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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 39% in 2018. 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 $300 annually on average. Household 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 reducing carbon dioxide emissions through electrification, and underscore the importance of pricing energy efficiently.

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.[3]

Policymakers are increasingly turning to electrification in an effort to reduce these externalities. The "electrify everything" movement recently gained attention when Berkeley CA, became the first city in the United States to ban natural gas on all new residential construction.[4] 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.[5]

Proponents argue that electrification is critical if the United States is to sharply re-

[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]For water contamination impacts see, e.g. Olmstead et al. (2013) and Llewellyn et al. (2015). For methane leakage see, e.g, McKain et al. (2015) and Alvarez et al. (2018).

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

[5]"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.

duce carbon dioxide emissions from the building sector.[6] The U.S. electricity sector 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, forthcoming). Critics argue that electric heating costs more than natural gas per unit of heating, so electrification mandates can be expensive and regressive.[7]

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 39% in 2018. 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 58% in real terms since 1950, while average residential prices for natural gas and heating oil have increased 27% and 79%, respectively. Heating choices are shown to be highly sensitive to energy prices

[6] A recent study commissioned by the California Energy Commission concluded that, "building electrification is likely to be a lower-cost, lower-risk long-term strategy compared to renewable natural gas [e.g. hydrogen]. Furthermore, electrification across all sectors, including in buildings, leads to significant improvements in outdoor air quality and public health." (Aas et al., 2020). A report commissioned for the California Air Resources Board includes building electrification among the "least-regrets" approaches for the state to reach carbon neutrality by 2045, with a "significant reduction" in residential consumption of natural gas in all scenarios (Mahone et al., 2020).

[7] "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.

such that the change in energy prices can explain over two-thirds of the increase in electrification.

Geography and climate matter too. Electric heating has lower initial capital costs than other forms of heating, so is preferred by households 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 this factor 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 since 1950 can explain 4% of the increase in electrification. Other housing characteristics like the number of bedrooms end up less quantitatively important. 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 calculate how much households would be willing-to-pay to be able to continue choosing natural gas. Households in warm states tend to prefer electricity anyway, so would be made worse off by less than $300 annually on average. Household in cold states, however, tend to strongly prefer natural gas so would be made worse off by $1000+ annually.

There are very few existing economic analyses of 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 (Dubin and McFadden, 1984; Dubin, 1985; Mansur et al., 2008; Davis and Kilian, 2011).

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.

Although there has been little previous economic analysis of electrification, there are 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 involve intertemporal tradeoffs between upfront investments and operating costs.

In evaluating mandates for new homes, this analysis is also related to an existing literature on building codes. This literature has primarily focused on measuring the energy savings and other benefits of building codes (Aroonruengsawat et al., 2012; Jacobsen and Kotchen, 2013; Levinson, 2016; Kotchen, 2017). With electrification mandates the benefits can be relatively easily quantified using the carbon content of various energy sources, but the costs are poorly understood.

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); Kahn (1988); Davis and Muehlegger (2010); Borenstein and Davis (2012); Borenstein and Bushnell (2018, forthcoming).

The paper proceeds as follows. Section 2 describes the data and presents descriptive statistics on U.S. heating choices, energy prices, new home construction, and climate. Section 3 presents regression estimates on the determinants of electric heating and then performs a decomposition analysis, calculating how much of the increase in electrification can be explained by various factors. 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 ten waves of the U.S. American Community Survey (ACS): 2000, 2002, 2004, 2006, 2008, 2010, 2012, 2014, 2016, and 2018. All of these surveys 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. (2020) for details.

Figure 1 shows the growth in electric heating 1950-2018. Only 1% of U.S. households in 1950 used electricity as their primary heating fuel.[9] By 1960, this had increased 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.

[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.

Electric heating reached 18% in 1980, 26% in 1990, 30% in 2000, 35% in 2010, and 39% in 2018. 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]

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 (1970-2018). Prices include all relevant

[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.

taxes and, where appropriate, delivery charges, and reflect the average price per unit paid by residential customers. All prices 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 58% in real terms since 1950, while average residential prices for natural gas and heating oil have increased 27% and 79%, 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. See Appendix Figure 1 for maps of residential average energy prices as of 2018. 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.

2.3 Heating Degree Days

Heating degree days (HDDs) by state and year since 1950 come from NOAA (2020). 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 conditions, 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.

Figure 3 describes the change in annual HDDs between 1950 and 2019. On average, HDDs decreased by 10% between 1950 and 2019. In absolute terms the HDD decreases are larger in the North. For example, Minnesota had 9,300 HDDs in 1950 and 8,400 HDDs in 2019, for a decrease of 900 HDDs. Florida, in contrast, had 800 HDDs in 1950 and 600 HDDs in 2019, for a decrease of 200 HDDs. See Appendix Figure 2 for maps plotting average HDDs by decade.

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 these retrofits is less clear and not observed in our 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 built during the 1950s. While the 1970 census and later surveys also include homes built in 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, a limitation of the early waves of the ACS and all waves of the census is that they instead provide a discrete range for age. 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. This assignment matters because it determines the energy prices and heating degree days to which each observation is matched. For a given state, energy prices and heating degree days change slowly year-to-year, however, so this imperfect assignment introduces only a small amount of measurement error.

2.5 Descriptive Statistics

Table 1 reports descriptive statistics. The estimation sample includes 4.2 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 53% 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 a 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) increased home construction in 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. Later in the paper, Section 4 introduces a discrete choice model, but for these regression and decomposition analyses, the linear probability model is preferred because it is particularly easy-to-interpret and makes fewer assumptions. Estimates are reported for specifications with and without year fixed effects, and with and without region-, and division- fixed effects.

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 2018, residential electricity prices ranged from 9.6 cents in Louisiana to 21.6 cents in Massachusetts, a difference of 0.81 log points. The model implies that, *ceteris paribus*, an increase in electricity prices of this magnitude would decrease electric heating by 32 percentage points.[12] The estimated coefficients on electricity prices are similar across columns and statistically significant at the 1% level throughout.

[12]These estimates shed light on the long-run price responsiveness of demand for electricity, in contrast to most previous studies of the price elasticity of demand for electricity which 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.

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 0.6 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 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.

The negative coefficient on income is a bit surprising. Electric heating is cleaner than other forms of heating, with no on-site combustion or on-site emissions. Also with electric heating there is no furnace repair, no storage tank, and no need to schedule fuel deliveries as one must do with heating oil. Regardless of the exact explanation, this lack of sensitivity to income implies that income growth over this time period is unlikely to explain more than a small amount of the increase in electrification.

Second, heating degree days have a strong negative impact. In column (6) an additional 1000 HDDs annually decreases electric heating by 6 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 47 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 1950-2018. (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.[13]

Figure 5 plots the results of this decomposition. There are five panels, one for each hypothesis. The black 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 orange line differs across panels – in each case plotting predicted outcomes, holding 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

[13] 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.

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. If one instead holds 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 on the increase in electrification.

Table 3 summarizes the results of the decomposition. Energy prices play a dominant role, explaining 82% of the increase in electrification since 1950. 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.

3.4 Alternative Specifications

Table 4 shows the results from the decomposition analysis with alternative specifications. Overall, results are quite similar across specifications, with energy prices explaining over two-thirds of the increase in electrification throughout.

A couple of alternative specifications merit additional discussion. Rows (4) and (5) 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. See Appendix Figures 3 and 4 for maps. HDDs and CDDs are strongly negatively correlated, and results from the decomposition analysis are similar with either measure or both.

Row (7) 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. See Appendix Table 1 for regression estimates from this multi-year specification.

Rows (8) and (9) report results from instrumental variables specifications. In row (8), residential energy prices are instrumented 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 (9) adds one-year lags of residential energy prices as additional instruments. See Appendix Table 2 for details.

These instrumental variables specifications are motivated by potential concerns about price endogeneity. In particular, one might have been concerned about residential prices reflecting local demand shocks.[14] The results with instrumental variables are quite similar, suggesting that the baseline results are not unduly influenced by price endogeneity.

The instrumental variables results are reassuring, but not entirely unexpected. Price endogeneity is likely to be mitigated in this context because residential energy prices tend to be driven by supply-side factors.[15] 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 prices are determined using rate-of-return regulation and only partly depend on the underlying commodity prices.

Finally, row (10) excludes households from the Northeast when comparing predicted outcomes to actual outcomes. This specification is motivated by potential concerns about the availability of natural gas. 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

[14] 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.

[15] 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.

households in Massachusetts from installing natural gas heating systems (Myers, 2019). Nonetheless, results are quite similar when predictions are compared only for the other three census regions, implying that the results are not driven by the experience in the Northeast.

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 change in utility from requiring households to choose electric heating. The data and key variables are the same as in the linear probability model described early. 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.

The modeling choices in this section are informed by a long history of economists using discrete choice models to describe household-level energy decisions, whether it be for air conditioning (Hausman, 1979), space heating (Dubin and McFadden, 1984; Dubin, 1985), or vehicles (Bento et al., 2009). These models describe intertemporal decisions in which households are making a tradeoff between capital and operating costs in producing household services like thermal comfort and transportation.[16]

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 2000, 88% of new U.S. homes use electricity or natural gas for their primary heating system. Accordingly, the choice set is restricted to include only 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 $u_{ie} > u_{ig}$.

[16] A question which arises in this context is whether households are "myopic" when they make energy choices. Early work by Hausman (1979) and Dubin and McFadden (1984) found heating and cooling choices consistent with high implied discount rates, perhaps indicating information problems or other market failures, but more recent work, including evidence from an analogous literature on automobile purchases has tended to find lower discount rates. See, e.g., Busse et al. (2013); Allcott and Wozny (2014); Sallee et al. (2016); Houde (2018); Myers (2019); Houde and Myers (forthcoming).

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} can be 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}, come from building energy model simulations from U.S. Department of Energy (2021). Output from these simulations includes household electricity and natural gas consumption by end use for homes heated with electricity and natural gas, respectively, under a variety of scenarios for eight climate zones and three moisture zones.[17] These data were then matched to the predominant climate and moisture zones in each U.S. county and aggregated to the state level using county-level populations. See Appendix Figures 6 and 7 for maps of energy consumption and expenditure by state.

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 parameter α_1 reflects households' willingness to trade off heating expenditures against other heating system characteristics, and

[17] These simulations were performed by Pacific Northwest National Laboratory using the *EnergyPlus* model. Predictions for electric space and water heating 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/development/residential/iecc_models` for details.

the parameter vector α_{2e} describes interactions between household characteristics and heating system alternatives. This specification allows households in multi-unit homes to prefer electric heating systems, for example. Finally, the error terms, ϵ_{ie} and ϵ_{ig}, capture unobserved differences across households' 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. In order to focus on relatively recent choices, the model is estimated using homes built within the last ten years of ACS samples 2000, 2002, 2004, 2006, 2008, 2010, 2012, 2014, 2016, and 2018.

4.3 Heating System Choice Estimates

Table 5 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 other 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 large, with a \$1000 increase in annual expenditures decreasing the probability that a household selects that alternative by 35 percentage points.

Household income continues to have only a modest impact. The implied marginal effect of a \$100,000 increase in annual household income is to decrease 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 Southwest and, in particular, in Florida.

The estimates from the heating system choice model are used to calculate 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 Willingness-to-Pay Estimates

Figure 7 plots average willingness-to-pay by state. Households in warm states throughout the Southeast tend to prefer electric heating anyway, so are willing-to-pay less than \$300 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 \$120. In Texas the average willingness-to-pay is \$342.

The West Coast is more temperate, with willingness-to-pay \$806 in California, \$741 in Oregon, and \$767 in Washington. The somewhat higher willingness-to-pay in California reflects, in part, the state's higher than average electricity prices. By the same argument, willingness-to-pay tends to be lower in states with below average electricity prices including Kentucky (\$316), West Virginia (\$343), and Oklahoma (\$390).

Household in cold states tend to strongly prefer natural gas so are willing-to-pay \$1000+ annually on average to avoid an electrification mandate. This includes populous states like Pennsylvania (\$1,094), Ohio (\$1,111), New York (\$1,325), and Illinois (\$1,343). Finally, willingness-to-pay is above \$1500 annually in particularly cold states Wyoming (\$1,517), Vermont (\$1,565), New Hampshire (\$1,567), and Montana (\$1,620). See Appendix Table 3 for a complete list of states with willingness-to-pay estimates.

Table 6 reports results for the baseline model and alternative specifications. Robustness analyses were already performed for the linear probability model so only a few additional alternative specifications are considered. In row (2), willingness-to-pay increases when new homes are assumed to be built to a less stringent building code. This reflects a complementarity between energy-efficiency and electrification; electrification mandates are cheaper when homes use less energy.

Rows (3) and (4) explore alternative assumptions about multi-unit homes. One of the interesting findings from the analysis is that multi-unit homes are considerably more likely to use electricity. Accordingly, willingness-to-pay is decreasing in the fraction of homes that are multi-unit. Multi-unit homes tend to be good candidates for electric heating so are low hanging fruit for electrification mandates.

4.5 Discussion

Before proceeding, it is important to note a couple of important caveats. First, these estimates depend on the parametric assumptions of the model. The conditional logit model makes strong assumptions about the functional form of the error term, for example. To the extent that these assumptions are violated, the estimates of willingness-to-pay will be biased.

Second, the 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 relatively 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.

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.[18] 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 relatively low 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 we should expect additional technological innovation

[18] U.S. Department of Energy, Energy Information Administration, "U.S. Households' Heating Equipment Choices are Diverse and Vary by Climate Region", April 6, 2017, https://www.eia.gov/todayinenergy/detail.php?id=30672#.

in 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.

Third, 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.[19] 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.

Fourth, 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 mar-

[19]According to the author's calculations using 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.

gins of adjustment goes beyond the scope of the study, but they will tend to reduce the overall economic costs of an electrification mandate.

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 dramatic growth in electric heating from only 1% of homes in 1950, to 8% in 1970, to 26% in 1990, to 39% in 2018. This dramatic increase in electrification has received very little attention from economists or other researchers.

The paper asked two research questions: (1) What explains the large increase in electrification of U.S. residential heating since 1950? and (2) How much would U.S. households be willing-to-pay to avoid an electrification mandate for new homes?

The paper proposed and tested five hypotheses. Of the five possible explanations, 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 in electrification. Household income growth, in contrast, is shown to have 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 was estimated to measure the economic cost of an electrification mandate. Households in warm states are shown to be close to indifferent between electricity and natural gas, so would be made worse off by less than \$300 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 results have direct implications for emerging policies aimed at electrification. A substantial existing literature quantifies the economic benefits of fossil fuel abatement. Those benefits can be compared to the costs estimated here to determine where and when electrification mandates would pass a cost-benefit test.

These measures of willingness-to-pay 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.

One implication of the research is that, nationally, it may be a lot easier than is generally believed to encourage electrification. While short of what the United States would need for deep decarbonization, this steady historical trend over the last seven decades means that millions of U.S. households have already electrified. Moreover, the analysis identifies large numbers of additional households for whom adopting electric heating would impose relatively modest costs.

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Figure 1: Growth in Electric Heating

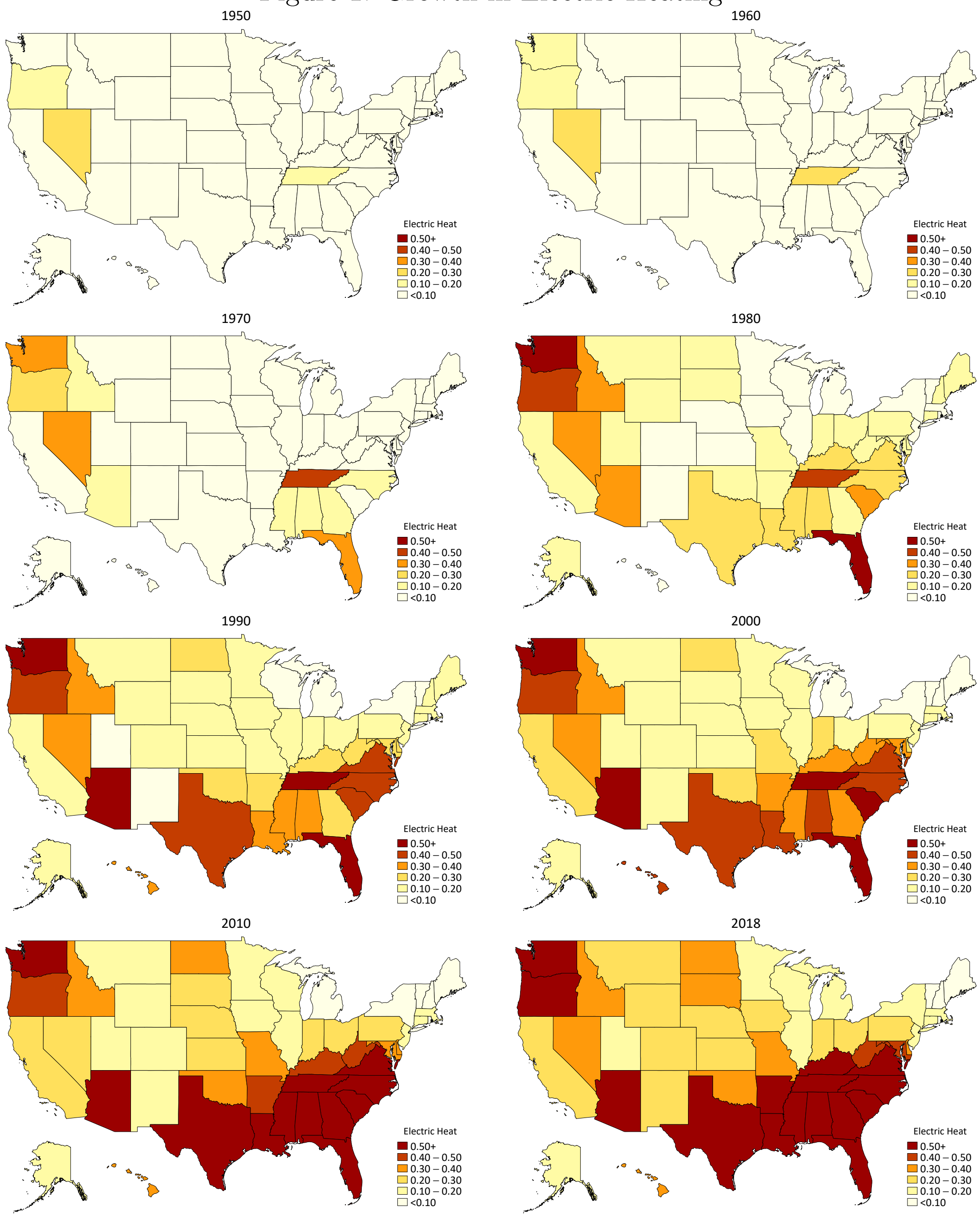
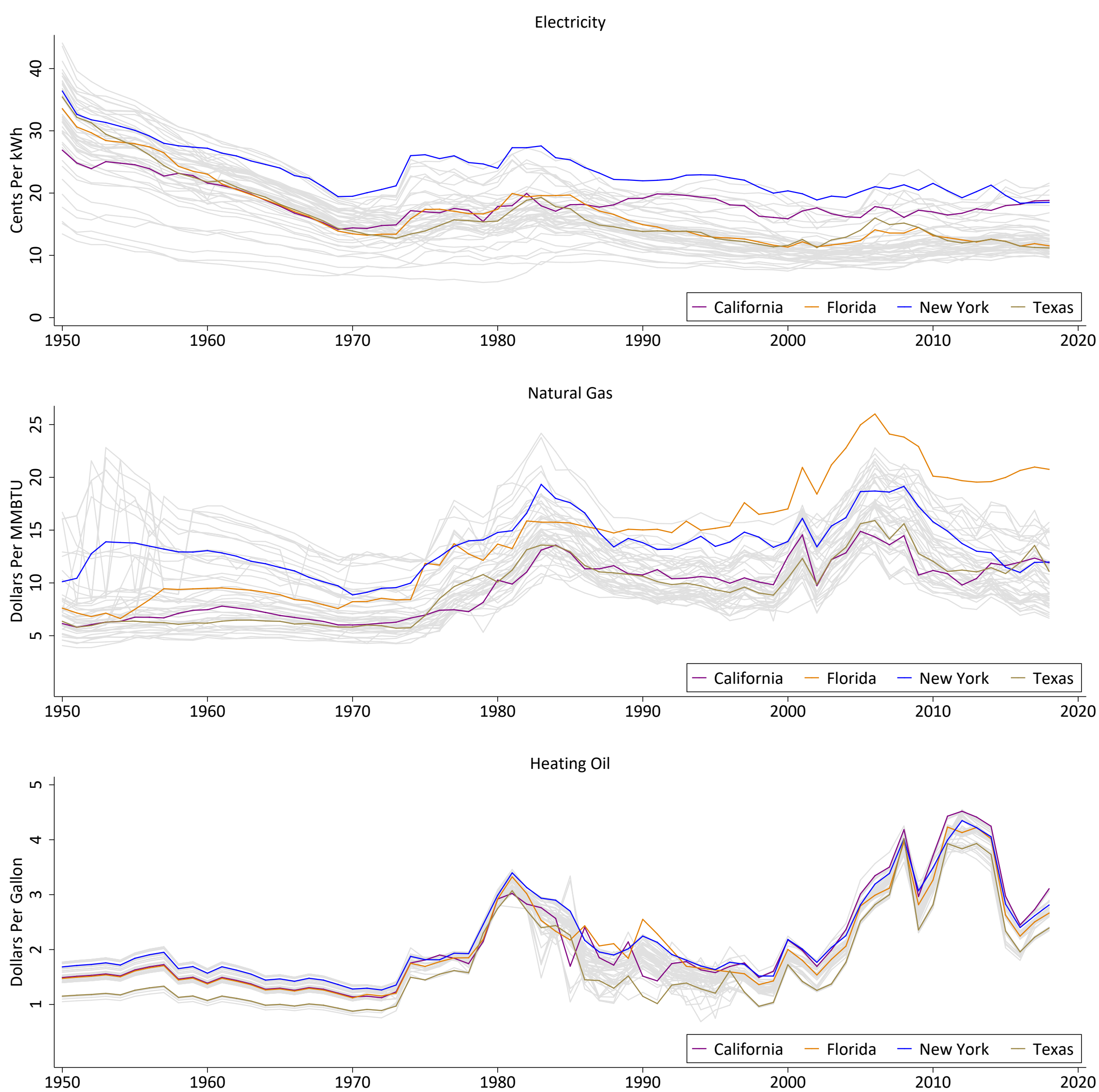
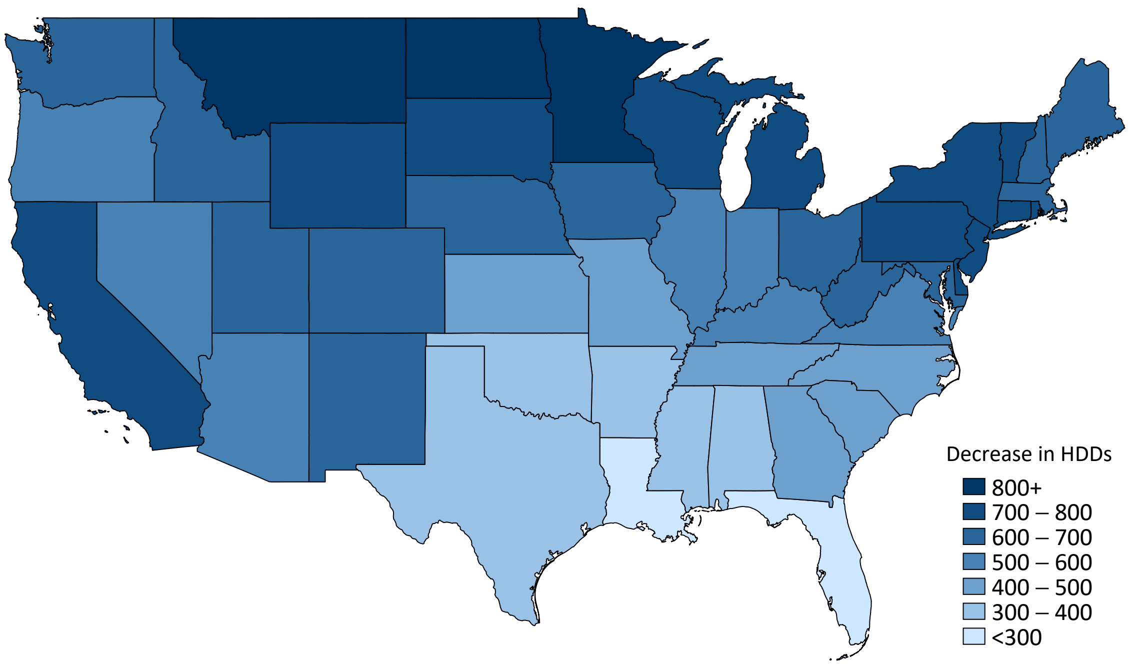


Figure 2: U.S. Residential Energy Prices By State Since 1950



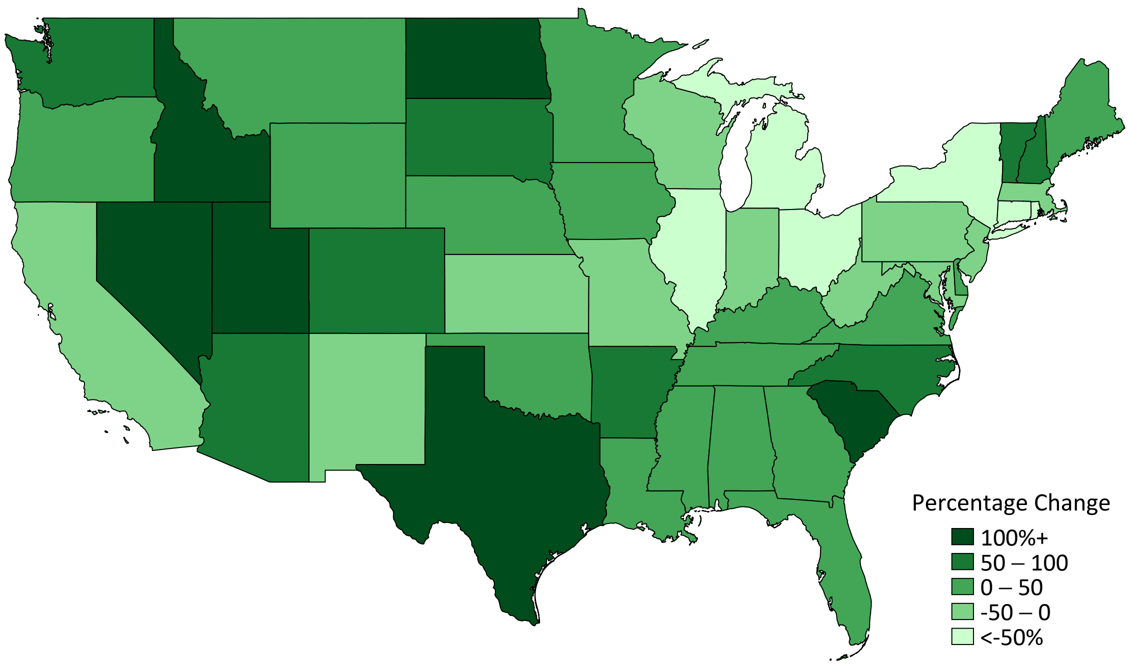
Notes: This figure plots average residential prices by state for electricity, natural gas, and heating oil. Prices are calculated as average annual revenue from residential sales and are plotted for all U.S. states except for Alaska and Hawaii. Data series are labeled for the four largest U.S. states by population (California, Texas, Florida, and New York). 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



Notes: This figure describes the change in annual heating degree days (HDDs) between 1950 and 2019. For example, Minnesota had 9,300 HDDs in 1950 and 8,400 HDDs in 2019, for a decrease of 900 HDDs. Florida, in contrast, had 800 HDDs in 1950 and 600 HDDs in 2019, for a decrease of 200 HDDs. This is based on annual state-level data from NOAA National Centers for Environmental information (2020). However, rather than use the raw data which reflect a large amount of year-to-year variation, these calculations are based on fitted values from a linear time trend estimated separately by state. See Appendix Figure 2 for maps showing HDDs for each decade separately.

Figure 4: Change in New Home Construction Since 1950s



Notes: This figure describes how new home construction has changed at the state level between the 1950s and the 2010s. Specifically, the figure reports the percentage change in the percentage of new homes constructed in each state. For example, Texas had 7% of new home construction in the 1950s, but 16% of new home construction in the 2010s, for a percentage increase of 130%. California in contrast, had 14% of new home construction in the 1950s, and 7% of new home construction in the 2010s, for a percentage decrease of 49%. By this measure Rhode Island had the largest decrease -70% while Nevada had the largest increase +270%. See Appendix Figure 5 for maps showing the distribution of new home construction for each decade separately.

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

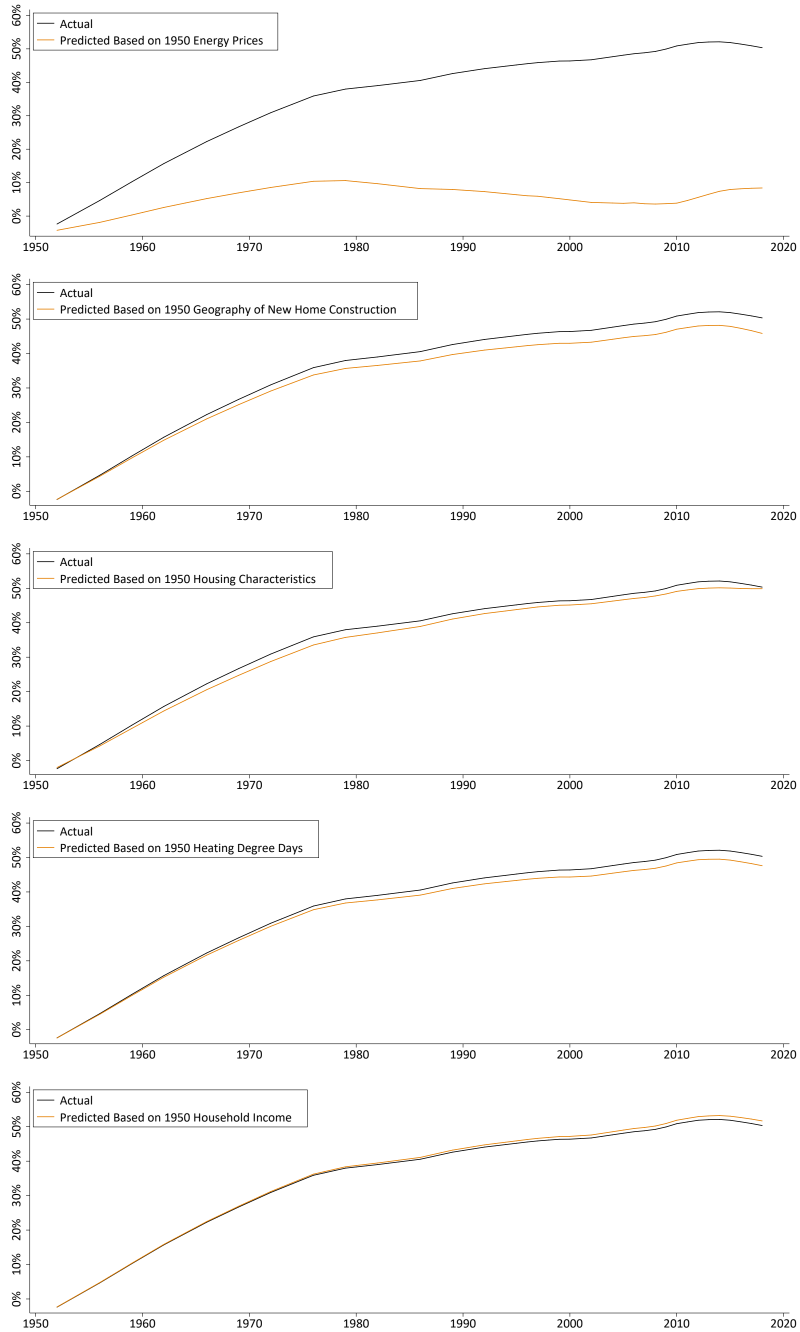
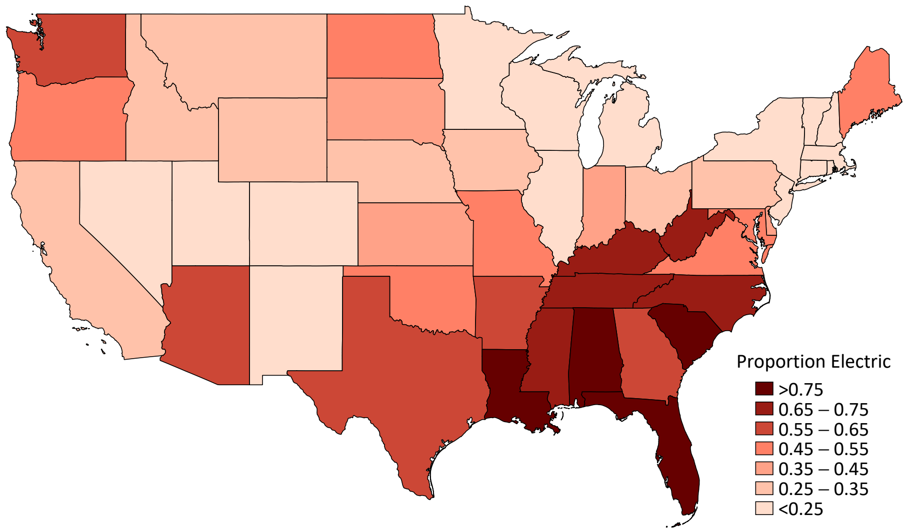


Figure 6: Evaluating the Fit of the Discrete Choice Model

A. Actual Heating System Choices



B. Predicted Heating System Choices

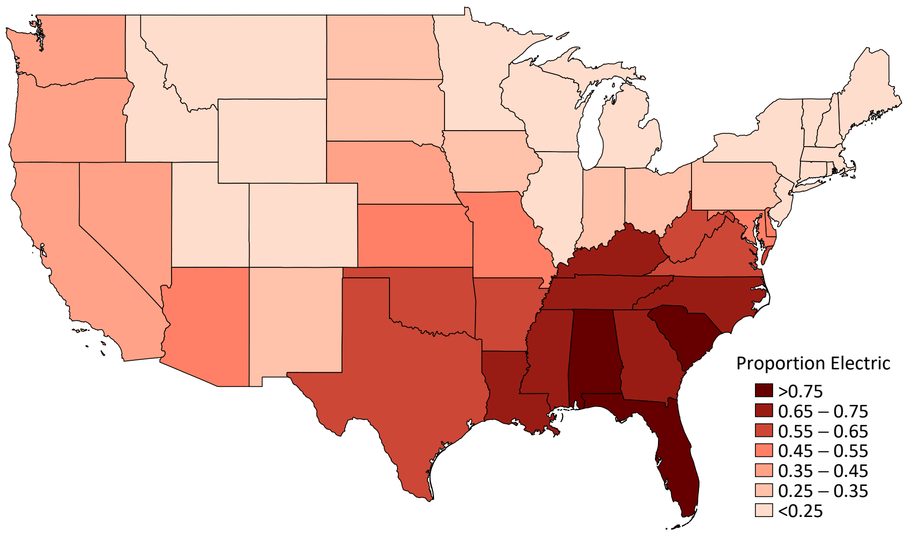


Figure 7: Willingness-to-Pay to Avoid an Electrification Mandate

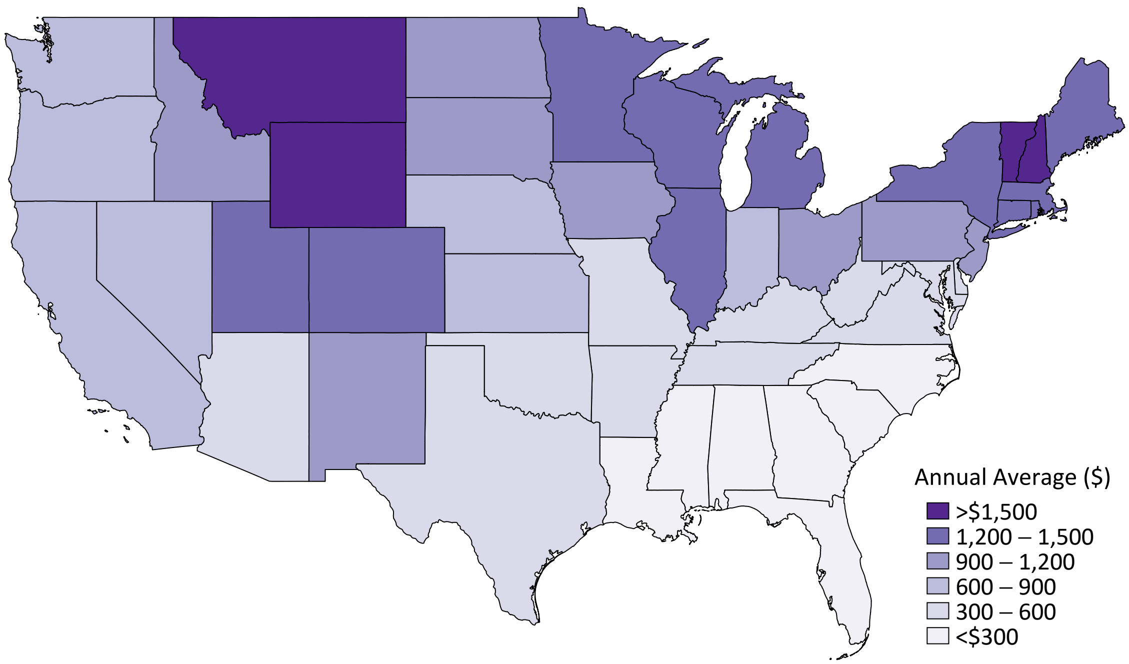


Table 1: Descriptive Statistics

	1950s	1960s	1970s	1980s	1990s	2000s	2010s
A. Primary Energy Source for Heating (percent)							
Electricity	4	18	41	47	42	45	53
Natural Gas	53	56	40	37	44	45	39
Heating Oil	32	17	8	4	3	2	1
Other	12	8	11	11	10	8	7
B. Residential Energy Prices							
Electricity (cents per kWh)	25.8	18.7	15.3	17.6	13.7	12.2	13.0
Natural Gas ($ per 1000 cuft)	8.9	8.7	8.3	13.4	10.6	14.1	12.5
Heating Oil ($ per gallon)	1.6	1.3	1.5	2.4	1.6	2.2	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	1.5	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)	61.0	73.9	65.8	79.9	97.9	99.3	106.4
Home Ownership (percent)	78	67	68	63	74	71	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	989	806	146

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 as well as from the American Community Survey samples 2000, 2002, 2004, 2006, 2008, 2010, 2012, 2014, 2016, and 2018. 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)	(0.05)	(0.04)	(0.06)
Natural Gas Price, in logs	0.21**	0.29**	0.18**	0.24**	0.15**	0.21**
	(0.06)	(0.08)	(0.05)	(0.07)	(0.05)	(0.07)
Heating Oil Price, in logs	0.04	-0.08	0.08*	0.08	0.09**	0.06
	(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**	-0.06**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Four Bedroom Home	-0.05**	-0.05**	-0.05**	-0.04**	-0.05**	-0.05**
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Five+ Bedroom Home	-0.10**	-0.08**	-0.10**	-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	0.03	0.02	0.03	0.02
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Single Family Home, Attached	0.04*	0.04**	0.04**	0.04**	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	4,163,308	4,163,308	4,163,308	4,163,308	4,163,308	4,163,308
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: What Explains the Increase in Electrification?

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

Table 4: Alternative Specifications For Decomposition

	Prices	Geography	Housing	Climate	Income	Total
1. Baseline Specification	82%	7%	4%	4%	-1%	96%
2. Census Region FEs	84%	6%	4%	4%	-2%	96%
3. Without Year FEs	73%	7%	5%	4%	-2%	87%
4. CDDs in addition to HDDs	68%	8%	4%	5%	-1%	83%
5. CDDs instead of HDDs	72%	8%	4%	5%	-1%	87%
6. Cubic in Income	82%	7%	4%	4%	-2%	96%
7. Including Lag and Lead	80%	7%	5%	4%	-1%	94%
8. Instrumental Variables	69%	7%	5%	4%	-1%	83%
9. Instrumental Variables (w/ lags)	73%	7%	5%	4%	-2%	87%
10. Excluding the Northeast	70%	10%	4%	3%	-1%	86%

Note: This table reports the percentage explained by the five hypotheses in the baseline specification and nine alternative specifications. The results in row (1) correspond to the baseline specification in Table 2, column 6. Rows (2) and (3) use the specifications in Table 2, columns 4 and 5, respectively. Rows (4) and (5) include CDDs in addition to and instead of HDDs, respectively. Row (6) includes a third-order polynomial in household income. Row (7) includes a one-year lag and a one-year lead for electricity prices. Rows (8) and (9) use instrumental variables specifications with wholesale price instruments and both wholesale price and lagged price instruments, respectively. Finally, row (10) excludes all households from the Northeast when comparing predicted outcomes to actual outcomes.

Table 5: Heating System Choice Model

	Estimated Coefficients	Implied Marginal Effects
Annual Energy Expenditures, in 1000s	-1.40**	-0.35**
	(0.31)	(0.08)
Electric Heating System x		
Household Income, 100,000s	-0.18**	-0.04**
	(0.03)	(0.01)
Heating Degree Days, 1000s	-0.21*	-0.05*
	(0.09)	(0.02)
Four Bedroom Home	-0.43**	-0.11**
	(0.04)	(0.01)
Five+ Bedroom Home	-0.64**	-0.16**
	(0.11)	(0.03)
Rented, i.e. not owner-occupied	0.45**	0.11**
	(0.05)	(0.01)
Mobile Home	1.42**	0.35**
	(0.17)	(0.04)
Single Family Home, Attached	-0.28*	0.07*
	(0.12)	(0.03)
Multi-Unit Home, 2-4 Units	0.50**	0.12**
	(0.09)	(0.02)
Multi-Unit Home, 5+ Units	1.09**	0.27**
	(0.12)	(0.03)
Constant	1.84	–
	(0.53)	

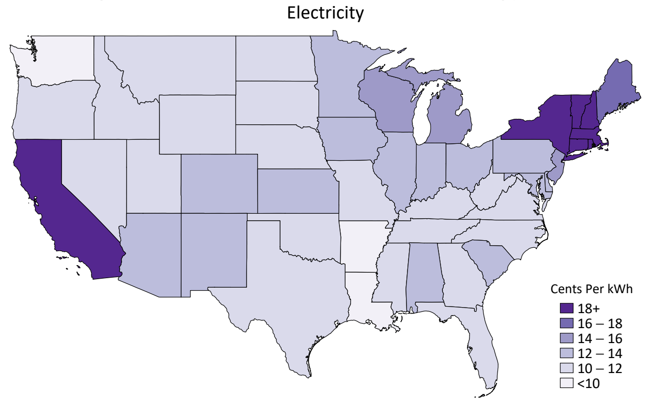
Note: This table reports coefficient estimates and standard errors as well as marginal effects and standard errors from a conditional logit model estimated using maximum likelihood with data on heating system choices from 950,469 households. The estimation sample includes all homes that are heated with electricity or natural gas and under ten years old in the American Community Survey samples 2000, 2002, 2004, 2006, 2008, 2010, 2012, 2014, 2016, and 2018. In addition to the variables listed the model includes indicator variables for the nine census divisions. 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.

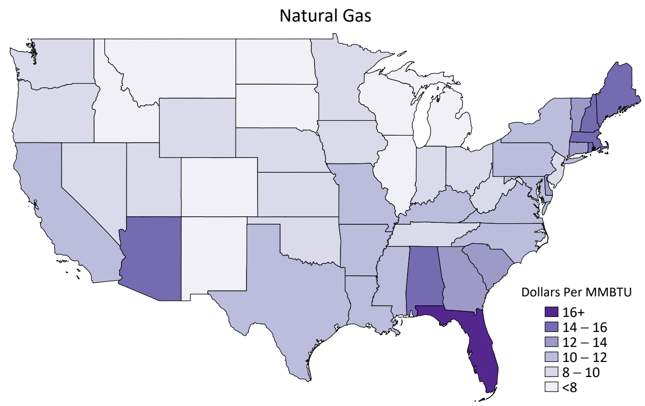
Table 6: Alternative Specifications for Willingness-to-Pay Estimates

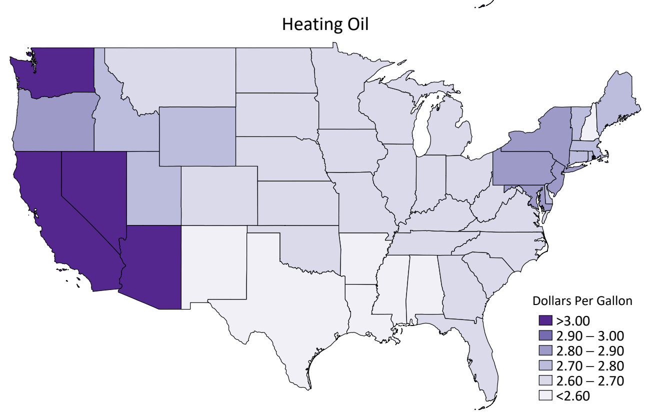
	Entire U.S.	California	Florida	Illinois	New York	Texas
1. Baseline Specification	\$642	\$806	\$121	\$1343	\$1325	\$342
2. Less Stringent Building Code	\$649	\$816	\$121	\$1358	\$1341	\$346
3. More Multi-Unit Homes	\$599	\$753	\$112	\$1253	\$1236	\$320
4. Fewer Multi-Unit Homes	\$685	\$859	\$129	\$1434	\$1414	\$365

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. Results are reported for the baseline specification and for three alternative specifications. Row (1) uses the parameters from the baseline heating system choice model described in Table 5. Row (2) assumes a less-stringent building code standard, i.e. 2015 IECC rather than 2018 IECC. Rows (3) and (4) assume that new homes are 40% and 20% multi-unit, respectively, compared to 30% multi-unit in the baseline specification.

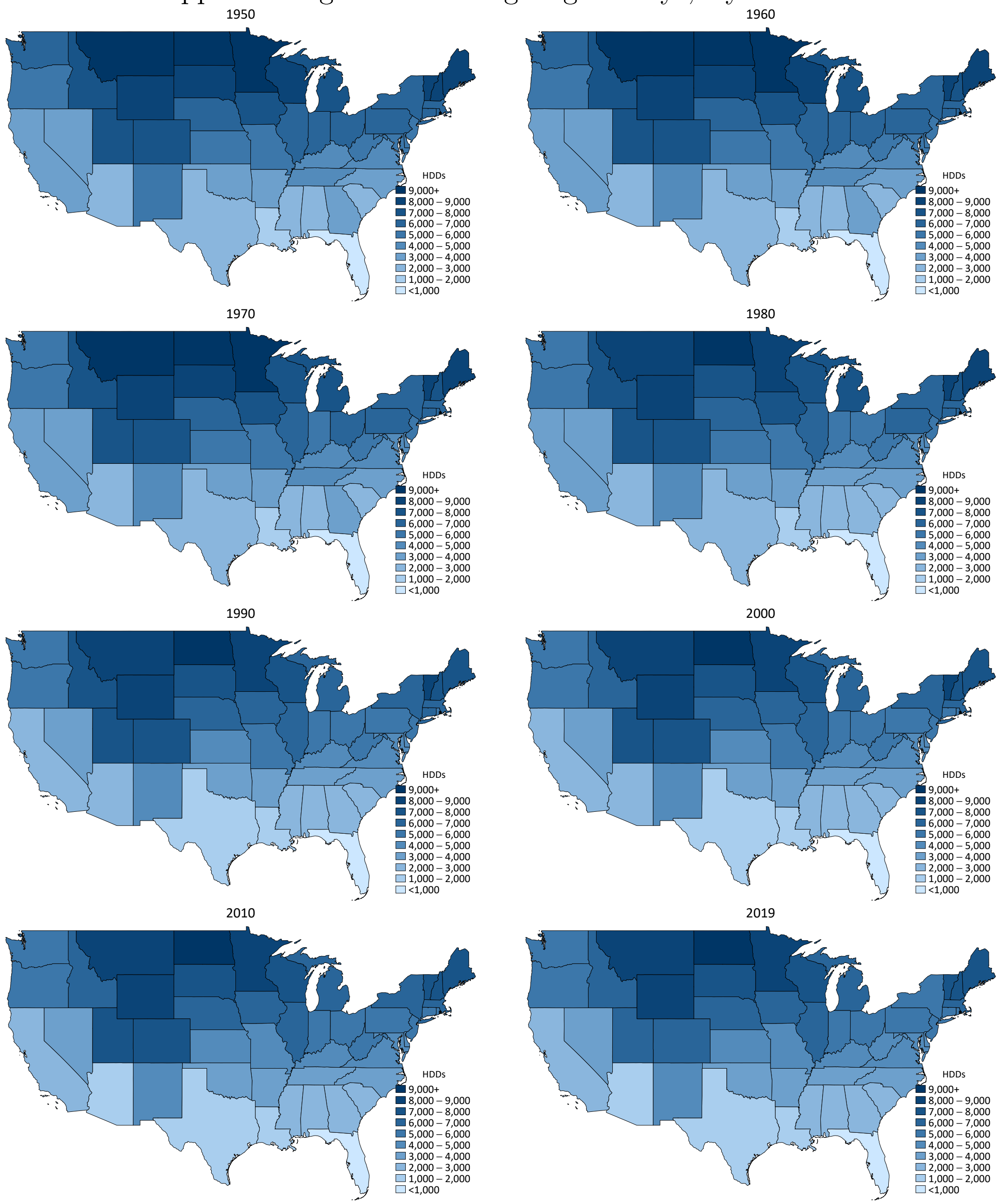
Appendix Figure 1: U.S. Residential Energy Prices in 2018



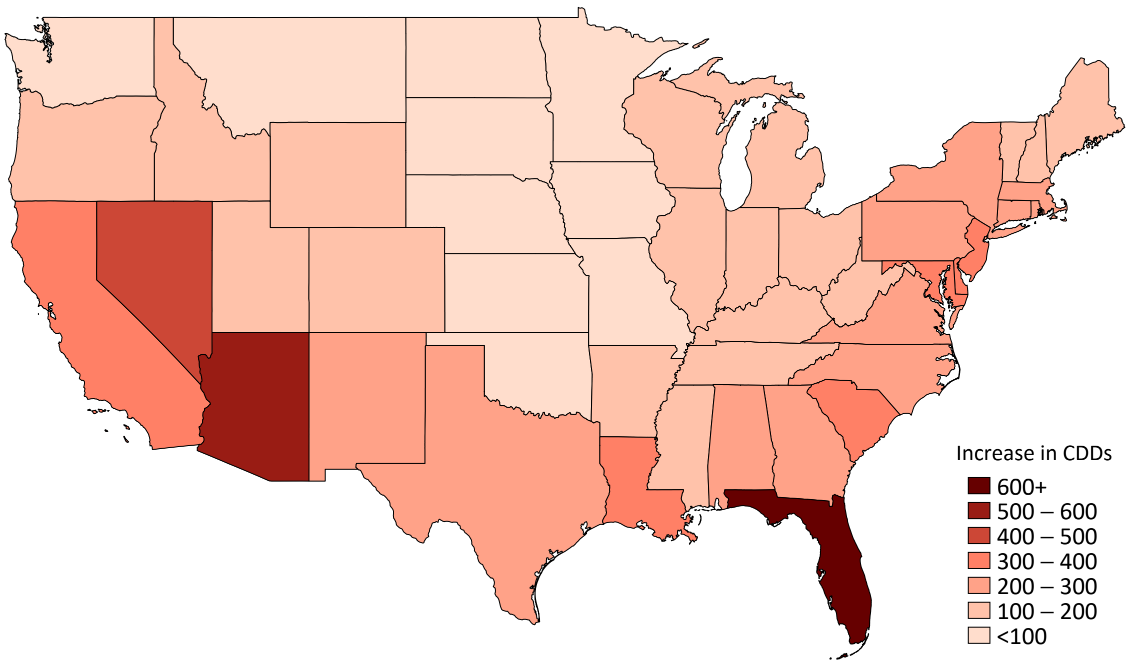




Appendix Figure 2: Heating Degree Days, By Decade

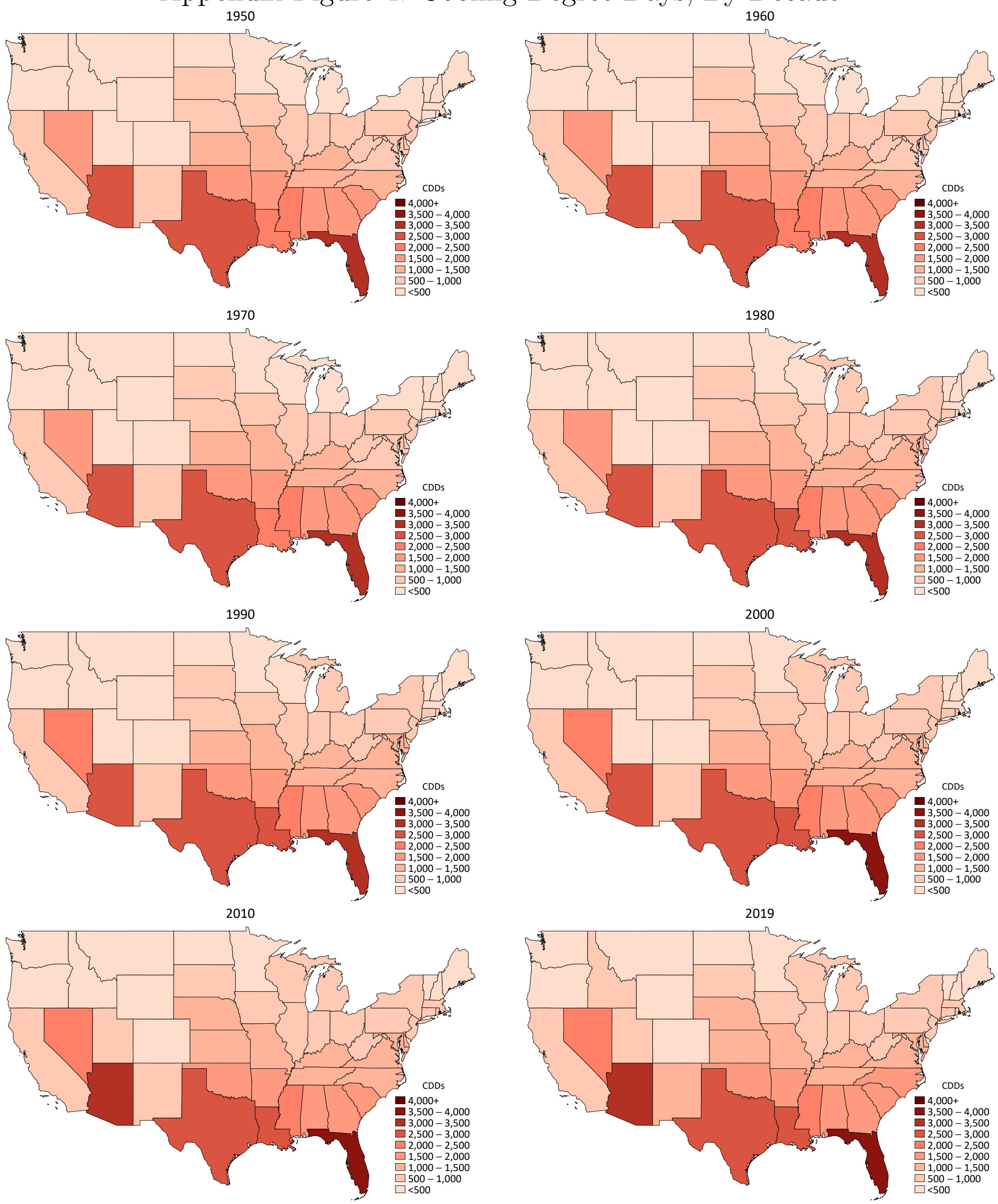


Appendix Figure 3: Increase in Cooling Degree Days Since 1950

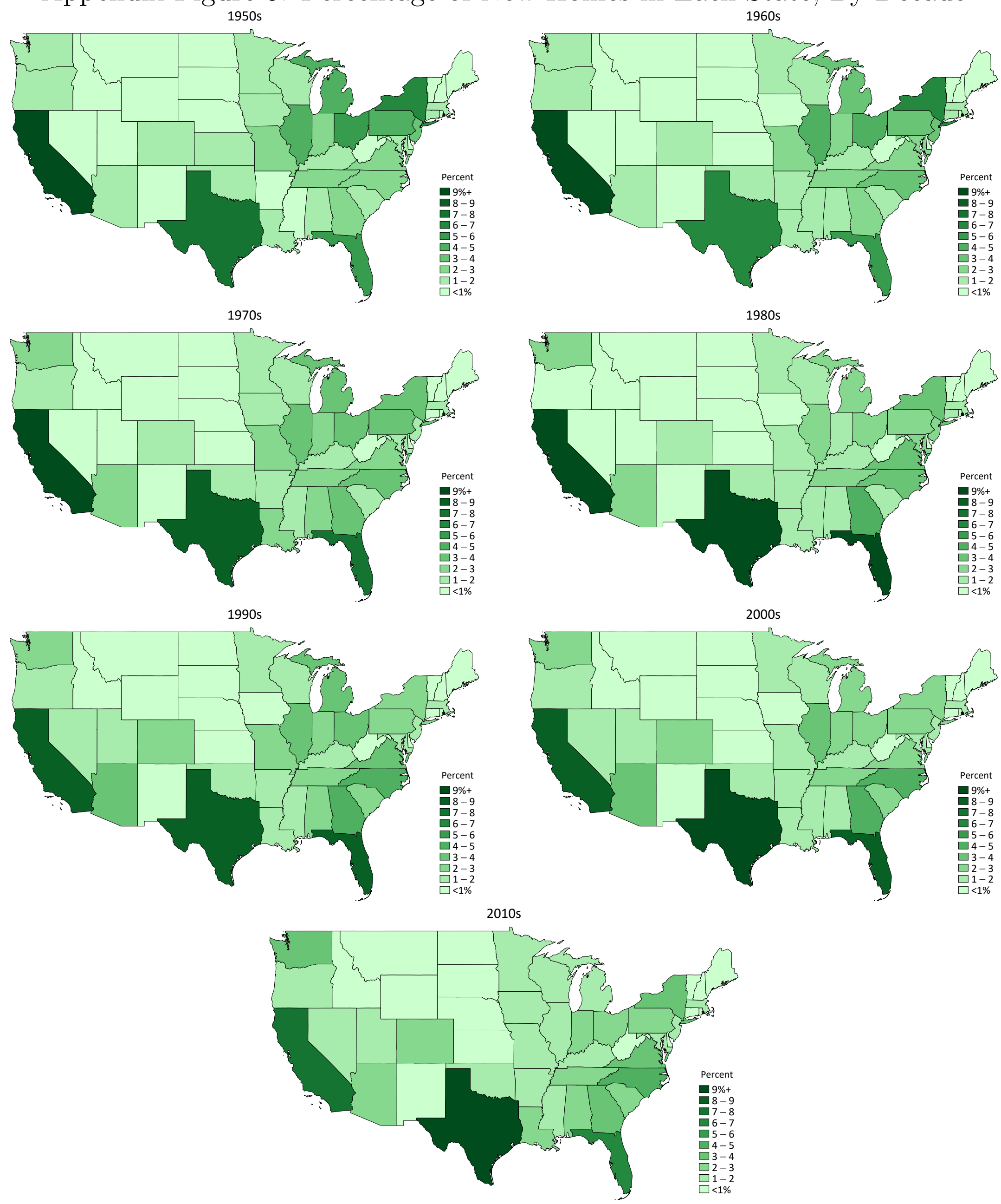


Notes: This figure describes the change in annual cooling degree days (CDDs) between 1950 and 2019. For example, Florida had 3,050 CDDs in 1950 and 3,700 CDDs in 2019, for an increase of 650 CDDs. These statistics are based on annual state-level data from NOAA National Centers for Environmental information (2020). However, rather than use the raw data which reflect a large amount of year-to-year variation, these calculations are based on fitted values from a linear time trend estimated separately by state. See Appendix Figure 4 for maps plotting state-level average CDDs by decade.

Appendix Figure 4: Cooling Degree Days, By Decade

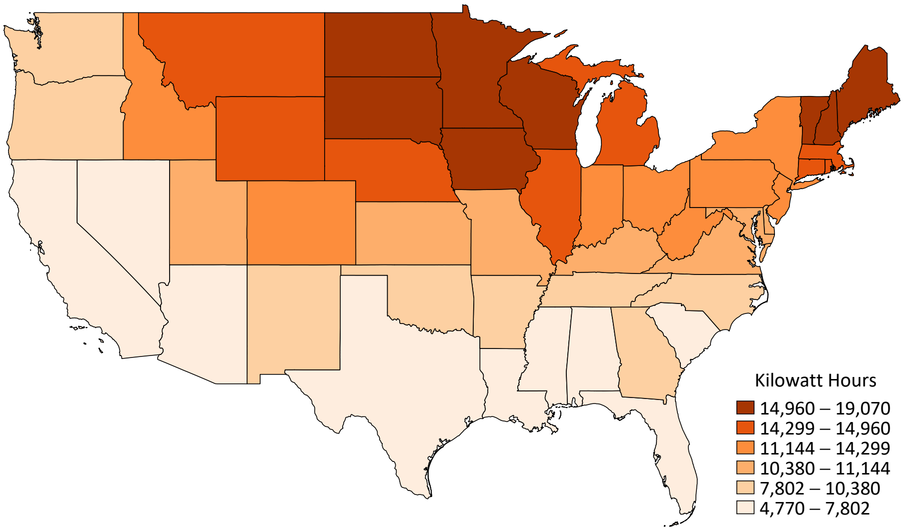


Appendix Figure 5: Percentage of New Homes in Each State, By Decade

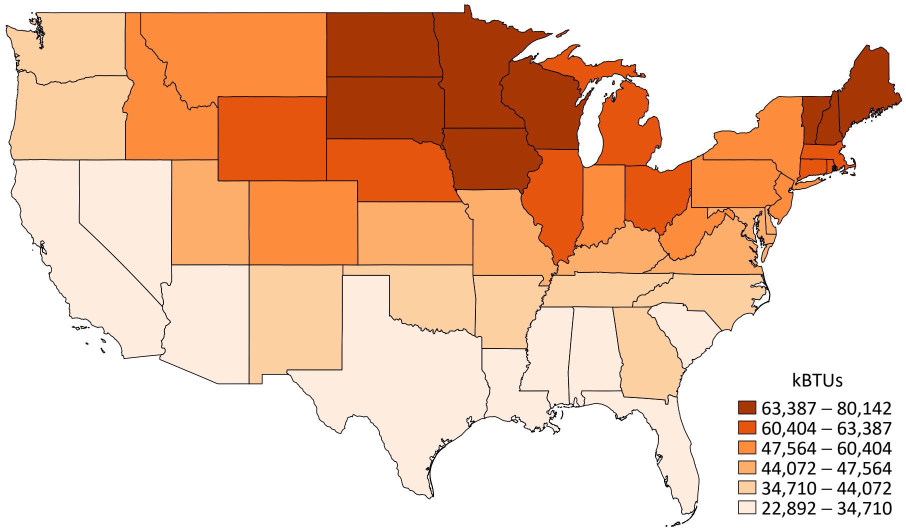


Appendix Figure 6: Average Household Energy Consumption for Heating

A. Annual Electricity Consumption for Homes Heated With Electricity



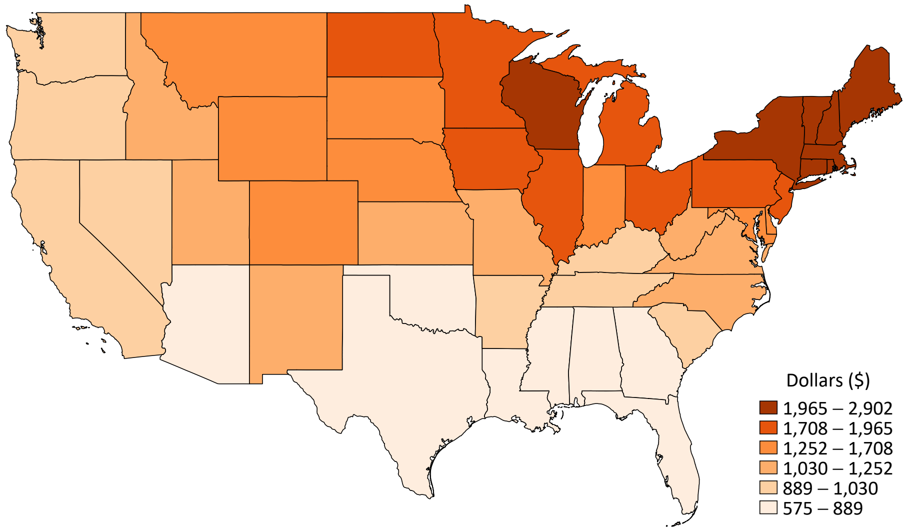
B. Annual Natural Gas Consumption for Homes Heated With Natural Gas



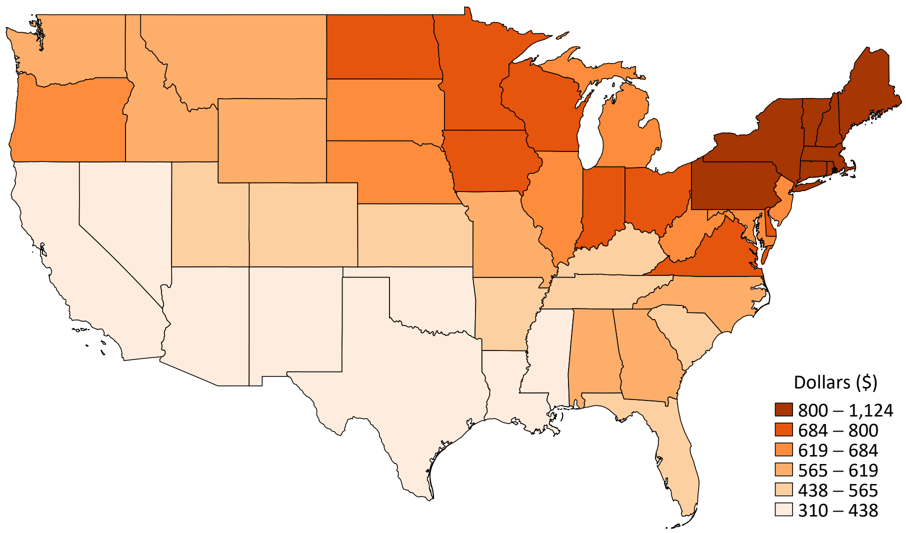
Notes: These maps plot average annual electricity and natural gas consumption for heating for homes heated with electricity and natural gas, respectively. The underlying simulation output from U.S. Department of Energy (2021) describes household electricity and natural gas consumption by end use under 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 then matched to the predominant climate and moisture zones in each U.S. county (U.S. Department of Energy, 2015) and aggregated up to the state level using county-level populations.

Appendix Figure 7: Average Household 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: Alternative Specifications for Electricity Price

	(1)	(2)	(3)	(4)
Current Price	-0.42**			-0.57*
	(0.06)			(0.21)
One Year Lag		-0.40**		0.20
		(0.06)		(0.20)
One Year Lead			-0.42**	-0.05
			(0.06)	(0.12)
Observations	4,163,308	4,163,308	4,161,805	4,161,805
R-squared	0.29	0.28	0.28	0.29
Cumulative Effect	-0.42**	-0.40**	-0.42**	-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 2: 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**	-0.42**	-0.39**
	(0.06)	(0.06)	(0.04)	(0.03)	(0.04)
Natural Gas Price, in logs	0.21**	0.25**	0.09	0.02	0.14**
	(0.07)	(0.08)	(0.06)	(0.06)	(0.05)
Heating Oil Price, in logs	0.06	0.26	0.15**	0.17**	0.10**
	(0.10)	(0.23)	(0.04)	(0.02)	(0.03)
Observations	4,163,308	4,163,308	4,163,308	4,163,308	4,163,308
R-squared	0.29	0.28	0.27	0.26	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 3: Average Willingness-to-Pay By State

1. Florida	$121	25. Indiana	$890
2. Alabama	$214	26. New Mexico	$960
3. South Carolina	$214	27. South Dakota	$984
4. Mississippi	$218	28. Iowa	$1,023
5. Louisiana	$243	29. Pennsylvania	$1,094
6. Georgia	$247	30. Ohio	$1,111
7. North Carolina	$290	31. North Dakota	$1,127
8. Tennessee	$304	32. Idaho	$1,158
9. Kentucky	$316	33. New Jersey	$1,193
10. Texas	$342	34. Rhode Island	$1,207
11. West Virginia	$343	35. Massachusetts	$1,251
12. Arkansas	$379	36. Connecticut	$1,272
13. Oklahoma	$390	37. Minnesota	$1,301
14. Virginia	$412	38. Wisconsin	$1,320
15. Arizona	$509	39. New York	$1,325
16. Missouri	$524	40. Illinois	$1,343
17. Maryland	$532	41. Michigan	$1,386
18. Delaware	$548	42. Utah	$1,398
19. Kansas	$608	43. Maine	$1,405
20. Oregon	$741	44. Colorado	$1,451
21. Nevada	$765	45. Wyoming	$1,517
22. Washington	$767	46. Vermont	$1,565
23. Nebraska	$780	47. New Hampshire	$1,567
24. California	$806	48. Montana	$1,620

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. See the paper for details.