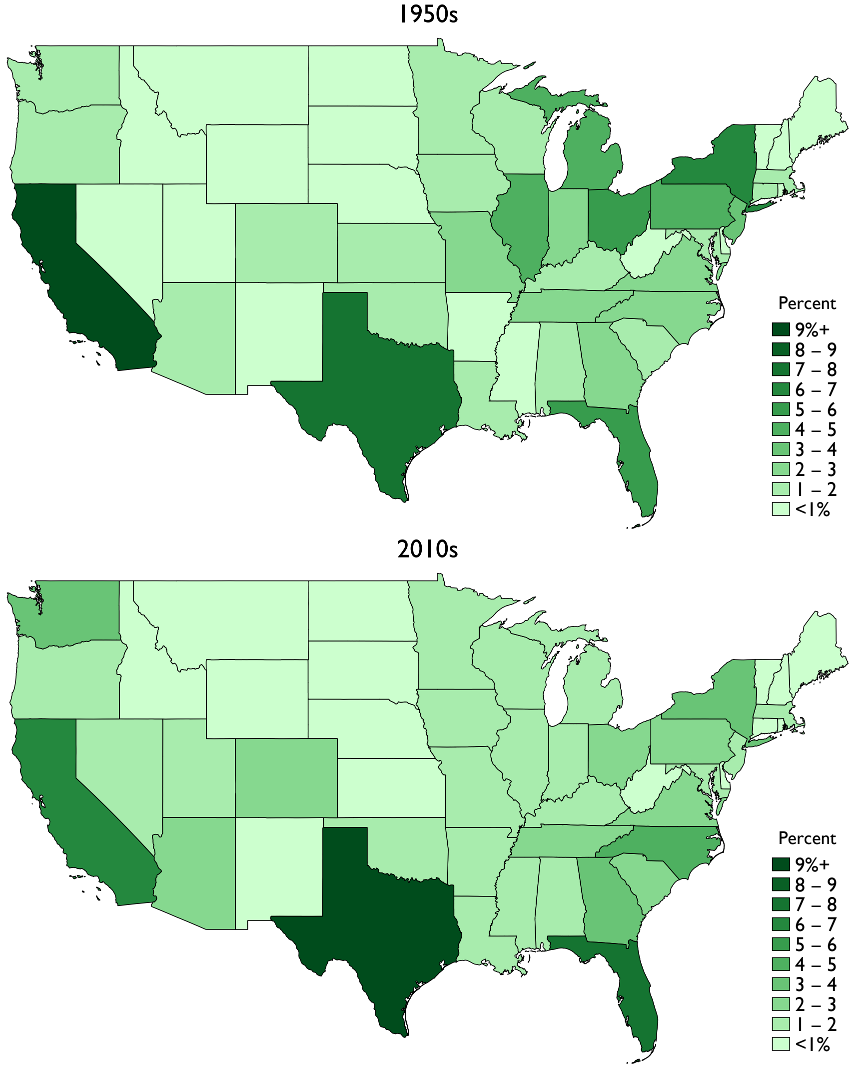


Figure 4: Percentage of New Homes in Each State



Notes: This figure shows the percentage of new homes constructed in each state. This is done separately for the 1950s and the 2010s, i.e the beginning and end of the sample period. Comparing the two panels reveals how the geography of new home construction has changed over time. For example, Texas had 7% of total U.S. new home construction in the 1950s, but 16% of total U.S. new home construction in the 2010s.

Figure 5: Percentage of New Homes Heated with Electricity, Decomposition

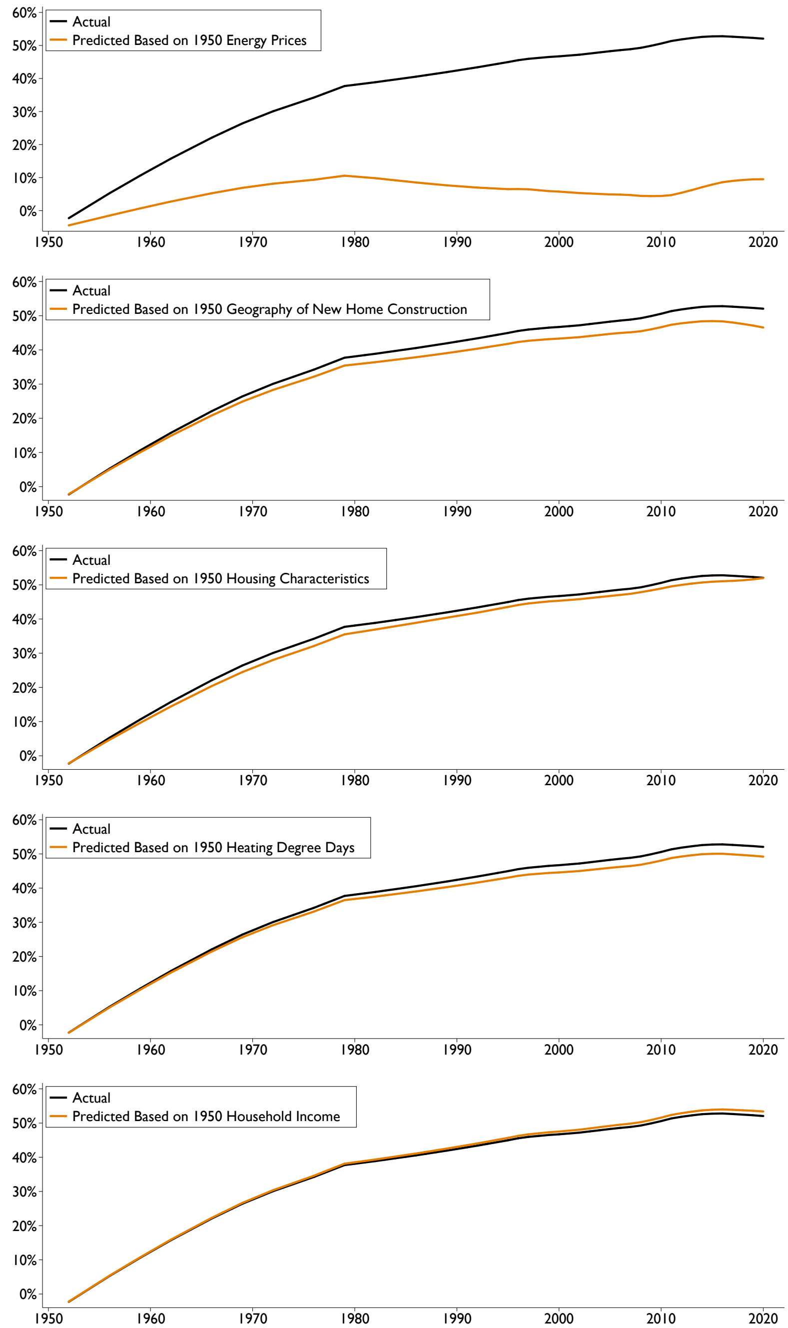
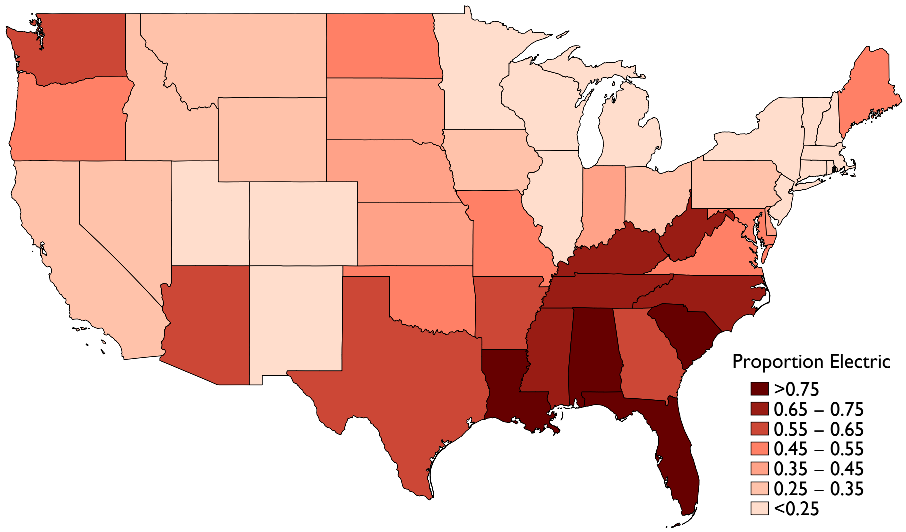


Figure 6: Evaluating Model Fit

A. Actual Heating System Choices



B. Predicted Heating System Choices

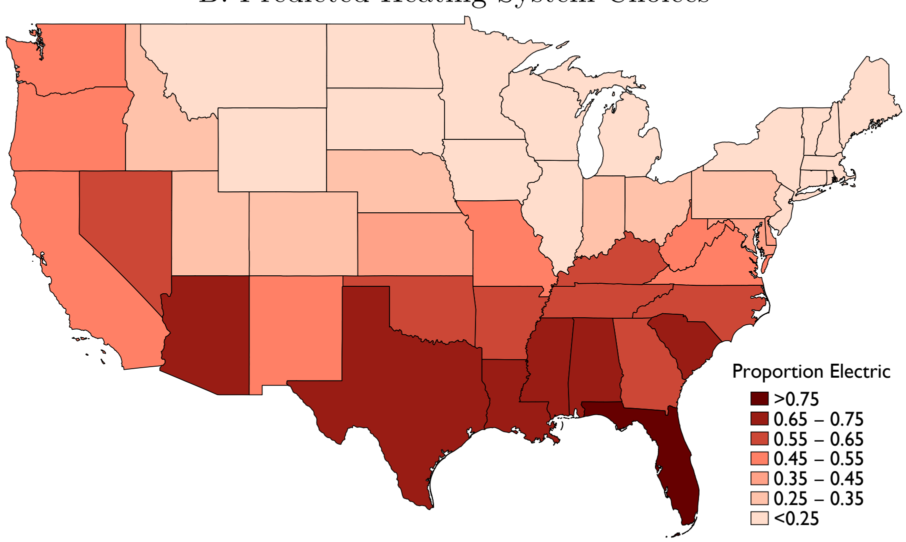


Figure 7: Annual Willingness-to-Pay to Avoid an Electrification Mandate

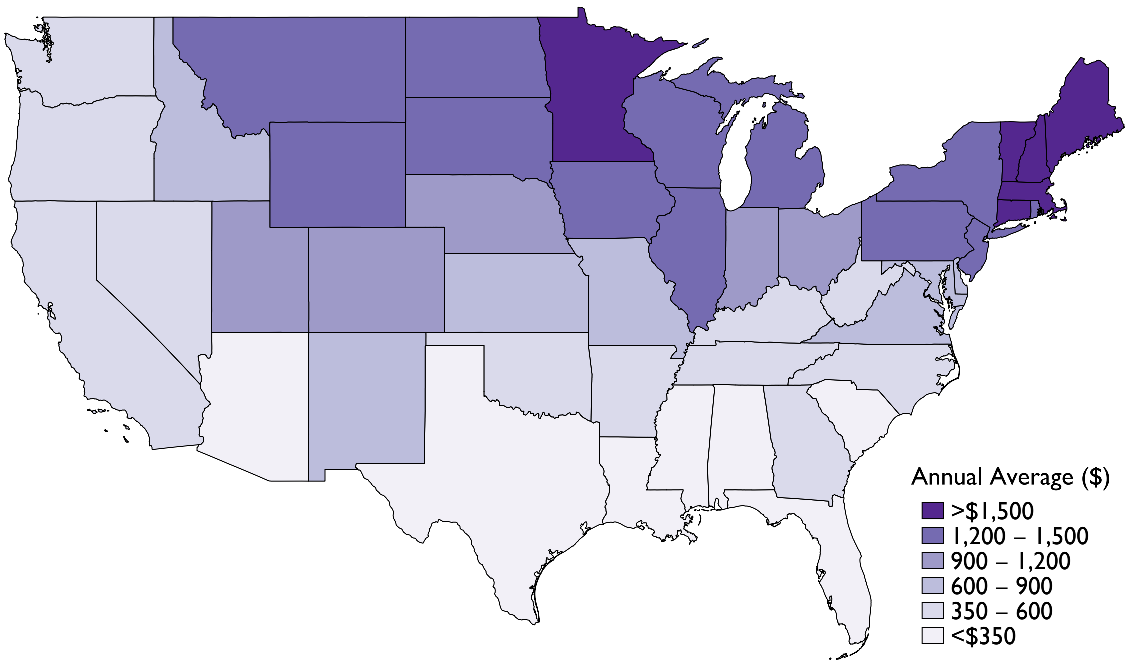


Table 1: Descriptive Statistics

	1950s	1960s	1970s	1980s	1990s	2000s	2010s
A. Primary Energy Source for Heating (percent)							
Electricity	4	18	41	47	42	45	54
Natural Gas	53	56	40	37	44	45	39
Heating Oil	32	17	8	4	3	2	1
Other	12	8	11	11	10	7	7
B. Residential Energy Prices							
Electricity (cents per kWh)	26.5	19.3	15.8	18.1	14.1	12.6	13.4
Natural Gas ($ per MMBTU)	8.8	8.8	8.5	13.8	10.9	14.6	12.8
Heating Oil ($ per gallon)	1.6	1.4	1.5	2.5	1.6	2.3	3.5
C. Climate							
Heating Degree Days, 1000s	4.9	4.7	4.5	4.1	4.2	4.0	3.9
Cooling Degree Days, 1000s	1.1	1.2	1.3	1.4	1.4	1.6	1.6
D. Percentage of New Homes By Region							
Northeast	19	17	13	13	10	9	10
Midwest	25	24	22	17	20	19	17
South	34	38	42	47	47	48	52
West	22	21	23	24	23	23	21
E. Household Demographics and Housing Characteristics							
Household Income (1000s)	62.9	76.1	67.8	82.4	102.4	102.5	112.3
Home Ownership (percent)	78	67	68	63	75	70	62
Multi-Unit (percent)	19	27	29	30	20	22	31
Number of Bedrooms	2.5	2.6	2.6	2.5	2.9	3.0	2.9
Number of Observations (1000s)	144	159	1025	895	1271	1600	405

Note: This table reports descriptive statistics by decade of home construction. The estimation sample includes all homes under ten years old in the decennial censuses from 1960, 1970, 1980, 1990, and 2000 and from the American Community Survey 2000-2020. Heating oil includes kerosene and other liquid fuels. "Other" energy sources for heating include propane, coal, wood, as well as homes with no heating. Prices and incomes have been normalized to reflect year 2020 dollars. The sample sizes are smaller in the 1960 and 1970 censuses because only a random subsample were asked about home heating. Observations are weighted using census and ACS sampling weights.

Table 2: Linear Probability Model, Estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Electricity Price, in logs	-0.40**	-0.43**	-0.39**	-0.40**	-0.40**	-0.42**
	(0.03)	(0.04)	(0.03)	(0.04)	(0.04)	(0.06)
Natural Gas Price, in logs	0.21**	0.29**	0.18**	0.23**	0.15**	0.21**
	(0.06)	(0.08)	(0.05)	(0.06)	(0.05)	(0.07)
Heating Oil Price, in logs	0.04	-0.07	0.08**	0.08	0.09**	0.07
	(0.04)	(0.15)	(0.03)	(0.10)	(0.03)	(0.10)
Household Income, 100,000s	-0.03**	-0.02**	-0.02**	-0.02**	-0.02**	-0.02**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Heating Degree Days, 1000s	-0.06**	-0.06**	-0.05**	-0.05**	-0.05**	-0.05**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Four Bedroom Home	-0.05**	-0.05**	-0.05**	-0.05**	-0.05**	-0.05**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Five+ Bedroom Home	-0.10**	-0.08**	-0.09**	-0.08**	-0.10**	-0.08**
	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)	(0.02)
Rented, i.e. not owner-occupied	0.01	0.01	0.01	0.02*	0.02*	0.02**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Mobile Home	0.04	0.02	0.04	0.02	0.03	0.02
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Single Family Home, Attached	0.04*	0.03**	0.04**	0.03**	0.04**	0.03**
	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Multi-Unit Home, 2-4 Units	0.12**	0.12**	0.12**	0.12**	0.12**	0.12**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Multi-Unit Home, 5+ Units	0.25**	0.24**	0.26**	0.24**	0.25**	0.24**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Year Fixed Effects	No	Yes	No	Yes	No	Yes
Geographic Fixed Effects	No	No	Regions	Regions	Divisions	Divisions
Observations	5,498,568	5,498,568	5,498,568	5,498,568	5,498,568	5,498,568
R-squared	0.26	0.28	0.27	0.28	0.27	0.29

Note: This table reports coefficient estimates and standard errors from six separate least squares regressions. In all regressions the dependent variable is an indicator variable for homes for which electricity is the primary form of space heating. Region and division fixed effects refer to the four census regions and nine census divisions. Year fixed effects are indicator variables for the year the home was constructed. All regressions are estimated using census and ACS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Table 3: Decomposition Analysis, Baseline and Alternative Specifications

	Prices	Geography	Housing	Climate	Income	Total
1. Baseline Specification	82%	7%	4%	4%	-2%	96%
2. Census Region FEs	83%	7%	4%	4%	-2%	97%
3. Without Year FEs	73%	7%	5%	4%	-2%	87%
4. Cubic in HDDs	74%	13%	4%	4%	-1%	94%
5. Binned HDDs	76%	8%	4%	3%	-2%	90%
6. CDDs in addition to HDDs	67%	7%	4%	5%	-2%	82%
7. CDDs instead of HDDs	72%	7%	4%	5%	-2%	87%
8. Binned HDDs x Year FEs	68%	9%	4%	4%	-1%	84%
9. Census Region x Year FEs	77%	9%	4%	4%	-1%	93%
10. Census Division x Year FEs	85%	8%	4%	4%	-1%	100%
11. Cubic in Income	82%	7%	4%	4%	-2%	96%
12. Including Lag and Lead	80%	7%	5%	4%	-1%	94%
13. Instrumental Variables	69%	7%	5%	4%	-1%	84%
14. Instrumental Variables (w/ lags)	73%	7%	5%	4%	-2%	87%
15. Excluding the Northeast	78%	7%	3%	4%	-1%	91%
16. Excluding Ten Most Rural States	81%	7%	5%	4%	-2%	95%

Note: This table reports the percentage explained by the five hypotheses in the baseline specification and alternative specifications. Row (1) corresponds to the baseline specification in Table 2, column 6. Rows (2) and (3) use the specifications in Table 2, columns 4 and 5, respectively. Row (4) includes a third-order polynomial in HDDs. Row (5) includes a flexible binned specification for HDDs. Rows (6) and (7) include CDDs in addition to and instead of HDDs, respectively. Rows (8), (9), and (10) include interaction terms between year fixed effects and binned HDDs, region fixed effects, and division fixed effects, respectively. Row (11) includes a third-order polynomial in household income. Row (12) includes a one-year lag and a one-year lead for electricity prices. Row (13) instruments for residential energy prices using crude oil prices, U.S. natural gas wholesale prices, and U.S. coal prices (bituminous, subbituminous, lignite, and anthracite), all measured at the national level. Row (14) adds one-year lags of residential energy prices as additional instruments. Finally, when comparing predicted choices to actual choices, rows (15) and (16) exclude the Northeast and the ten states with the highest proportion of rural households (ME, VT, WV, MS, MT, AR, SD, KY, AL, ND), respectively.

Table 4: Heating System Choice Model

	Estimated Coefficients	Implied Marginal Effects
Annual Energy Expenditures, in 1000s	-1.31**	-0.33**
	(0.31)	(0.08)
Electric Heating System x		
Household Income, 100,000s	-0.18**	-0.04**
	(0.02)	(0.01)
Heating Degree Days, 1000s	-0.26**	-0.07**
	(0.09)	(0.02)
Four Bedroom Home	-0.41**	-0.10**
	(0.04)	(0.01)
Five+ Bedroom Home	-0.60**	-0.15**
	(0.08)	(0.02)
Rented, i.e. not owner-occupied	0.36**	0.09**
	(0.08)	(0.02)
Mobile Home	1.47**	0.37**
	(0.16)	(0.04)
Single Family Home, Attached	-0.17	-0.04
	(0.11)	(0.03)
Multi-Unit Home, 2-4 Units	0.49**	0.12**
	(0.09)	(0.02)
Multi-Unit Home, 5+ Units	1.11**	0.28**
	(0.12)	(0.03)
Constant	1.80**	–
	(0.35)	

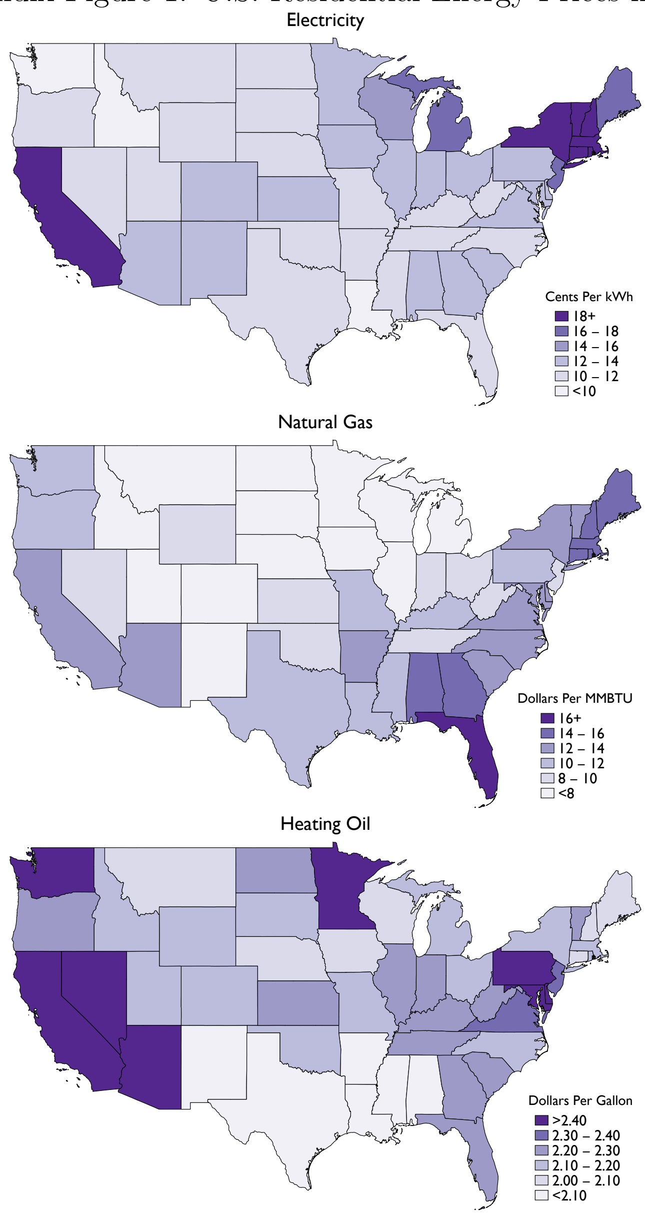
Note: This table reports coefficient estimates and standard errors as well as marginal effects and standard errors from a conditional logit model estimated using maximum likelihood with data on heating system choices from 2,124,140 households. The estimation sample includes all homes that are heated with electricity or natural gas and under ten years old in the American Community Survey 2000-2020. Marginal effects are evaluated at the means for all variables, and reflect the implied change in the probability that a household would select electric heat. See the paper for details. The model is estimated using ACS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Table 5: Annual Willingness-to-Pay, Baseline and Alternative Specifications

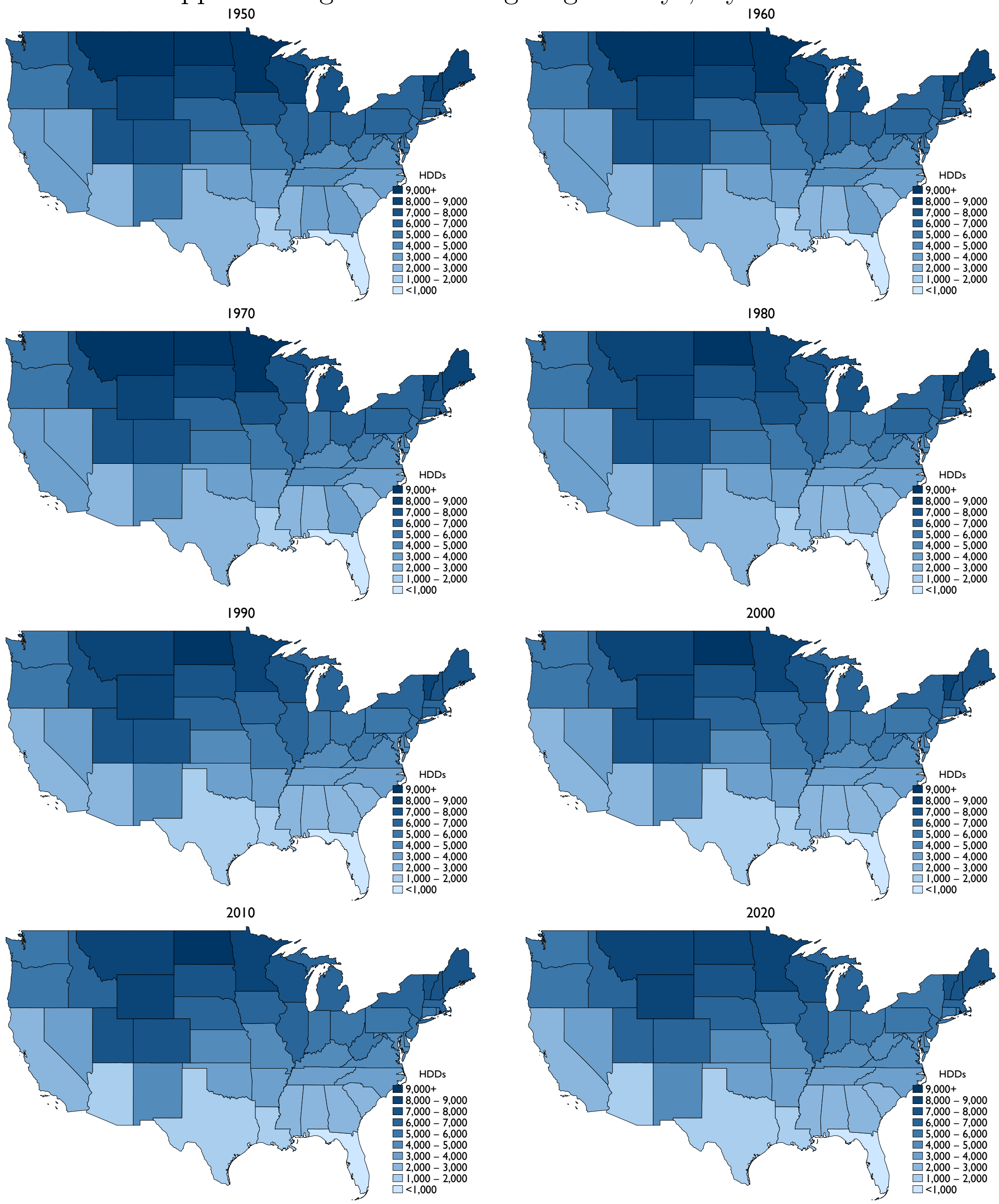
	Entire U.S.	California	Florida	Illinois	New York	Texas
1. Baseline Specification	$656	$537	$177	$1365	$1467	$338
2. Adding Census Division Fixed Effects	$670	$845	$128	$1408	$1365	$360
3. Less Stringent Building Code	$664	$547	$178	$1380	$1490	$341
4. More Multi-Unit Homes	$610	$502	$164	$1269	$1365	$314
5. Fewer Multi-Unit Homes	$702	$573	$190	$1460	$1569	$361

Note: This table reports average annual household willingness-to-pay to avoid an electrification mandate for the entire United States and for the five largest states by population. Row (1) uses the parameters from the baseline heating system choice model described in Table 4. Row (2) adds indicator variables for the nine census divisions. Row (3) assumes a less-stringent building code standard, i.e. 2015 IECC rather than 2018 IECC. Rows (4) and (5) assume that new homes are 40% and 20% multi-unit, respectively, compared to 30% multi-unit in the baseline specification.

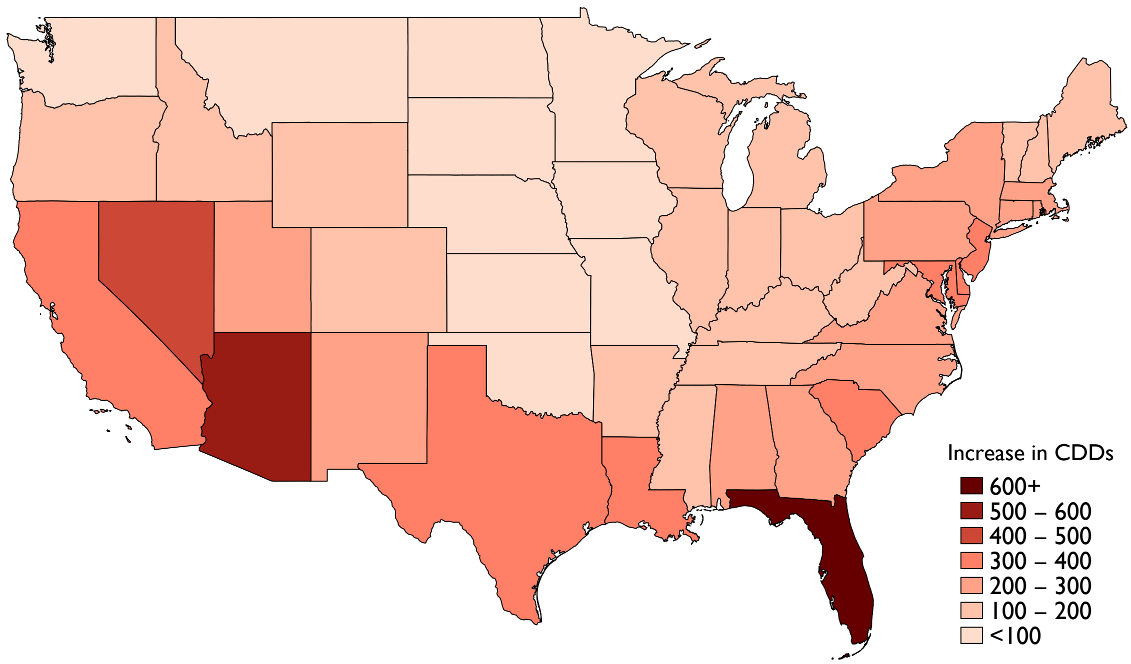
Appendix Figure 1: U.S. Residential Energy Prices in 2020



Appendix Figure 2: Heating Degree Days, By Decade

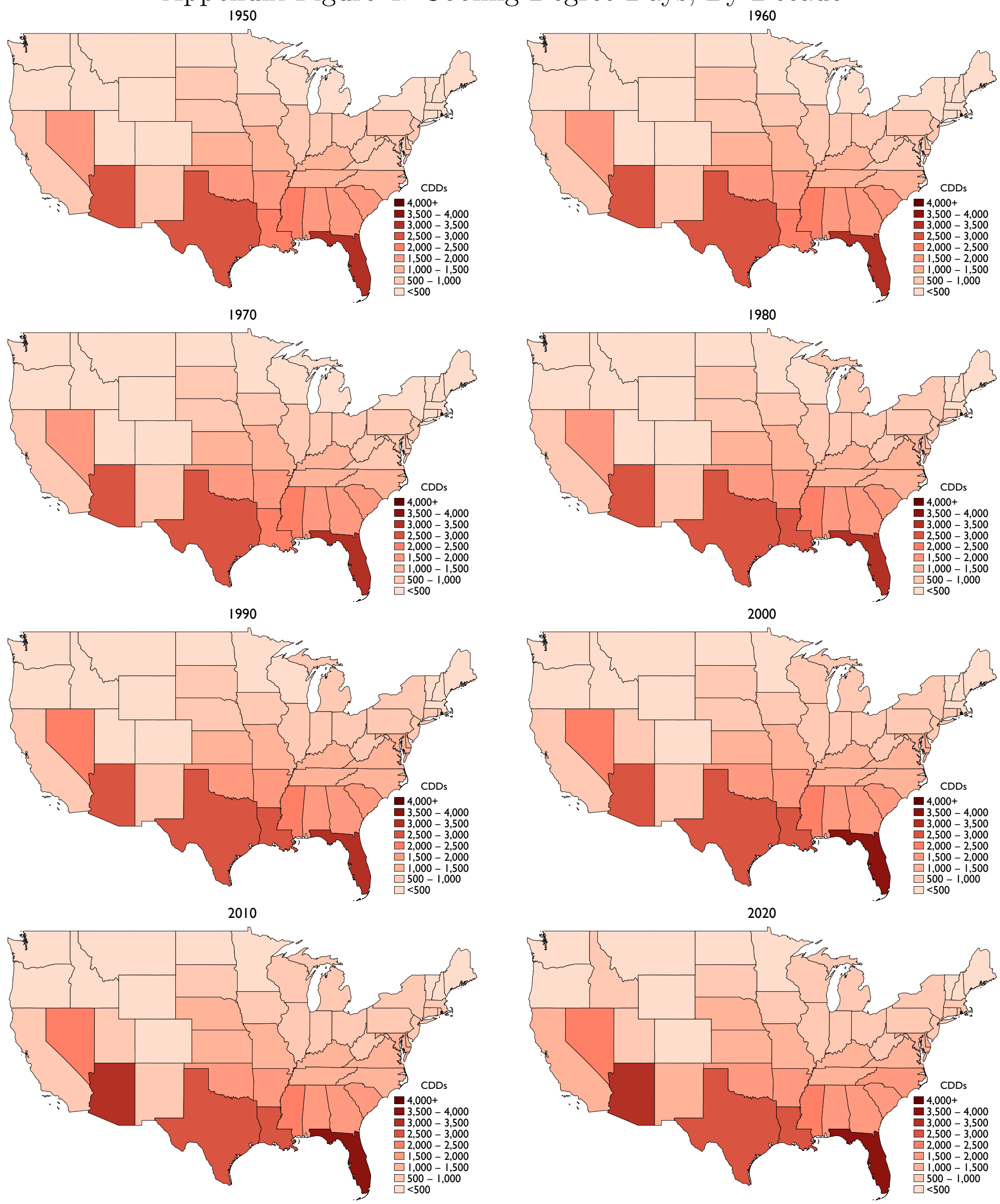


Appendix Figure 3: Increase in Cooling Degree Days Since 1950

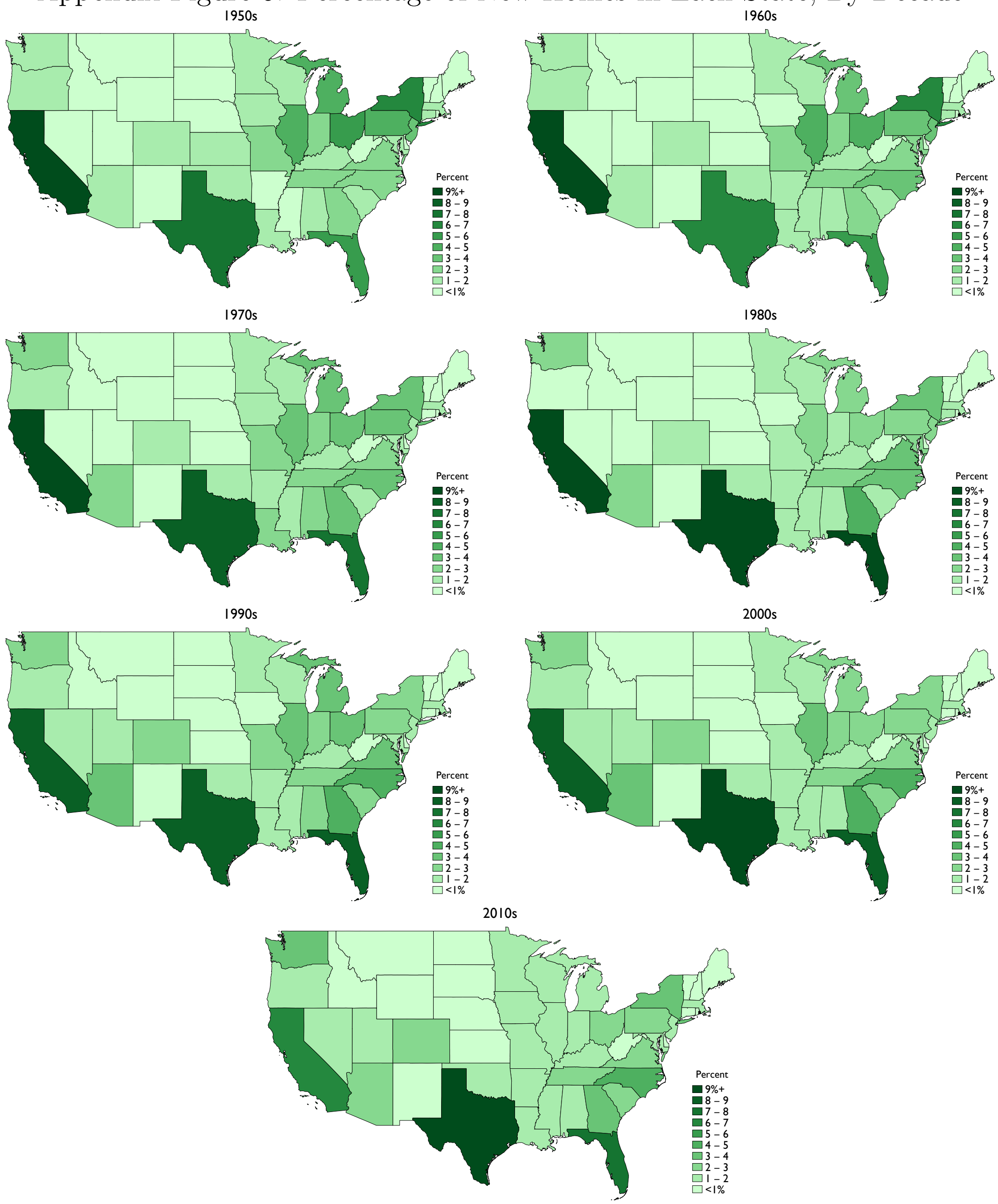


Notes: This figure describes the change in annual cooling degree days (CDDs) between 1950 and 2020. For example, Minnesota had 400 CDDs in 1950 and 500 CDDs in 2020, for an increase of 100 CDDs. Florida, in contrast, had 3,000 CDDs in 1950 and 3,700 CDDs in 2020, for an increase of 700 CDDs. On average, CDDs increased by 23% between 1950 and 2020. These data are based on annual state-level data from NOAA National Centers for Environmental information (2022). Rather than use the raw data which reflect a large amount of year-to-year variation, all analyses in the paper are based on fitted values from a linear time trend estimated separately by state.

Appendix Figure 4: Cooling Degree Days, By Decade

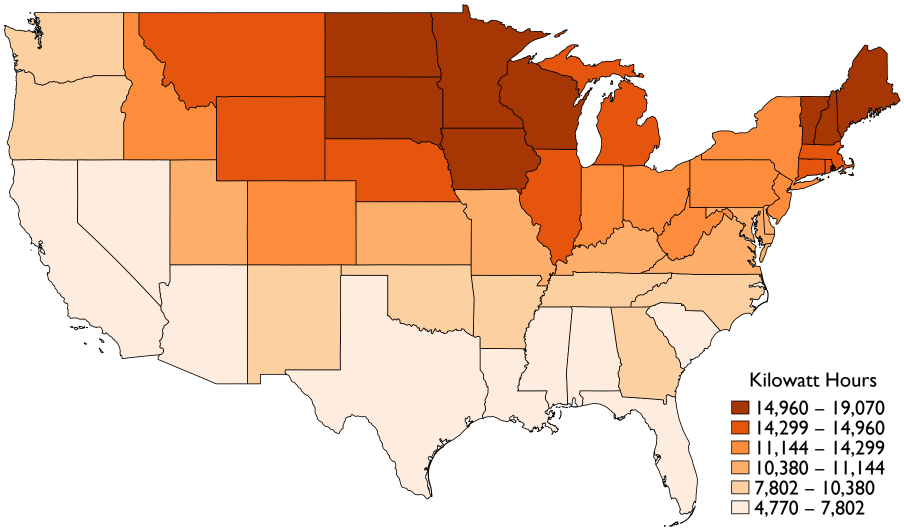


Appendix Figure 5: Percentage of New Homes in Each State, By Decade

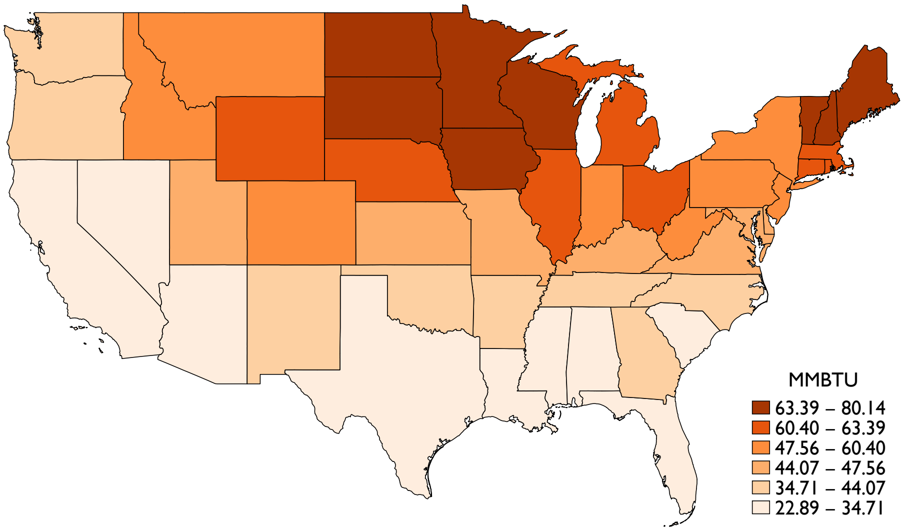


Appendix Figure 6: Energy Consumption for Heating

A. Annual Electricity Consumption for Homes Heated With Electricity



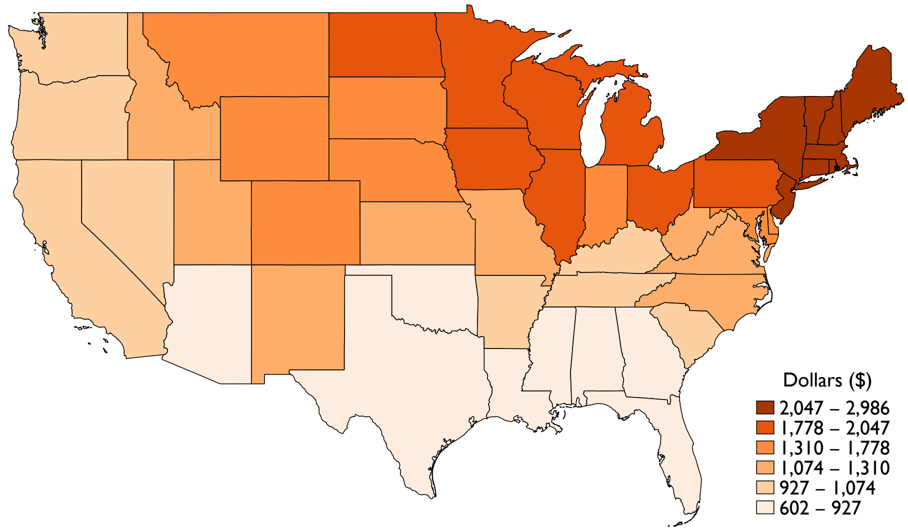
B. Annual Natural Gas Consumption for Homes Heated With Natural Gas



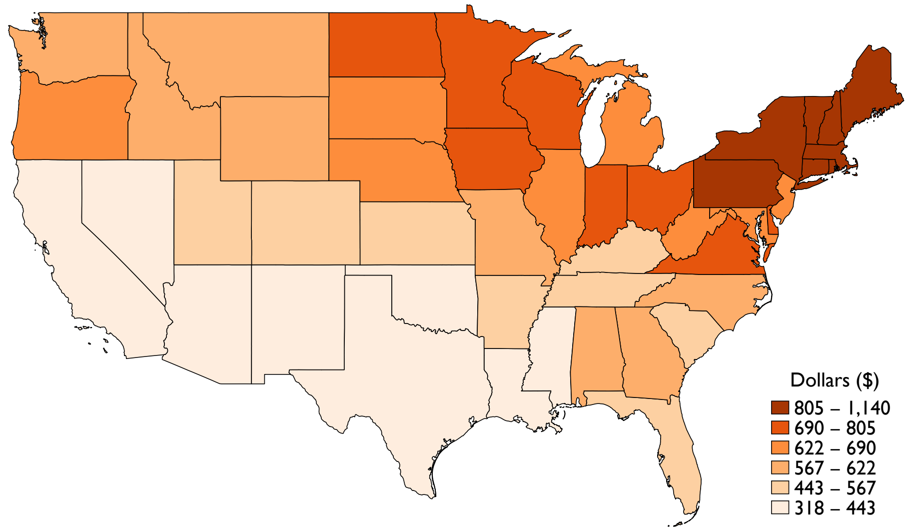
Notes: These maps plot average annual electricity and natural gas consumption for heating for homes heated with electricity and natural gas, respectively. The underlying simulation output from U.S. Department of Energy (2021) describes household electricity and natural gas consumption by end use under a variety of scenarios for eight climate zones and three moisture zones. These averages reflect predictions for space and water heating for single- and multi-unit homes, weighted 70% and 30% respectively, based on homes with a crawl space built to the 2018 International Energy Conservation Code (IECC) standard. These data were matched to the predominant climate and moisture zones in each U.S. county (U.S. Department of Energy, 2015) and aggregated to the state level using county-level populations.

Appendix Figure 7: Energy Expenditure for Heating

A. Annual Electricity Expenditures for Homes Heated With Electricity



B. Annual Natural Gas Expenditures for Homes Heated With Natural Gas



Notes: These maps plot average annual electricity and natural gas expenditures for heating for homes heated with electricity and natural gas, respectively. Expenditures were calculated by multiplying average annual energy consumption as plotted in Appendix Figure 6 by average residential energy prices in each state.

Appendix Table 1: Linear Probability Model, More Flexible Specifications

	(1)	(2)	(3)	(4)
Electricity Price, in logs	-0.37**	-0.40**	-0.44**	-0.49**
	(0.07)	(0.09)	(0.06)	(0.06)
Natural Gas Price, in logs	0.20*	0.12	0.15**	0.17**
	(0.08)	(0.09)	(0.05)	(0.05)
Heating Oil Price, in logs	0.08	-0.01	0.02	0.01
	(0.11)	(0.11)	(0.10)	(0.13)
Household Income, 100,000s	-0.02**	-0.02**	-0.02**	-0.02**
	(0.00)	(0.00)	(0.00)	(0.00)
Heating Degree Days, 1000s			-0.06**	-0.06**
			(0.01)	(0.01)
Four Bedroom Home	-0.05**	-0.05**	-0.05**	-0.05**
	(0.01)	(0.01)	(0.01)	(0.01)
Five+ Bedroom Home	-0.09**	-0.09**	-0.08**	-0.08**
	(0.02)	(0.02)	(0.02)	(0.02)
Rented, i.e. not owner-occupied	0.02*	0.02*	0.02**	0.02**
	(0.01)	(0.01)	(0.01)	(0.01)
Mobile Home	0.01	0.01	0.01	0.01
	(0.03)	(0.03)	(0.03)	(0.03)
Single Family Home, Attached	0.03**	0.05**	0.04**	0.04**
	(0.01)	(0.01)	(0.01)	(0.01)
Multi-Unit Home, 2-4 Units	0.12**	0.13**	0.12**	0.12**
	(0.01)	(0.01)	(0.01)	(0.01)
Multi-Unit Home, 5+ Units	0.24**	0.25**	0.24**	0.24**
	(0.02)	(0.02)	(0.02)	(0.02)
Observations	5,498,568	5,498,568	5,498,568	5,498,568
R-squared	0.28	0.30	0.30	0.31

Note: This table reports coefficient estimates and standard errors from four separate least squares regressions. In all regressions the dependent variable is an indicator variable for homes for which electricity is the primary form of space heating. All regressions include year fixed effects and Census Division fixed effects, as in the baseline estimates in the last column of Table 2. Column (1) replaces heating degree days with a flexible binned specification for HDDs, e.g. 2000-3000, 3000-4000, etc. Column (2) adds interaction terms between binned HDDs and year fixed effects. Columns (3) and (4) go back to the standard linear specification for HDDs, but add interaction terms between year fixed effects and census region and census division fixed effects, respectively. All regressions are estimated using census and ACS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Appendix Table 2: Alternative Specifications for Electricity Price

	(1)	(2)	(3)	(4)
Current Price	-0.42**			-0.59**
	(0.06)			(0.22)
One Year Lag		-0.40**		0.21
		(0.06)		(0.20)
One Year Lead			-0.41**	-0.04
			(0.06)	(0.12)
Observations	5,498,568	5,498,568	5,497,494	5,497,494
R-squared	0.29	0.28	0.29	0.29
Cumulative Effect	-0.42**	-0.40**	-0.41**	-0.42**
	(0.06)	(0.06)	(0.06)	(0.06)
Other Energy Prices, Household Income	Yes	Yes	Yes	Yes
HDDs, Housing Characteristics	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Census Division Fixed Effects	Yes	Yes	Yes	Yes

Note: This table reports coefficient estimates and standard errors from four separate least squares regressions. Column (1) is the baseline specification, identical to the results in the final column of Table 2. Other specifications substitute a one-year lead or one-year lag or both as indicated. All regressions are estimated using census and ACS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Appendix Table 3: Instrumental Variables Specification for Linear Probability Model

	OLS	IV Lags	IV Lags	IV Wholesale Prices	IV Both
	(1)	(2)	(3)	(4)	(5)
Electricity Price, in logs	-0.42**	-0.39**	-0.41**	-0.41**	-0.39**
	(0.06)	(0.06)	(0.04)	(0.03)	(0.04)
Natural Gas Price, in logs	0.21**	0.25**	0.10	0.04	0.14**
	(0.07)	(0.08)	(0.06)	(0.06)	(0.05)
Heating Oil Price, in logs	0.07	0.25	0.14**	0.16**	0.10**
	(0.10)	(0.21)	(0.04)	(0.02)	(0.03)
Observations	5,498,568	5,498,568	5,498,568	5,498,568	5,498,568
R-squared	0.29	0.28	0.27	0.27	0.27
Year Fixed Effects	Yes	Yes	No	No	No
Household Income	Yes	Yes	Yes	Yes	Yes
HDDs, Housing Characteristics	Yes	Yes	Yes	Yes	Yes
Census Division Fixed Effects	Yes	Yes	Yes	Yes	Yes

Note: This table reports coefficient estimates and standard errors from five separate regressions. Column (1) is the baseline specification estimated using least squares, identical to the results in the final column of Table 2. The remaining columns instrument for residential electricity, natural gas, and heating oil prices. Columns (2) and (3) instrument using the one-year lag of residential prices. Column (4) instruments using crude oil prices, U.S. natural gas wholesale prices, and U.S. coal prices (bituminous, subbituminous, lignite, and anthracite). These prices are all measured at the national level, and all from EIA. For example, the data on coal prices comes from EIA's Annual Coal Report 2019, Table ES-4, which provides data back to 1949. Column (5) uses both sets of instruments. These wholesale price instruments do not vary cross-sectionally so year fixed effects cannot be included in columns (4) or (5). All regressions are estimated using census and ACS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Appendix Table 4: Decomposition Analysis, Baseline Estimates with Standard Errors

Energy Prices	82%
	(16%)
Geography	7%
	(2%)
Housing Characteristics	4%
	(1%)
Climate	4%
	(1%)
Household Income	-2%
	(<1%)

Note: This table reports the percentage explained by each of the five hypotheses. This decomposition uses the regression estimates from Table 2, column 6. See Figure 5 for figures corresponding to these five counterfactual analyses. Standard errors in parentheses were estimated using a block bootstrap by state with 100 replications.

Appendix Table 5: Average Willingness-to-Pay By State

1. Florida	$177	(40)	25. Idaho	$883	(405)
2. Louisiana	$237	(51)	26. Indiana	$901	(250)
3. Arizona	$273	(68)	27. Nebraska	$1,017	(303)
4. Alabama	$311	(87)	28. Utah	$1,098	(416)
5. Mississippi	$314	(77)	29. Ohio	$1,119	(247)
6. South Carolina	$335	(92)	30. Colorado	$1,152	(363)
7. Texas	$338	(75)	31. Pennsylvania	$1,204	(310)
8. Georgia	$381	(90)	32. Wyoming	$1,269	(548)
9. Arkansas	$403	(98)	33. South Dakota	$1,287	(398)
10. Oklahoma	$418	(129)	34. Iowa	$1,290	(317)
11. North Carolina	$449	(112)	35. New Jersey	$1,294	(219)
12. Tennessee	$456	(130)	36. Montana	$1,352	(611)
13. Nevada	$473	(125)	37. Illinois	$1,365	(328)
14. Kentucky	$482	(133)	38. Wisconsin	$1,412	(417)
15. California	$537	(91)	39. Michigan	$1,441	(315)
16. Oregon	$545	(204)	40. Rhode Island	$1,447	(204)
17. West Virginia	$557	(183)	41. New York	$1,467	(239)
18. Washington	$575	(190)	42. North Dakota	$1,494	(607)
19. Virginia	$630	(176)	43. Massachusetts	$1,524	(276)
20. New Mexico	$639	(150)	44. Connecticut	$1,565	(245)
21. Missouri	$670	(189)	45. Minnesota	$1,679	(583)
22. Kansas	$764	(218)	46. Maine	$1,739	(388)
23. Maryland	$789	(195)	47. New Hampshire	$1,866	(276)
24. Delaware	$819	(194)	48. Vermont	$1,900	(425)

Note: This table reports the average annual willingness-to-pay to avoid an electrification mandate per household in dollars. Willingness-to-pay is reported for the 48 continental states, in ascending order. Standard errors in parentheses were estimated using a block bootstrap by state with 100 replications.