The Economic Determinants of Heat Pump Adoption

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Abstract

A potential concern with subsidies for low-carbon technologies is that they tend to go predominantly to high-income households. Previous research has shown, for example, that the top income quintile receives 60% of subsidies for rooftop solar and 90% of subsidies for electric vehicles. This paper finds that heat pumps are an important exception. Using newly available U.S. nationally representative data, the paper finds that there is remarkably little correlation between heat pump adoption and household income. Nationwide, 15% of U.S. households have a heat pump as their primary heating equipment, and adoption levels are essentially identical for all income levels ranging from the bottom of the income distribution (<$30,000 annually) to the top ($150,000+). Instead, the paper shows that heat pump adoption is strongly correlated with geography, climate, and electricity prices.

Key Words: Low-Carbon Technologies, Carbon Emissions, Distributional Impacts, Efficiency vs Equity
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1 Introduction

Increased deployment of heat pumps plays a central role in most envisioned pathways for U.S. decarbonization (Princeton University, 2021; National Academies, 2021; Williams et al., 2021). U.S. electricity generation has become much less carbon-intensive (Holland et al., 2020), so substituting away from natural gas or other fossil fuels for home heating and towards electric heat pumps offers the potential for large-scale reductions in carbon emissions.

Policymakers are increasingly introducing subsidies for heat pumps in an effort to accelerate this substitution. For example, U.S. households can now receive a federal income tax credit of up to $2,000 for purchasing and installing a heat pump. This marks a considerable increase compared to the $300 tax credit that was available previously. Many states, cities, and utility districts offer additional subsidies.

A potential concern that is often raised with regard to subsidies for low-carbon technologies is that they tend to go predominantly to higher-income households. Previous research on U.S. federal clean energy tax credits, for example, finds that the top income quintile receives 60% of tax credits for solar panels and 90% of tax credits for electric vehicles (Borenstein and Davis, 2016).

This paper finds that heat pumps are an important exception. Using newly available U.S. nationally representative data, the paper shows that there is remarkably little correlation between heat pump adoption and household income. Nationwide, 15% of U.S. households have a heat pump as their primary heating equipment and heat pump adoption is essentially identical for all levels of household income, ranging from the bottom of the income distribution (<$30,000 annually) to the top ($150,000+).

This lack of correlation contrasts sharply with the pattern for other low-carbon technologies. Using these same data, the paper documents a sharp gradient with regard to income for electric vehicles, solar panels, LED light bulbs, and energy-efficient clothes washers. Households in the top income category (\$150,000+), are, for example, ten times more likely than households in the bottom income category (<\$30,000 annually) to have an electric vehicle, and five times more likely to have solar panels.

These findings have large potential policy implications. Probably most importantly, the lack of correlation between heat pump adoption and income suggests that the distributional impacts of heat pump subsidies are likely to be quite different from the distributional impacts of subsidies for other low-carbon technologies, upending the standard "efficiency versus equity" trade-off that has tended to characterize adoption patterns in this context.

Instead, heat pump adoption is shown to be strongly correlated with geography, climate, and energy prices. The correlation between heat pump adoption and electricity prices, for example, is shown to be negative, statistically significant, and robust even in regressions which control for other variables. These patterns are of considerable independent interest and point to, for example, where heat pump adoption is likely to occur in the future.

Finally, the paper performs a series of back-of-the-envelope calculations aimed at better understanding the cost-effectiveness of heat pump and electric vehicle subsidies (the latter for comparison purposes). These calculations rely on many strong assumptions but, overall, it appears that these two subsidies yield a similar amount of carbon abatement per dollar. Thus these two subsidies appear to be quite similar from an efficiency perspective, despite having very different distributional implications.

This study contributes to a growing literature on the economics of decarbonization through electrification. Whereas most of the literature has focused on the electrification of transportation (Holland et al., 2016; Li et al., 2017; Li, 2019; Burlig et al., 2021; Springel, 2021; Xing et al., 2021; Muehlegger and Rapson, 2022), the electrification of buildings has received relatively less attention (Borenstein and Bushnell, 2022b; Davis, forthcoming).

The study is also related to a literature on the distributional impacts of energy policies. Previous papers have examined, for example, gasoline taxes (Poterba, 1991; Bento et al., 2009), carbon taxes (Cronin et al., 2019), fuel economy standards (Davis and Knittel, 2019), building codes (Bruegge et al., 2019), utility rates (Borenstein, 2012; Borenstein et al., 2021), and solar panel subsidies (Borenstein, 2017; Feger et al., 2022).

Although the paper focuses on the United States, it has implications for heat pump adoption elsewhere. A recent report by the International Energy Agency argues that heat pumps will play a critical role in global decarbonization efforts. According to the report, 10% of space heating needs worldwide are currently being met with heat pumps, but this would need to increase to approximately 24% by 2030 to meet the carbon abatement goals outlined by the Paris Agreement (IEA, 2022).

The paper proceeds as follows. Section 2 documents the lack of correlation between heat pump adoption and household income, and contrasts this with correlations for electric vehicles and other low-carbon technologies. Sections 3 and 4 provide additional background and examine other determinants of heat pump adoption, including geography, climate, and energy prices. Section 5 performs back-of-the-envelope calculations aimed at understanding cost-effectiveness, and Section 6 concludes.

2 Technology Adoption and Income

2.1 Heat Pumps

Figure 1 plots U.S. heat pump adoption rates by household income. Nationwide, 15% of U.S. households have a heat pump as their primary heating equipment. As the figure illustrates, the percent of households with a heat pump is essentially the same for all levels of household income, ranging from the bottom of the income distribution (<$30,000 annually) to the top ($150,000+).

This figure was constructed using household-level microdata from the 2020 wave of the *Residential Energy Consumption Survey* (RECS). Conducted approximately every five years by the U.S. Department of Energy, Energy Information Administration, RECS collects rich data about household energy-related durable goods and behaviors, as well information about household income and other characteristics. The underlying income variable in RECS has 16 categories but some categories were combined when making this figure, for example, $30-$35 and $35-$40 were combined to make a single category $30-$40.

RECS is a U.S. nationally representative survey. The target population for RECS is all occupied housing units in the 50 states and District of Columbia. The RECS sample is selected using stratified sampling by state to ensure sufficient coverage even in states with relatively small populations. Accordingly, RECS sampling weights are used in all calculations throughout the analysis. An attractive feature of the 2020 RECS is its relatively large sample size. The total sample for the 2020 RECS is 18,496 households, including more than 2,600 households with heat pumps.

As with all surveys, a potential concern is non-response bias. The 2020 RECS had a 39% response rate, down sharply compared to the 51% response rate with 2015 RECS and 79% response rate with the 2009 RECS. Survey documentation attributes this lower response rate to the 2020 RECS being entirely self-administered.[1] The RECS sampling weights attempt to correct for non-response by balancing observable household characteristics, but it is impossible to rule out concerns about unobserved differences between responders and non-responders.

2.2 Other Technologies

Figure 2 plots U.S. adoption rates by household income for electric vehicles, solar panels, LED light bulbs, and energy-efficient clothes washers. There is a sharp gradient with regard to income for all four low-carbon technologies. Relative to lowest income category, households in the highest income category are, for example, ten times more likely to have an electric vehicle, and five times more likely to have solar panels.

Baseline adoption levels vary widely across technologies. Electric vehicles and solar panels are relatively rare with adoption rates in the single digits. LEDs and efficient washers are much more common, with adoption rates ranging from 40% to 55% for LEDs and from 10% to near 50% for efficient washers. LEDs, in particular, are much less expensive upfront than these other technologies, which helps explain the higher adoption rates.

Previous economic analyses have posited that signaling to others may be an important driver of adoption decisions for low-carbon technologies.[2] If higher-income households derive more utility from this type of signaling, it could help explain the correlation between adoption and income. Interestingly, however, a sharp income gradient is observed both for

[1] That is, the 2020 RECS was implemented entirely via online and paper questionnaires. Prior waves of the RECS used a combination of in-person interviews and these self-administered modes. See, U.S. Energy Information Administration "2020 RECS Technical Documentation Summary", for details.

[2] Sexton and Sexton (2014), for example, finds that green communities have higher market shares of the Toyota Prius relative to less conspicuous hybrids like the Toyota Camry hybrid, consistent with what they call "conspicuous conservation". This builds on earlier work showing increased registrations of hybrid vehicles like the Toyota Prius in green communities (Kahn, 2007), "In green communities, social pressure may reinforce the urge to take green actions such as driving a Toyota Prius."

technologies that are visible to other households like electric vehicles, as well as for less visible technologies like clothes washers.

Table 1 summarizes the information from Figures 1 and 2. Adoption rates differ little for heat pumps, ranging from 14% to 16% across income categories. In contrast, there is a clear gradient for all other low-carbon technologies. For example, with solar panels, adoption levels range from 1% in the lowest income category to 5% in the highest.

These differences across income levels are strongly statistically significant for electric vehicles, solar panels, LEDs, and washers. For each technology a statistical test is performed for which the null hypothesis is that all eight percentages are equal.[3] The last row of the table reports p-values from these tests. With heat pumps, this null hypothesis cannot be rejected (p-value .45). In the other four cases, however, the null hypothesis is firmly rejected (p-value .00 for all four).

3 Background

Before proceeding, it is helpful to provide some additional background about heat pumps. This content is not crucial for understanding Figures 1 and 2, but is valuable for motivating the exploration of other determinants of heat pumps in the rest of the paper. Section 3.1 provide a basic introduction to heat pumps including what they are and how they work. Section 3.2 describes how much heat pumps cost to purchase and operate. Section 3.3 explains U.S. federal subsidies for heat pumps.

[3] Formally, this is implemented using a regression-based statistical test. Separate regressions are estimated for each technology. In each case, the dependent variable is an indicator variable for whether the household has a particularly technology, and the independent variables are indicator variables for seven of the eight income bins. Following each regression a Wald test is performed to assess whether the seven coefficients are equal to zero, i.e. equal to the value for the excluded category.

3.1 What is a Heat Pump?

Put simply, a heat pump is an air conditioner that can be operated in reverse. Whereas an air conditioner provides cooling, a heat pump provides both heating and cooling. Moreover, because electric heat pumps operate using electricity, they can be substituted for natural gas furnaces and other forms of heating equipment, and thus offer the potential to significantly reduce on-site consumption of natural gas, propane, and other fossil fuels used for heating. Heat pumps are widely deployed in both residential and non-residential settings, though this paper focuses entirely on the former.

Electric heat pumps provide heating using a completely different approach than electric resistance heating. Whereas electric resistance heating converts electricity into heat, a heat pump uses electricity to move heat between the inside and outside of the home. Similar to refrigerators, freezers, air conditioners, and other compressor-based appliances, heat pumps move heat by compressing a refrigerant and then releasing it again. As the refrigerant evaporates (i.e. turns from a liquid into a gas) it absorbs heat, which then can be moved and released as the refrigerant turns back into a liquid.

The advantage of this approach is that heat pumps are considerably more energy-efficient than electric resistance heating. Electric resistance heating, with one kWh of electricity, delivers approximately one kWh of heat. In contrast, a heat pump, with one kWh of electricity, can deliver 2, 3, or even 4 kWh of heat. Again, this is because with a heat pump electricity is not *converted* into heat, it is used to *move* heat. Heat pump energy-efficiency is typically measured using the coefficient of performance (COP), which is defined as the ratio of the delivered power to the electricity consumed. Heat pump COP typically ranges from 2 to 4.

The energy-efficiency of a heat pump depends on the outdoor temperature. Heat pumps are most efficient at relatively high outdoor temperatures, e.g. 60°F, because there is more warmth in the outside air to be moved. Energy-efficiency decreases at lower outdoor temperatures because there is less heat outside to be moved, so a heat pump uses more electricity for each unit of heat that it delivers. For this reason, heat pumps are particularly well-suited to locations with relatively mild winters.[4]

Heat pump capacity also decreases at lower temperatures. That is, the total amount of heat that can be supplied decreases when outdoor temperatures are low, sometimes making it impossible to sufficiently heat a home. Consequently, in colder locations heat pumps are often combined with some other form of backup heating. In Kaufman et al. (2019), for example, heat pumps are assumed to be equipped with a backup electric resistance heater that provides additional heat when the building's heating demands exceed the compressor's capabilities.

3.2 Upfront and Operating Costs

Table 2 reports upfront costs for selected residential heating and cooling equipment. This information comes from the U.S. Department of Energy and includes purchase and installation costs, but not operating costs.

According to these estimates, an air source heat pump has an upfront cost of $5,400 to $6,400, which is about $1,500 more than a central air conditioner. This incremental cost is less than the upfront cost of a natural gas furnace, and, in many cases, less than the upfront cost of electric resistance heating. Thus heat pumps are particularly attractive for households who are already installing central air conditioning.

[4]See, e.g., Washington Post, "U.S. Home Heating is Fractured in Surprising Ways: Look Up Your Neighborhood" March 6, 2023 by John Muyskens, Shannon Osaka, and Naema Ahmed. See also U.S. Department of Energy, Energy Information Administration, "U.S. Households' Heating Equipment Choices are Diverse and Vary by Climate Region", April 6, 2017.

This upfront cost for a heat pump does not include any backup heating system for very cold days. One way to see why backup systems are often necessary is to look at the capacities of the different systems. The natural gas furnace described here has a capacity of 80 kBtu/hour, compared to 36 kBtu/hour for the air source heat pump. Most of the time this lower capacity is not a problem because the heat pump simply cycles less and runs more total hours. However, at very cold temperatures this may not be enough to keep the home warm.

Ground source heat pumps are considerably more expensive. Whereas air source heat pumps transfer heat to and from the air, ground source heat pumps transfer heat to and from the ground, with refrigerant lines running through holes drilled underground. Air source heat pumps represent 90% of U.S. residential heat pumps in the RECS 2020, and 85% of heat pumps worldwide (IEA, 2022). Ground source heat pumps have certain advantages, but tend to have considerably higher initial purchase and installation costs.

In addition to these upfront costs, all heating systems also have operating costs. In the United States, natural gas heating tends to have lower operating cost than electric resistance heating. Based on U.S. average residential prices for electricity and natural gas in 2021, for example, the price per MMBTU (million British thermal units) of heating was $13 for natural gas and $40 for electric resistance heating.[5] Operating costs can be considerably lower for heat pumps, depending on the COP. For a COP of 3.0, for example, the price per MMBTU of heating would be $13, equivalent to natural gas.[6]

[5]This back-of-the-envelope calculation is based on national average residential prices of $12.18 per thousand cubic feet for natural gas and 13.7 cents per kWh for electricity. One kWh is equivalent to 3,412 Btu, or 0.003412 MMBTU and one thousand cubic feet is equivalent to 1.037 MMBTU. Electric resistance and natural gas heating are assumed to be 100% and 90% efficient, respectively.

[6]It is hard to say whether a COP of 3.0 is representative. The U.S. federal minimum efficiency standard for air source heat pumps was 2.40 between 2015 and 2022, before increasing to 2.58 in 2023. U.S. federal minimum efficiency standards for heat pumps are measured using Heating Seasonal Performance Factor (HSPF) which is average heating (in BTU) per watt hour. The minimum standard was HSPF 8.2 between 2015 and 2022 and then HSPF 8.8 starting in 2023. There are 3412 BTU per kilowatt hour of electricity,

These upfront and operating costs illustrate why there would be a regional pattern to heating choices. In warmer states like Florida, households tend to prefer electric heating because of its lower upfront costs. In colder states, however, the low operating costs associated with natural gas tend to make it attractive relative to a heat pump with backup heating system. Moreover, where natural gas is not available, a heat pump will often be preferred relative to electric resistance heating based on its considerably lower operating costs.[7]

3.3 U.S. Federal Subsidies for Heat Pumps

The U.S. Inflation Reduction Act provides tax credits and direct point-of-sale rebates for heat pumps.[8] Both types of subsidies have various requirements, but there is no specific restriction preventing a household from receiving both a tax credit and direct rebate.

The tax credit is equal to 30% of the upfront cost of a heat pump, up to a maximum of $2,000. For example, if a household spends $6,000 purchasing and installing a heat pump, it can receive a tax credit of $1,800. Available since January 1, 2023, this tax credit was implemented by extending and amending the "Energy Efficient Home Improvement Credit", formerly known as the "Non-Business Energy Property Credit" (Internal Revenue Code Section 25C), which was originally established by the Energy Policy Act of 2005 and

so HSPF 8.2 and 8.8 correspond to average coefficients of performance (COP) of 2.4 and 2.58, respectively. Borenstein and Bushnell (2022b) assume for their calculations a COP of 2.5 (i.e. 0.4 kWh of electricity per 1 kWh of heat). Other studies report results for a range of different COP values. See, e.g., Kaufman et al. (2019) and Walker et al. (2022).

[7] This trade-off between upfront and operating costs is a central theme in previous economic analyses of residential heating and cooling. See, e.g., Hausman (1979); Dubin and McFadden (1984); Mansur et al. (2008); Rapson (2014). None of these four studies consider heat pumps, which points to their relatively recent rise to prominence.

[8] The Inflation Reduction Act was signed into law by President Biden on August 16, 2022. See Inflation Reduction Act of 2022, H.R. 5376, 117th Congress. Public Law 117-169. See also, Congressional Research Service, "Residential Energy Tax Credits: Changes in 2023", November 21, 2022, and Internal Revenue Service, "Frequently Asked Questions about Energy Efficient Home Improvements and Residential Clean Energy Property Credits", December 2022.

subsidizes certain investments that reduce energy consumption in homes. Heat pumps have long been included under this tax credit, but at much lower subsidy levels. For example, as of 2022, a qualifying heat pump could qualify for a maximum tax credit of only $300.

The Inflation Reduction Act also created a grant program called the "High-Efficiency Electric Home Rebate Program" which awards grants to states for point-of-sale rebates of up to $8,000 for heat pumps. These rebates are subject to income requirements: (1) households with annual income below 80% of median local income are eligible for a 100% rebate, up to $8,000, (2) households with annual income between 80% and 150% of median local income are eligible for a 50% rebate, up to $8,000, and (3) households with annual income above 150% of median local income are ineligible. In addition to heat pumps, these rebates are available for electric load service upgrades and other electrification investments, up to a total household maximum of $14,000.

As of May 2023, federal and state agencies are finalizing the rules and regulations for distributing rebates. States have some discretion with regard to how they implement these rebates so there is likely to be variation across states in when these rebates are first available, as well as variation with regard to how income requirements are enforced. Rewiring America, an electrification non-profit, is reporting that funding for these rebates will likely be distributed to state agencies in 2023, with rebates available to consumers by late-2023 or 2024.

Tax credits and point-of-sale rebates are likely to be used by different types of households. Probably most importantly, the maximum income requirements for the rebates mean that they are supposed to go only to low- and middle-income households. At the same time, there are also subtle factors affecting take-up of tax credits. As emphasized by Borenstein and Davis (2016), these are nonrefundable tax credits. Consequently, there are millions of mostly lower-income taxpayers who are ineligible because they have insufficient tax liability. Moreover, tax credits require households to wait many months before receiving the credit, which also tends to tilt take-up toward higher-income households who are less liquidity constrained.

4 Other Determinants of Heat Pump Adoption

This section explores other determinants of heat pump adoption. If not income, then what other factors are correlated with heat pump adoption? Guided by the background provided in the previous section, most of the factors considered in this section have implications for the operating costs and overall effectiveness of heat pumps.

Geography, climate, and energy prices are all shown to strongly predict heat pump adoption by U.S. households. Sections 4.1, 4.2, and 4.3 explore these relationships. Section 4.4 summarizes these findings, and presents evidence on several additional factors which turn out not to be important. Section 4.5 describes a regression analysis aimed at better disentangling the various factors.

These additional findings are interesting because they point to heat pump adoption having a very different pattern from electric vehicles, solar panels, and other low-carbon technologies. These patterns also have important implications about where the tax credits and other subsidies for heat pumps are likely to go.

4.1 Geography

Figure 3 maps heat pump adoption by state. As with the previous analyses related to household income, this information comes from the RECS 2020. This is the first wave of RECS for which such a state-level analysis was possible. Previous waves identified households in large states, e.g. Texas and California, but state of residence was not identified for most respondents, so a map like this would not have been possible with the 2015 or 2009 RECS.

As the figure reveals, there is a pronounced regional pattern to heat pump adoption. Heat pumps are most common in southern states like Alabama, South Carolina, and North Carolina. In those three states, more than 40% of households have a heat pump as their primary heating equipment. Throughout the rest of the South, heat pump adoption rates range between 20% and 40%. In Texas and Florida, for example, 22% and 33% of households have heat pumps, respectively. See Appendix Table 1 for the complete list of states.

Another area of increased heat pump adoption is the Pacific Northwest. Heat pump adoption is 13% in Washington and 15% in Oregon. This higher rate of adoption is not a coincidence. As will be explored in more detail later, electricity prices are negatively correlated with heat pump adoption, and these two states have lower electricity prices than most other states due to the availability of low-cost hydroelectric power.

Heat pumps are rare throughout the rest of the country. This includes most of the West, the Midwest, and the Northeast, as well as Hawaii and Alaska. Perhaps surprisingly, California also has relatively low heat pump adoption. Again, this is not a coincidence. California has unusually high electricity prices, as has been highlighted by several recent economic analyses (Borenstein et al., 2021; Borenstein and Bushnell, 2022a,b).

4.2 Climate

Figure 4 plots annual average heating degree days (HDDs) by state. HDDs are a widely used measure of heating demand that reflects the number of days with cold weather as well as the intensity of cold on those day. 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 contributes ten HDDs, whereas a day with an average temperature above 65°F contributes zero.

HDDs range widely across the United States. Warmer states like Hawaii, Florida, Arizona, Louisiana, and Texas experience less than 2000 HDDs annually. Colder states like Maine, Vermont, Minnesota, North Dakota, and Alaska experience 7000+ HDDs annually.

This measure of HDDs is a 30-year annual average. Heat pumps tend to be used for many years before they are replaced. For example, the U.S. Department of Energy, *National Energy Modeling System* assumes that heat pumps have a minimum lifetime of 9 years and a maximum lifetime of 22 years. Thus, it makes sense to think about heating choice decisions as responding to a location's climate, rather than to year-to-year weather variation.

Figure 5 presents a scatterplot of heat pump adoption versus HDDs. There is a pronounced negative correlation. For example, all 16 states with heat pump adoption above 20% have HDDs below or right at median HDDs. The correlation between the two variables is negative (-0.64) and strongly statistically significant.

Hawaii is a fascinating outlier. Households in Hawaii experience virtually no HDDs, yet heat pump adoption is near zero. There is so little need for heating in Hawaii that most households choose not to have any heating equipment whatsoever. At the same time, Hawaii also has surprisingly little air conditioning. Only 57% of households in Hawaii have air conditioning, compared to a national average above 90%. In part, this lack of air conditioning reflects that Hawaii has the highest residential electricity prices in the United States. The average residential electricity price in Hawaii in 2020 was 30 cents per kWh, compared to a national average of 14 cents per kWh. The lack of air conditioning in Hawaii is also likely related to the housing stock. Because it tends not to get very cold in Hawaii, homes are built with less insulation, making air conditioning less effective and more expensive.

Interestingly, for European countries there is a *positive* correlation between heat pump adoption and HDDs (Rosenow et al., 2022). This positive correlation is largely due to three countries – Finland, Norway, and Sweden – which all experience high levels of HDDs and have heat pump adoption rates above 40%. Heat pump popularity in these Scandinavian countries reflects many factors including low electricity prices, high taxes for fossil fuel alternatives, lack of natural gas infrastructure, and government subsidies for heat pumps (Gross and Hanna, 2019).

Appendix Figures 1 and 2 present analogous evidence for cooling degree days (CDDs). Whereas HDDs measure overall demand for heating, CDDs measure overall demand for cooling. As discussed earlier, heat pumps are, essentially, air conditioners operating in reverse, so the incremental cost of a heat pump is smaller for a household that already has or is planning to install central air conditioning. Heat pump adoption is positively correlated with CDDs (0.55).

4.3 Energy Prices

Figure 6 plots average residential electricity prices as of 2020. U.S. electricity prices vary widely from less than 10 cents per kWh in Louisiana, Washington State, and Idaho, to more than 20 cents per kWh in California, Massachusetts, Rhode Island, Alaska, Connecticut, and Hawaii.

Figure 7 plots heat pump adoption versus electricity prices. The correlation between the two variables is negative (-0.41) and strongly statistically significant. All of the states with adoption rates above 20% have electricity prices below 13 cents per kilowatt hour, and adoption rates are below 10% for all states with prices above 15 cents per kilowatt hour.

The states with high electricity prices are very different from the state with low electricity prices, so it is hard to make a strong causal statement about this relationship. Still, the negative relationship makes sense given that electricity prices determine operating costs for heat pumps, and consistent with an existing literature documenting the responsiveness of electricity demand to prices. See, e.g., Reiss and White (2005), Reiss and White (2008) and Ito (2014).

To the extent that lower electricity prices cause increased heat pump adoption, this underscores the importance of pricing electricity efficiently. A key theme in recent economic analyses of U.S. electricity markets is that electricity is *not* priced efficiently (Borenstein and Bushnell, 2022a,b). In particular, there are many parts of the country where residential electricity prices are too high, i.e. higher than social marginal cost, which would imply inefficiently low levels of heat pump adoption.

Appendix Figures 3 and 4 present analogous evidence for natural gas prices. Natural gas furnaces are a substitute for heat pumps, so this "cross-price" effect would be expected to be positive with, everything else equal, heat pumps being more attractive in states with high natural gas prices. Indeed, the correlation between heat pump adoption and natural gas prices is positive. The correlation is smaller in magnitude than the correlation with electricity prices, and not statistically significant, but has the expected sign.

4.4 Additional Evidence

Table 3 describes heat pump adoption percentages and the implied total number of households for different categories of U.S households. Nationwide, 15% of households have a heat pump as their primary heating equipment, implying 18.9 million total U.S. households with heat pumps.

The breakdown by geography, electricity prices, and climate confirms the patterns shown in the previous subsections. Heat pump adoption in the South is three times higher than in the West, and six times higher than in the Midwest and Northeast. Heat pump adoption in states with low electricity prices (i.e. below median) is three times higher than heat pump adoption in states with high electricity prices (i.e. above median). And, heat pump adoption in warm states (i.e. below median HDDs) is more than three times higher than in cold states (i.e. above median HDDs).

The table also presents evidence on several additional potential determinants, which turn out not to be important determinants of heat pump adoption. Interestingly, heat pump adoption is similar for homeowners vs renters. This is perhaps surprising given previous evidence on the "landlord-tenant" problem, i.e. the idea that landlords have too little incentive to invest in energy-efficiency when their tenants pay the energy bills. See, e.g., Gillingham et al. (2012). But in many cases heat pumps are actually less expensive upfront than installing separate heating and cooling systems, so the analogy to the literature on energy-efficiency is not so straightforward.

Heat pump adoption is also similar for single-family versus multi-unit homes, and for homes with different numbers of bedrooms. The lack of predictive ability for these housing characteristics is notable because one might have expected economies-of-scale to provide clear advantages or disadvantages for heat pumps relative to alternative technologies. Were this only a comparison between heat pumps and electric resistance heating, then one might indeed expect to see single-family homes and larger homes disproportionately choosing heat pumps. But households are also considering natural gas heating which tends to be attractive in larger homes because of the relatively low operating costs.

Regardless of the exact explanations, the lack of correlation with these other factors helps explain the lack of correlation between heat pumps and household income, and why heat pumps are so different from solar panels and other technologies. One of the reasons solar panels tend to be more frequently adopted by higher-income households is that they are more likely to be homeowners in single-family homes. It is typically easier to install solar panels in a single-family home relative to multi-unit, which tends to strengthen the correlation between solar panel adoption and household income. Similarly, households in single-family homes are also more likely to have a convenient parking spot with a garage or driveway, which makes charging an electric vehicle easier.

4.5 Regression Analysis

Table 4 reports estimates from a regression model aimed at better disentangling the various determinants of heat pump adoption. Coefficient estimates and standard errors are reported from eight separate least squares regressions. In all eight regressions the dependent variable is an indicator variable for homes for which an electric heat pump is the primary form of space heating.

Table 4 exhibits a striking lack of association between household income and heat pump adoption. Across all eight columns, the point estimates corresponding to household income are close to zero. For example, in column (1) without any additional variables, the coefficient on income is -0.01. Thus a $100,000 increase in annual household income is associated with a 1.0 percentage point decrease in heat pump adoption, a relatively small effect. With additional variables the coefficient on income becomes positive but remains small in magnitude in all specifications, and is only statistically significant in the final two columns. Thus whether one controls or does not control for these other variables there is a pronounced lack of association with household income.

Instead, heat pump adoption is strongly associated with geography, energy prices, and climate. These patterns are largely consistent with the results presented earlier but it is interesting to see that most of these relationships persist even in regressions with other variables.

- Heat pump adoption is more common in the South, and less common in the Midwest and Northeast. These region effects attenuate somewhat but remain mostly statistically significant after controlling for additional variables. The magnitude of these effects is large. For example, in column (5) a household in the South is 15 percentage points more likely to have a heat pump, which is a doubling relative to the national mean of 15 percent.

- Heat pump adoption decreases with electricity prices. The point estimates are large. For example, the estimate in column (5) implies that a 10% increase in electricity prices decreases heat pump adoption by 1.8 percentage points. In 2020, residential electricity prices in the continental U.S. ranged from 9.7 cents in Louisiana to 22.6 cents in Connecticut, a difference of 0.85 log points. The regression implies that, everything else equal, an increase in electricity prices of this magnitude would decrease heat pump adoption by 15 percentage points. One standard deviation in log electricity prices is .261, so a one standard deviation increase in electricity prices decreases adoption by 4.7 percentage points, or 31 percent.

- Heat pump adoption increases with natural gas prices. In column (5), for example, a 10% increase in natural gas prices increases heat pump adoption by 1.2 percentage points. Thus, both the own-price and cross-price effects have the expected signs.

- Heat pump adoption decreases with HDDs and CDDs. These effects are not statistically significant, but the point estimates are large when viewed relative to the relevant range. HDDS, for example, range within the continental U.S. from 600 in Florida to 8,400 in Minnesota, so the -.014 estimate in column (8) implies that an increase in HDDs of this magnitude would decrease heat pump adoption by 11 percentage points. One standard deviation in HDDs is 2,300, so a one standard deviation increase in HDDs decreases adoption by 3.2 percentage points, or 22 percent.

- There is little association between heat pump adoption and whether the household is a homeowner or renter, the type of home (i.e. single family versus multi-unit), or the number of bedrooms. This is not unexpected given the lack of correlation for these factors in Table 3, but it is interesting to see that this lack of correlation persists even in a regression with other variables.

Thus the main takeaways from the regression analysis are as follows: (1) there is very little association between heat pump adoption and household income, (2) instead, heat pump adoption is strongly associated with geography, climate, and energy prices, and (3) these patterns are similar whether one examines simple correlations or estimates from a regression framework. The following section switches gears and considers the question of cost-effectiveness of subsidies, but the conclusion returns to this evidence and offers some additional broader lessons with regard to potential policy implications.

5 Cost-Effectiveness of Subsidies

This section performs back-of-the-envelope calculations aimed at better understanding the cost-effectiveness of heat pump subsidies. As discussed previously, there is growing enthusiasm about heat pumps as a means to reduce carbon emissions from residential heating. In the United States, for example, 56 million households (46%) heat their homes with natural gas, 5 million households (4%) heat their homes with propane, and 5 million households (4%) heat their homes with heating oil.[9]

The goal in this section is to calculate how much carbon abatement occurs per dollar spent on heat pump subsidies in the United States. Then, as a point of comparison, a similar calculation is performed for electric vehicles. These calculations require many strong assumptions. Where possible, existing data and previous estimates in the literature are used as points of comparison. Nonetheless, these should be viewed as preliminary back-of-the-envelope calculations and interpreted with considerable caution.

The focus is on carbon abatement. In future research, it would be interesting to expand the analysis to incorporate other externalities. For example, burning fossil fuels releases nitrogen oxides (NOx) and other local pollutants that are dangerous for human health. In addition, there are negative externalities from fossil fuel production including methane leaks, water use, and water contamination. On the other hand, heat pumps use refrigerants which are a potent greenhouse gas. Quantifying these additional externalities is challenging but also important, as they have the potential to significantly impact the trade-offs associated with heat pumps.

5.1 Baseline Assumptions

This section describes the baseline assumptions used to quantify the carbon abatement from heat pump subsidies. The basic thought experiment is to focus on the U.S. federal tax credit of $2000 for heat pumps. As discussed previously, under the U.S. Inflation Reduction Act, low-and moderate income households will also be able to receive point-of-sale rebates of up to $8,000, but the exact implementation of these rebates is still being

[9] U.S. Department of Energy, Residential Energy Consumption Survey 2020, Table HC6.1 Space Heating in U.S. Homes, Released May 2022.

finalized.

Percentage Additional: For the baseline calculation, it is assumed that 50% of subsidy recipients are induced to purchase a heat pump because of the subsidy whereas 50% of subsidy recipients would have purchased a heat pump even without the subsidy. That is, half of recipients are "additional" and the other half are "non-additional". This is an important assumption and, unfortunately, one about which there is no existing empirical evidence. Thus, in addition to 50%, results are also reported for 25% and 75%.

Counterfactual Heating Source: The baseline calculation assumes that households induced to use a heat pump otherwise would have heated their homes using natural gas. This is another important assumption and, again, one for which there is little existing empirical evidence. Natural gas is the most common form of residential heating in the United States, but heat pump subsidies will also lead to substitution away from other heating fuels. Accordingly, results are also reported for propane, heating oil, and electric resistance heating.

Level of Heating Demand: Households are assumed to consume 35 MMBTU of heating annually, regardless of energy source.[10] As already discussed, the United States has a wide range of climates. Thus, in addition to reporting results for 35 MMBTU, the paper also reports results for 20 MMBTU and 50 MMBTU.

Operating Efficiency: Heat pumps are assumed to deliver 3.0 MMBTU of heating for each MMBTU of electricity (i.e. 300% efficient), compared to 1-to-1 (100% efficient) for electric resistance heating and 0.9-to-one (90% efficient) for natural gas, propane, and

[10]U.S. Department of Energy, Energy Information Administration, 2015 Residential Energy Consumption and Expenditures Tables, Table CE3.1 "Annual Household Site End-Use Consumption in the U.S. – Total and Averages" reports that the average U.S. household uses 35.3 MMBTU annually for space heating. This approach of assuming a fixed level of heating consumption implicitly ignores the potential for a "rebound effect", i.e. the idea that lower operating costs would cause a household to consume more heating (Dubin et al., 1986), which would be a refinement worth incorporating in future research.

heating oil.[11] Based on these assumptions, 35 MMBTU of heating can be met using 3,419 kWh of electricity (via a heat pump), 10,257 kWh of electricity (via electric resistance heating), 37.4 thousand cubic feet of natural gas, 425 gallons of propane, or 281 gallons of heating oil.[12]

Emissions Factors: Standard emissions factors are used to convert electricity and fuel consumption into carbon emissions. Electricity is assumed to emit 310 pounds of carbon dioxide per MMBTU of electricity consumed.[13] Natural gas, propane, and heating oil are assumed to emit 116.65, 138.63, and 163.45 pounds of carbon dioxide per MMBTU, respectively.[14] It is perhaps surprising that electricity produces more carbon dioxide per MMBTU than fossil fuels but this reflects that a considerable amount of energy is lost when fossil fuels are converted into electricity. On average, U.S. natural gas power plants

[11]The assumption of 90% efficiency for natural gas, propane, and heating oil is based on DOE (2018) and reflects typical efficiency for new furnaces. The current federal minimum efficiency standard for gas furnaces (including both natural gas and propane) is 80% Annual Fuel Utilization Efficiency (AFUE). Pages 8 and 9 of DOE (2018) report "typical" and "high" efficiencies of 92% and 99% in the North, and 80% and 99% in the rest of the country. The current federal minimum efficiency standard for oil-burning furnaces is 83% Annual Fuel Utilization Efficiency (AFUE), and page 12 of DOE (2018) reports "typical" and "high" efficiencies of 83% and 97%.

[12]These calculations are based on standard conversion factors from the U.S. Department of Energy, Energy Information Administration, "Energy Units and Calculators Exlained", https://www.eia.gov/energyexplained/units-and-calculators/. Electricity consumption for heating with a heat pump is calculated using the COP of 3.0 and the conversion rate: 1 kilowatt hour = 3412 BTUs. Electric resistance heating in kilowatt hours is calculated using the conversion rate: 1 kilowatt hour = 3412 BTUs. Natural gas consumption in Mcf (thousand cubic feet) is calculated using the conversion rate: 1 Mcf = 1.039 MMBTU. Propane consumption in gallons is calculated using the conversion rate: 1 gallon = 0.091452 MMBTU. Heating oil consumption in gallons is calculated using the conversion rate: 1 gallon = 0.1385 MMBTU.

[13]Holland et al. (2022) finds that current marginal carbon dioxide emissions for the Western grid are about 1 pound of carbon dioxide per kWh (0.5 tons per MWh), which is equivalent to 293 pounds of carbon dioxide per MMBTU. This reflects typical emissions for electricity generation from natural gas. From this same source, the emissions factor for the entire United States is about 1.3 pounds per kWh. The lower value is used in the baseline assumptions to reflect the widespread view that the U.S. grid will continue getting cleaner over time. Finally, these emissions are scaled up by 5% following U.S. Department of Energy, Energy Information Administration, "How much electricity is lost in electricity transmission and distribution in the United States?", to reflect that approximately 5% of electricity is lost between the power plant and the point of consumption.

[14]These coefficients are from U.S. Department of Energy, Energy Information Administration, "Carbon Dioxide Emissions Coefficients", Released October 2022, https://www.eia.gov/environment/emissions/co2_vol_mass.php These emissions factors do not account for the assumed 90% efficiency; these are emissions factors per MMBTU of energy not MMBTU of heat.

convert only 45% of the energy content of natural gas into electricity, while U.S. coal power plants convert only 32% of the energy content of coal into electricity.[15] While these are rough averages, even the most efficient fossil fuel power plants typically have an efficiency below 60%.

System Lifetime: Heating systems are assumed to have a 20-year lifetime, with no changes in operating efficiency or emissions factors over that time period. This is a bit longer than typical assumptions in the literature. For example, the U.S. Department of Energy, *National Energy Modeling System* assumes that heat pumps have a minimum lifetime of 9 years and a maximum lifetime of 22 years. But the somewhat longer lifetime is intended to reflect the inertia in heating system choices and that a heat pump subsidy could impact heating system choices even beyond the lifetime of the initial equipment.

Discount Rate: Finally, these calculations assume a 5% annual discount rate. Discounting future carbon abatement takes into account that while the costs of these subsidies are borne upfront, the carbon abatement occurs over many years. Discounting has little effect on the comparison between heat pumps and electric vehicles, but it lowers the overall level of abatement from both types of subsidies. Results are also reported for discount rates of 3% and 7%.

5.2 Cost-Effectiveness: Results

Table 5 presents the cost-effectiveness calculations. Under the baseline assumptions, a $2000 heat pump subsidy reduces lifetime carbon dioxide emissions by 4 tons. Carbon abatement scales as expected in response to alternative assumptions about the proportion additional, level of heating demand, and discount rates. For example, carbon abatement

[15] See, for example, U.S. DOE EIA, "More Than 60% of Energy Used for Electricity Generation is Lost in Conversion", July 21, 2020.

is lower when one assumes that only 25% of recipients are additional. This makes sense. After all, from a carbon abatement perspective the worst case scenario would be that all recipients are "free riders", i.e. getting paid for doing what they would have done otherwise.

The results for other heating fuels are interesting and merit additional discussion. Carbon abatement is higher if one assumes that household otherwise would have used propane or heating oil. This reflects that these fuels are more carbon intensive than natural gas. Interestingly, carbon abatement is much higher if the household otherwise would have used electric resistance heating. This is a bit surprising because typically heat pump subsidies are described as inducing households to substitute away from natural gas and other on-site direct consumption of fossil fuels. These calculations illustrate, however, that there are significant reductions in carbon dioxide emissions from encouraging households to switch to a much more energy-efficient form of electric heating.

It is tempting to compare the calculations in Table 5 to estimates in the literature for the social cost of carbon. For example, the U.S. government currently uses a social cost of carbon of $51 per ton (U.S. Interagency Working Group, 2021) and one recent study finds a preferred social cost of carbon of $185 per ton (Rennert et al., 2022). However, this is not an apples-to-apples comparison. Subsidies are transfers, not economic costs, and many households value subsidies at close to $1-for-$1. Non-additional recipients, for example, value each $1 subsidy at exactly $1, so for them the subsidy should be viewed as a pure transfer from taxpayers to households. These transfers are not costless because they must be financed through distortionary taxes, i.e. the marginal cost of public funds, but this is typically thought of as imposing economic costs much lower than $1 per $1 raised.

The following section presents analogous estimates for electric vehicles. This is more of an apples-to-apples comparison because in both cases the objective is to calculate the carbon abatement that would result from a $2000 subsidy. These comparisons can viewed in the spirit of Hendren and Sprung-Keyser (2020) and the "marginal value of public funds" (MVPF). Intended as a metric for evaluating the desirability of government policies, the MVPF is the ratio of a policy's benefits to a policy's cost to the government. The advantage of the MVPF is that it makes it possible to easily compare the societal returns to alternative uses of government expenditure.

5.3 Cost-Effectiveness: Comparison to EVs

The approach taken for the back-of-the-envelope calculations for electric vehicles is quite similar. For comparability, the basic thought experiment is to consider a $2000 subsidy for electric vehicles. At this subsidy level, it is assumed under the baseline assumptions that 25% of subsidy recipients are additional. A lower percentage is used here than the 50% assumed for heat pumps because a $2000 subsidy is a smaller percent of total costs.[16]

These calculations implicitly assume that the incidence of the subsidy is at least partly on buyers. If supply were perfectly inelastic then sellers would capture 100% of the subsidy and there would be no change in the number of electric vehicles sold, and 0% of subsidy recipients would be additional. Although this is an interesting extreme case, it makes more sense to think about suppliers having at least some ability to increase the quantity supplied, particularly over the medium- and long-run. Muehlegger and Rapson (2022), for example, find that buyers capture 73% to 85% percent of electric vehicle subsidies in California.

[16]The assumption that 25% of subsidy recipients is additional is probably optimistic. Muehlegger and Rapson (2022) estimate that the price elasticity of demand for electric vehicles is -2.1. Thus, a subsidy that decreases the upfront cost of electric vehicles by 10% would increase demand by 21%. In their study the baseline price of an electric vehicle is $26,000, so a $2,000 subsidy would be an 8% decrease in upfront cost, expected to increase demand by 16%. Their study focuses on a California electric vehicle subsidy program focused on a program aimed at low- and middle-income households.

Households are assumed to otherwise have used a gasoline-powered vehicle that gets 30 miles-per-gallon and is driven 10,000 miles per year, with a 15 year lifetime. These assumptions are informed by previous research and empirical data on driving behavior. Perhaps most relevantly, Xing et al. (2021) use U.S. vehicle sales data 2010-2014 and a discrete choice model to find that households with an electric vehicle otherwise would have driven a vehicle with an average fuel economy of 28.9 miles-per-gallon. Holland et al. (2016) assumes vehicles are driven 15,000 miles per year while other studies of electric vehicle driving behavior have tended to find lower levels of driving intensity (Davis, 2019; Burlig et al., 2021). Finally, Bento et al. (2018) finds that the average lifetime for passenger vehicles in the United States is 15.6 years.

Table 6 presents the cost-effectiveness results for electric vehicles. Under the baseline assumptions, a $2000 electric vehicle subsidy reduces lifetime carbon dioxide emissions by 5 tons. Carbon abatement scales as expected in response to alternative assumptions about the proportion additional, fuel efficiency, vehicle-miles-traveled, and discount rates.

These calculations suggest that heat pump and electric vehicle subsidies yield a similar amount of carbon abatement per subsidy dollar. This finding of roughly equivalent efficiency is notable given the very different patterns for distributional impacts presented earlier. Economists have pointed out that many energy-related policies involve efficiency vs equity trade-offs, with, for example, policymakers sometimes eschewing more efficient policies due to concerns about equity (Deryugina et al., 2019). These results suggest, however, that heat pump subsidies achieve a similar amount of carbon abatement as electric vehicle subsidies, but with more equitable distributional impacts.

Before proceeding, it is worth reiterating that Tables 5 and 6 should be viewed as preliminary back-of-the-envelope calculations. This exercise requires many strong assumptions and, as more evidence becomes available, it will be interesting to update these calculations to reflect better information about additionality, substitution patterns, usage levels, and other factors. Perhaps most importantly, these calculations assume that emissions from the U.S. electricity sector remain constant. The argument for heat pumps and electric vehicles as a climate solution hinges on the assumption that the U.S. grid will continue to become less carbon intensive over time. Although this would not tend to affect much the comparison between heat pump and electric vehicles, it would significantly increase the overall carbon abatement from both types of technologies.

6 Conclusion

This paper started off by showing that heat pump adoption is remarkably similar across U.S. households with different income levels. This surprising finding stands in sharp contrast to adoption patterns for electric vehicles, solar panels, and other low-carbon technologies, which are disproportionately adopted by high-income households. The paper showed, for example, that households with annual income above $150,000 are twice as likely to have solar panels and six times more likely to have an electric vehicle than households with income between $50,000 and $60,000.

This lack of correlation between heat pump adoption and household income has large potential implications for the distributional impact of heat pump subsidies. Whereas subsidies for other low-carbon technologies have tended to go overwhelmingly to high-income households, heat pump subsidies are likely to be much more widely distributed across the income distribution.

Instead, geography, climate, and energy prices were all shown to strongly predict heat pump adoption. Regression evidence showed, for example, that a one standard deviation increase in HDDs decreases heat pump adoption by one-fifth, while a one standard deviation increase in electricity prices decreases heat pump adoption by one-third. Other factors like homeowner vs renter, single-family vs multi-unit, and the size of the home were shown to be less important.

Finally, the paper presented back-of-the-envelope calculations aimed at quantifying the carbon abatement from heat pump and electric vehicle subsidies. These calculations suggest that the two types of subsidies yield a similar amount of carbon abatement per subsidy dollar. These calculations rely on strong assumptions and should be interpreted cautiously, but they suggest that these two subsidies are quite similar from an efficiency perspective, despite having very different distributional implications.

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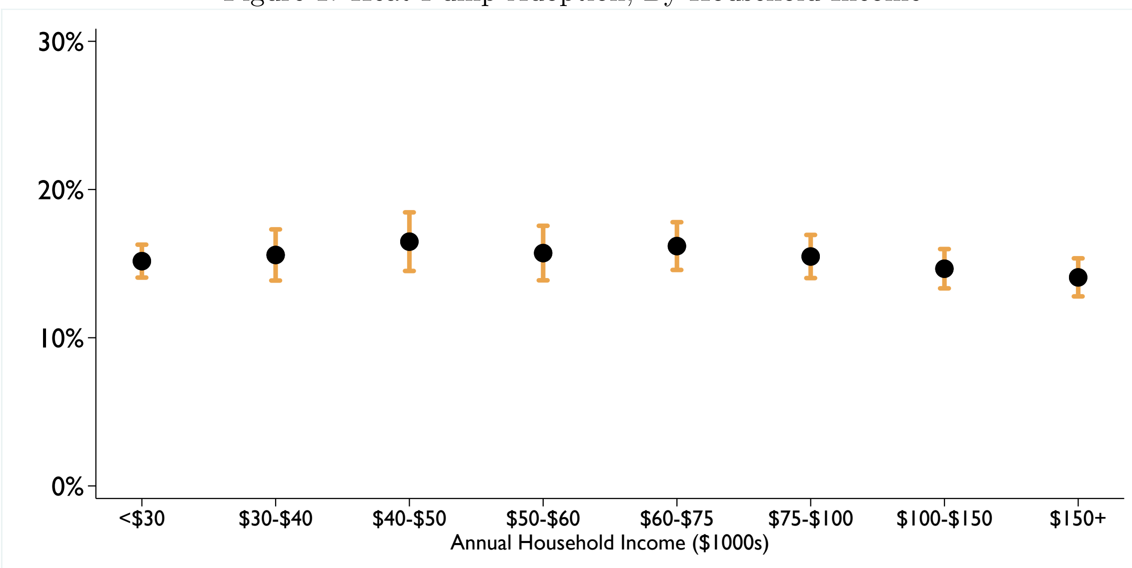
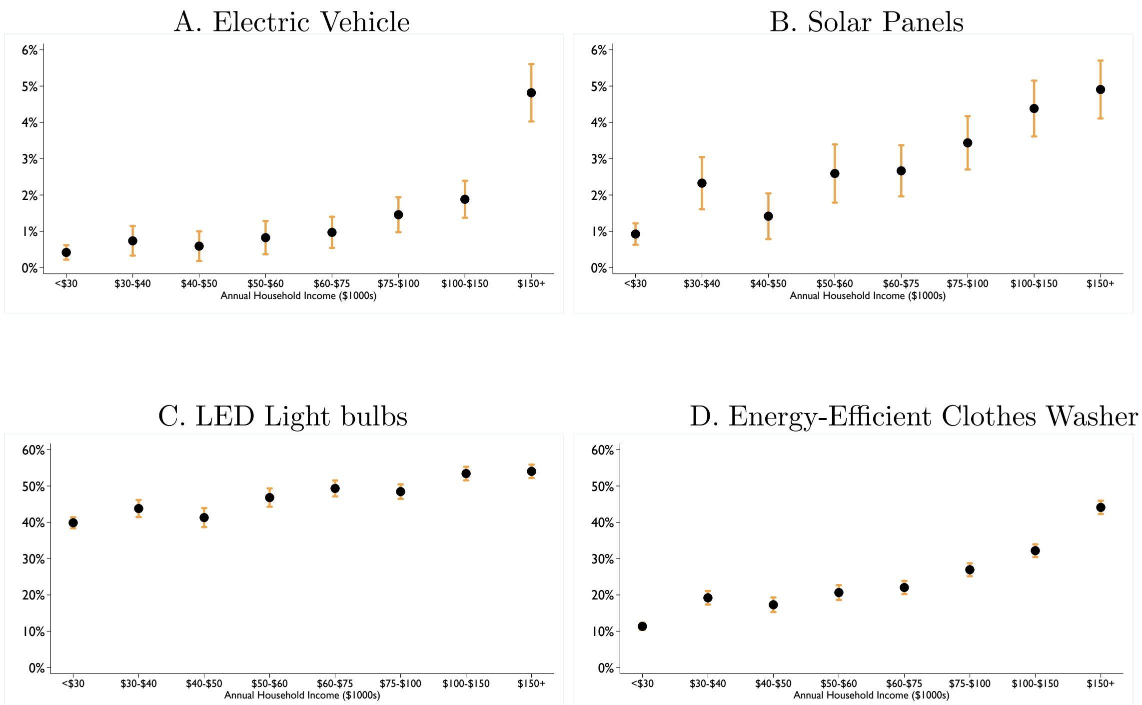
Figure 1: Heat Pump Adoption, By Household Income



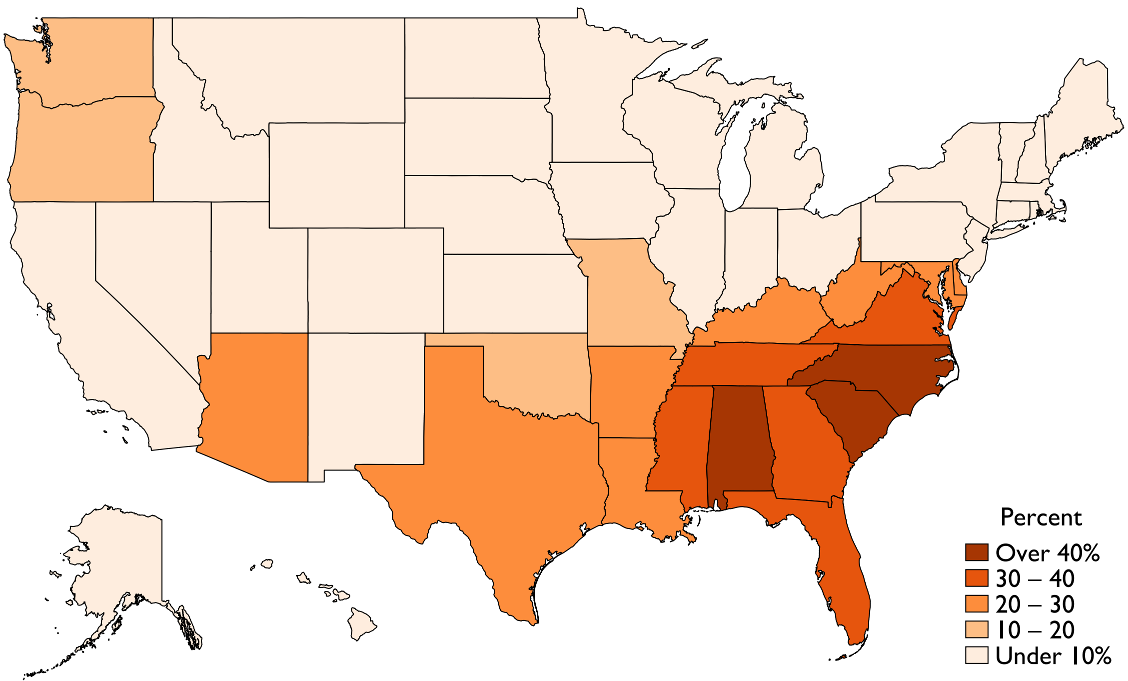
Note: This figure shows how the percent of U.S. households with a heat pump varies with annual household income. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights. Brackets indicate 95 percent confidence intervals.

Figure 2: Adoption of Other Low-Carbon Technologies, By Household Income



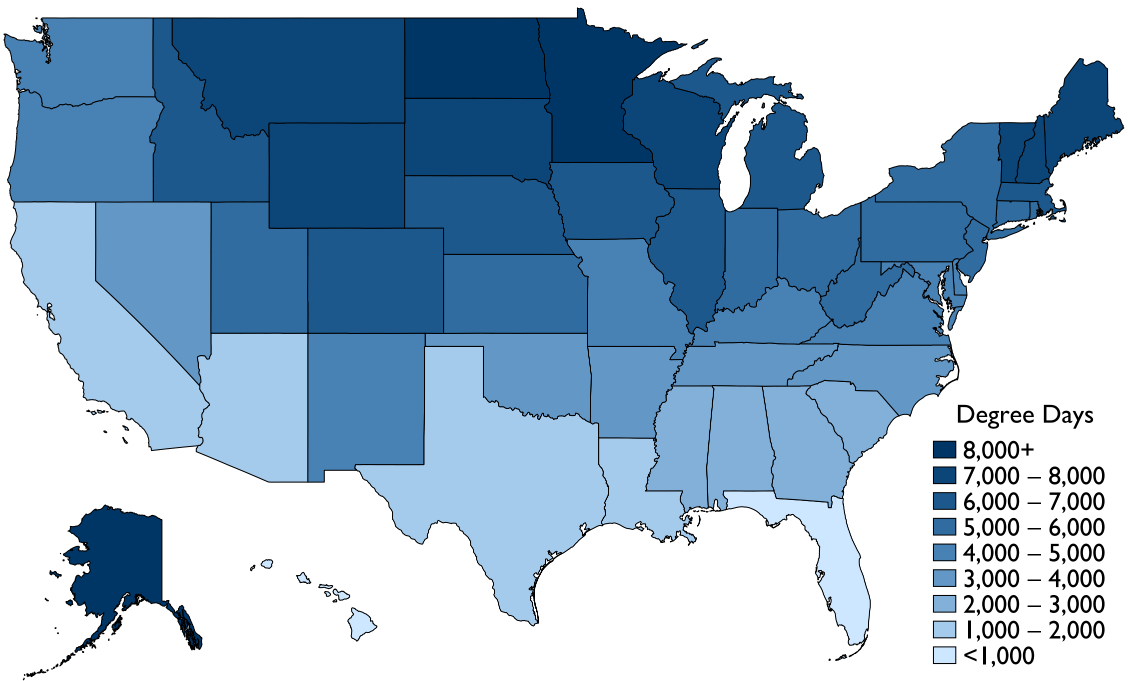
Note: This figure shows how the percent of U.S. households with low-carbon technologies varies with annual household income. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Brackets indicate 95 percent confidence intervals. LED light bulbs is defined as having "mostly" or "all" LEDs. Energy-efficient clothes washers are defined as being front-loading rather than top-loading.

Figure 3: Heat Pump Adoption By State



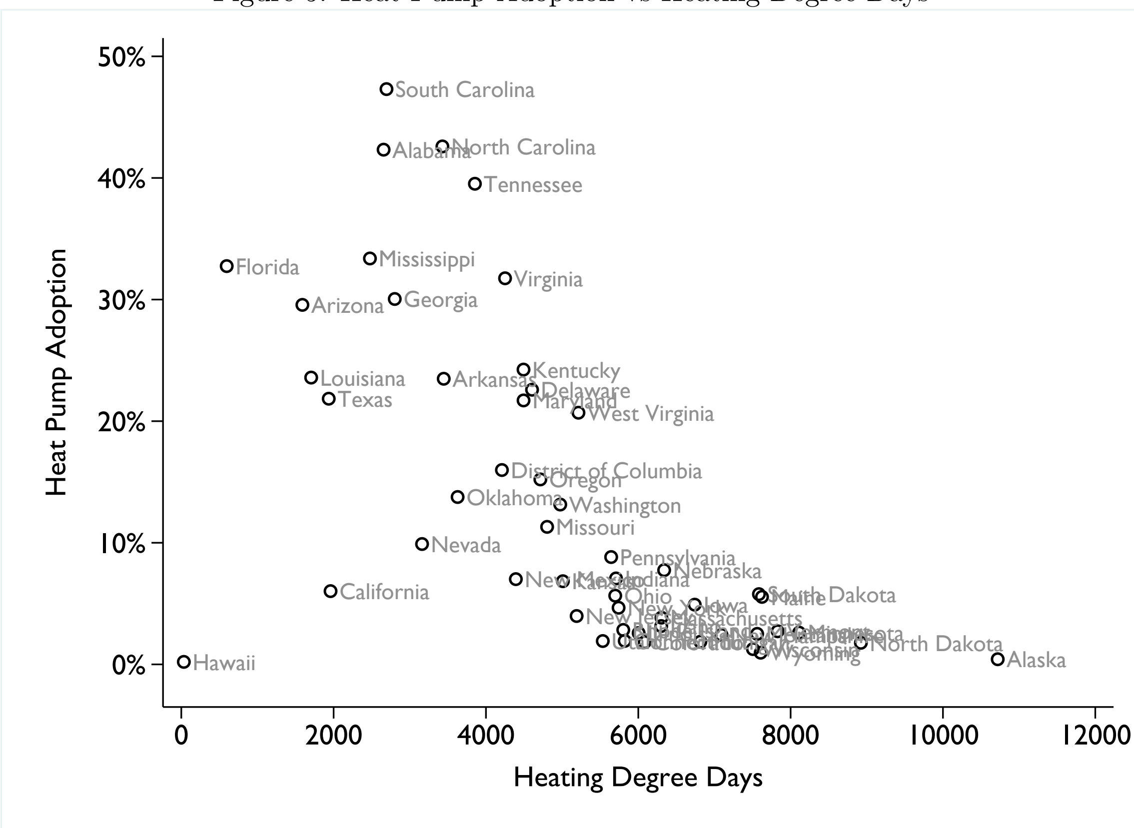
Note: This map plots the percent of households in each state that have a heat pump as their primary heating equipment. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights.

Figure 4: Heating Degree Days By State



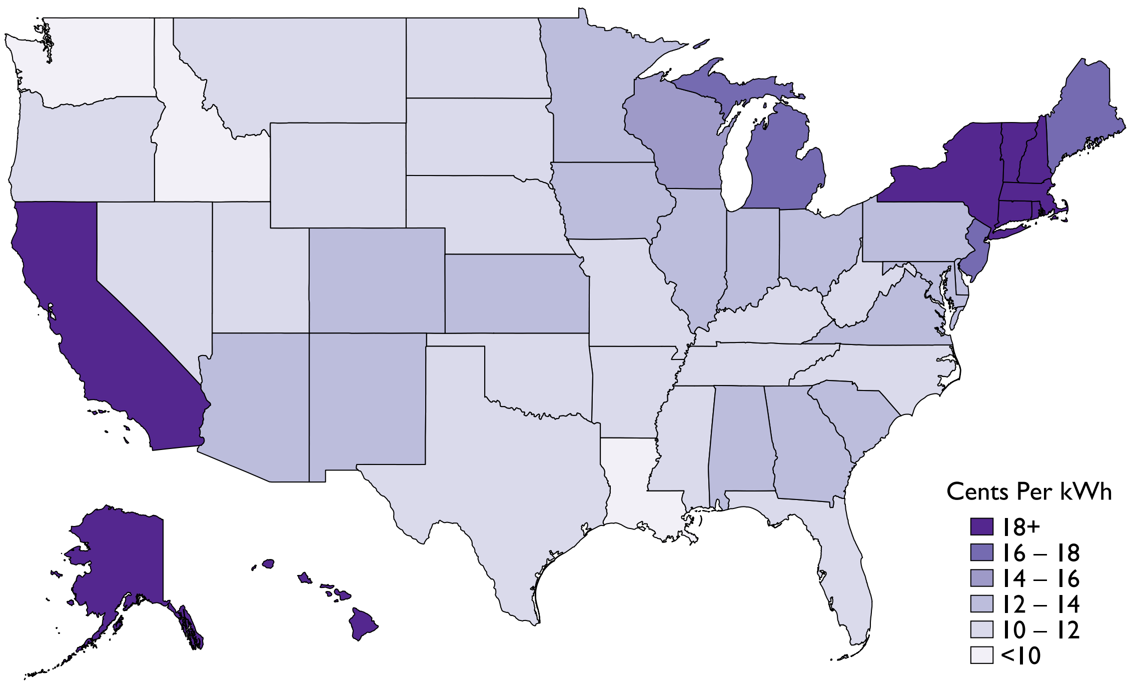
Note: This map plots heating degree days (HDDs) by state. HDDs are a widely used measure of heating demand that reflects the number of days with cold weather as well as the intensity of cold on those days. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020* and are 30-year annual averages 1981-2010, relative to a base temperature of 65°F. Households are weighted using RECS sampling weights.

Figure 5: Heat Pump Adoption vs Heating Degree Days



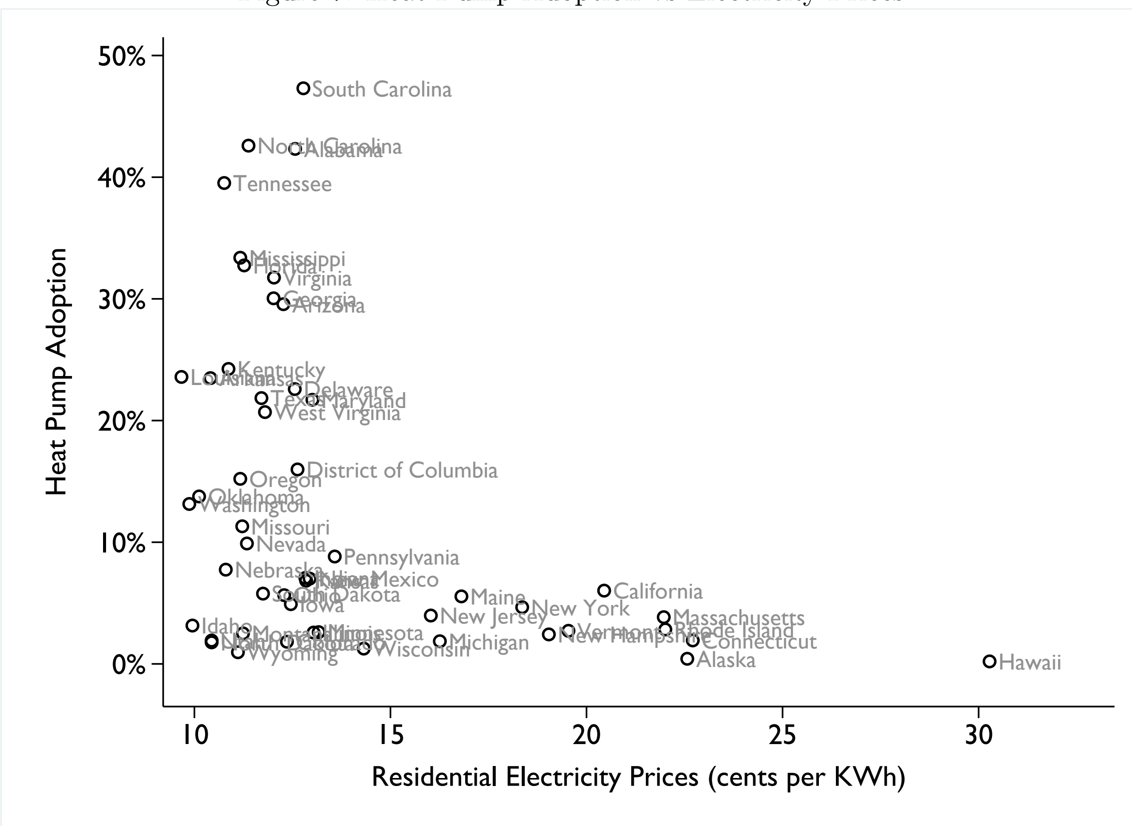
Note: This scatterplot shows the percent of households with heat pumps versus annual heating degree days. Both variables come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights. The correlation between the two variables is negative (-0.64) and strongly statistically significant (p-value .00).

Figure 6: Average Residential Electricity Prices



Note: This map plots average residential electricity prices in 2020. These data come from the U.S. Department of Energy, *Energy Information Administration*, *Electricity Data Browser* and include all relevant taxes and delivery charges.

Figure 7: Heat Pump Adoption vs Electricity Prices



Note: This scatterplot shows the percent of households with heat pumps versus residential electricity prices. The percent of households with heat pumps by state comes from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020* and was calculated using RECS sampling weights. Average residential electricity prices by state come from the U.S. Department of Energy, *Energy Information Administration*, *Electricity Data Browser* and include all relevant taxes and delivery charges. The correlation between the two variables is negative (-0.41) and strongly statistically significant (p-value .00).

Table 1: Technology Adoption By Income

Income ($1000s)	Heat Pump	Electric Vehicle	Solar Panels	LED Lights	Efficient Washer
<$30	15%	0%	1%	40%	11%
$30-$40	16%	1%	2%	44%	19%
$40-$50	16%	1%	1%	41%	17%
$50-$60	16%	1%	3%	47%	21%
$60-$75	16%	1%	3%	49%	22%
$75-$100	15%	1%	3%	48%	27%
$100-$150	15%	2%	4%	53%	32%
$150+	14%	5%	5%	54%	44%
Test of Equality (p-value)	.45	.00	.00	.00	.00

Note: This table describes U.S. adoption levels by annual household income for five low-carbon technologies. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights. The last row reports p-values from a statistical test for which the null hypothesis is that all eight percentages are equal. Except for heat pumps, there is strong evidence against the null.

Table 2: Upfront Costs for Selected Residential Equipment

Natural Gas Furnace	\$2,400 - \$3,200
Electric Resistance Furnace	\$1,300
Electric Resistance Baseboard Heaters	\$800 - \$1,700
Central Air Conditioner	\$3,900 - \$4,900
Air Source Heat Pump	\$5,400 - \$6,400
Ground Source Heat Pump	\$20,700 - \$21,700

Note: This table presents upfront costs for selected residential heating and cooling equipment. These cost estimates come from DOE (2018), and include purchase and installation costs. The table reports estimates for 2020 for equipment with a "typical" or "high" level of energy efficiency. In cases where equipment costs vary between "typical" and "high" or vary by region, this table reports the range. For electric resistance baseboard heaters, the assumed installation size is six units. Cost estimates have been normalized to reflect year 2020 dollars, and rounded to the nearest \$100.

Table 3: Heat Pump Adoption in the United States

	Percent of Households With Heat Pumps	Total Households (in Millions)
Entire United States	15%	18.9
By Geography:		
South	30%	14.0
West	9%	2.5
Midwest	5%	1.2
Northeast	5%	1.1
By Electricity Prices:		
Below Median	22%	14.0
Above Median	8%	4.9
By Climate:		
Below Median HDDs	24%	14.7
Above Median HDDs	7%	4.2
Homeowner vs Renter:		
Homeowner	16%	13.0
Renter	14%	5.9
By Type of Home:		
Single Family	16%	14.5
Multi-Unit	14%	4.4
By Size of Home:		
One or Two Bedrooms	14%	6.5
Three Bedrooms	17%	8.4
Four or more Bedrooms	14%	4.0

Note: This table describes heat pump adoption for different categories of U.S. households, as well as the implied total number of households in each category. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights. The four regions are as defined by the U.S. census. Single family homes include single family detached homes as well as single family attached homes, i.e. duplexes and townhouses.

Table 4: Heat Pump Adoption, Regression Estimates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Household Income, 100,000s	-0.01	0.01	0.01	0.01	0.01	0.01	0.01*	0.01*
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
1(South)		0.21**	0.15**	0.15**	0.15**			
		(0.04)	(0.04)	(0.05)	(0.05)			
1(Northeast)		-0.04	-0.02	-0.00	-0.00			
		(0.03)	(0.01)	(0.02)	(0.02)			
1(Midwest)		-0.04	-0.02	-0.01	-0.01			
		(0.03)	(0.02)	(0.03)	(0.03)			
Electricity Price, in logs			-0.16**	-0.18**	-0.18**			
			(0.05)	(0.03)	(0.03)			
Natural Gas Price, in logs			0.13*	0.12*	0.12*			
			(0.06)	(0.06)	(0.06)			
Heating Degree Days, 1000s				-0.01	-0.01		-0.01	-0.01
				(0.01)	(0.01)		(0.01)	(0.01)
Cooling Degree Days, 1000s				-0.01	-0.01		-0.01	-0.00
				(0.03)	(0.03)		(0.03)	(0.03)
1(Homeowner)					0.01			0.01
					(0.01)			(0.01)
1(Single Family Home)					-0.00			-0.01
					(0.02)			(0.02)
Number of Bedrooms					-0.00			-0.00
					(0.00)			(0.00)
State Fixed Effects	No	No	No	No	No	Yes	Yes	Yes
Observations	18,496	18,496	18,496	18,496	18,496	18,496	18,496	18,496
R-squared	0.00	0.10	0.11	0.11	0.11	0.14	0.14	0.14

Note: This table reports coefficient estimates and standard errors from eight separate least squares regressions. In all regressions the dependent variable is an indicator variable for homes for which an electric heat pump is the primary form of space heating. The indicator variables 1(South), 1(Northeast), and 1(Midwest) refer to three of the four census regions, with 1(West) as the excluded variable. Electricity and natural gas prices are both state-level averages, so these variables are excluded in the regressions with state fixed effects in columns (6), (7), and (8). All regressions are estimated using RECS sampling weights. Standard errors are clustered by state. ** Significant at the 1% level, *Significant at the 5% level.

Table 5: Carbon Abatement for a $2000 Heat Pump Subsidy

Baseline Assumptions	4 tons
Higher Proportion of Recipients Additional (75% rather than 50%)	5 tons
Lower Proportion of Recipients Additional (25% rather than 50%)	2 tons
Household Otherwise Would Have Used Propane	6 tons
Household Otherwise Would Have Used Heating Oil	10 tons
Household Otherwise Would Have Used Electric Resistance Heating	22 tons
Households Assumed To Use Less Heating (20 MMBTU rather than 35)	2 tons
Households Assumed To Use More Heating (50 MMBTU rather than 35)	5 tons
Lower Discount Rate (3% rather than 5%)	4 tons
Higher Discount Rate (7% rather than 5%)	3 tons

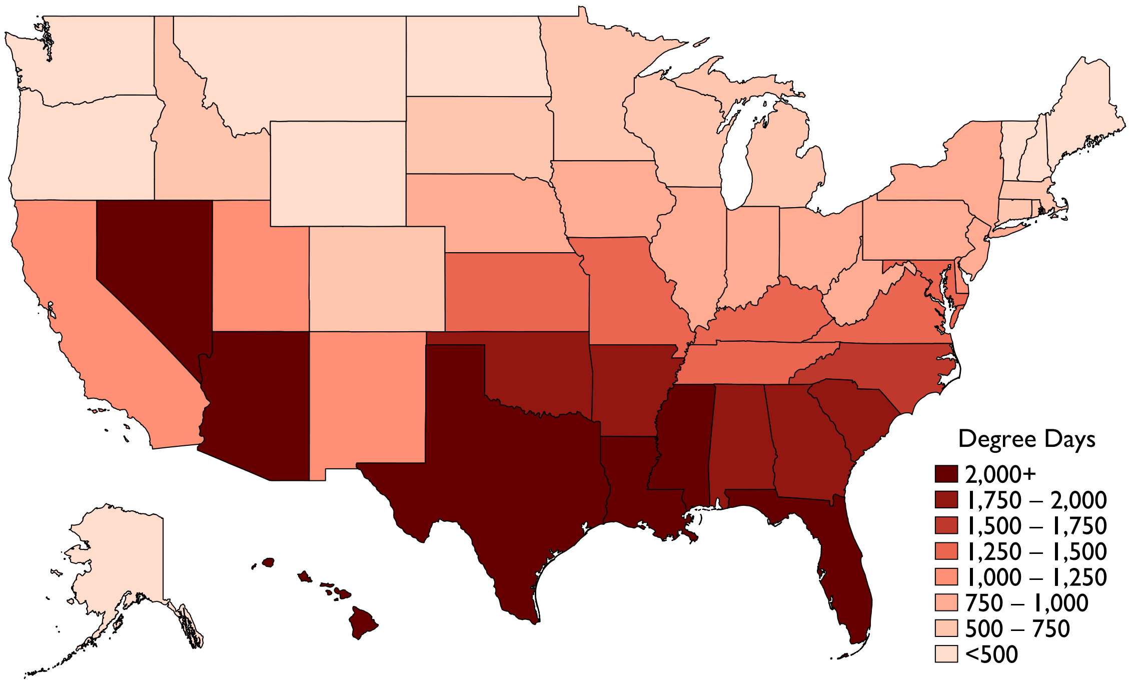
Note: This table reports calculated lifetime carbon abatement in tons for a $2000 heat pump subsidy. Under the baseline assumptions, 50% of subsidy recipients are additional, the household otherwise would have used natural gas, households use 35 MMBTU of heating per annually, heat pumps have a 20 year lifetime, and there is a 5% annual discount rate. Abatement is rounded to the nearest ton.

Table 6: Carbon Abatement for a $2000 Electric Vehicle Subsidy

Baseline Assumptions	5 tons
Higher Proportion of Recipients Additional (35% rather than 25%)	10 tons
Lower Proportion of Recipients Additional (15% rather than 25%)	3 tons
Vehicle Otherwise Less Fuel Efficient (20mpg compared to 30)	7 tons
Vehicle Otherwise More Fuel Efficient (40mpg compared to 30)	3 tons
Vehicles Driven Less (7,500 Annual Miles Traveled)	4 tons
Vehicles Driven More (12,500 Annual Miles Traveled)	7 tons
Lower Discount Rate (3% rather than 5%)	6 tons
Higher Discount Rate (7% rather than 5%)	5 tons

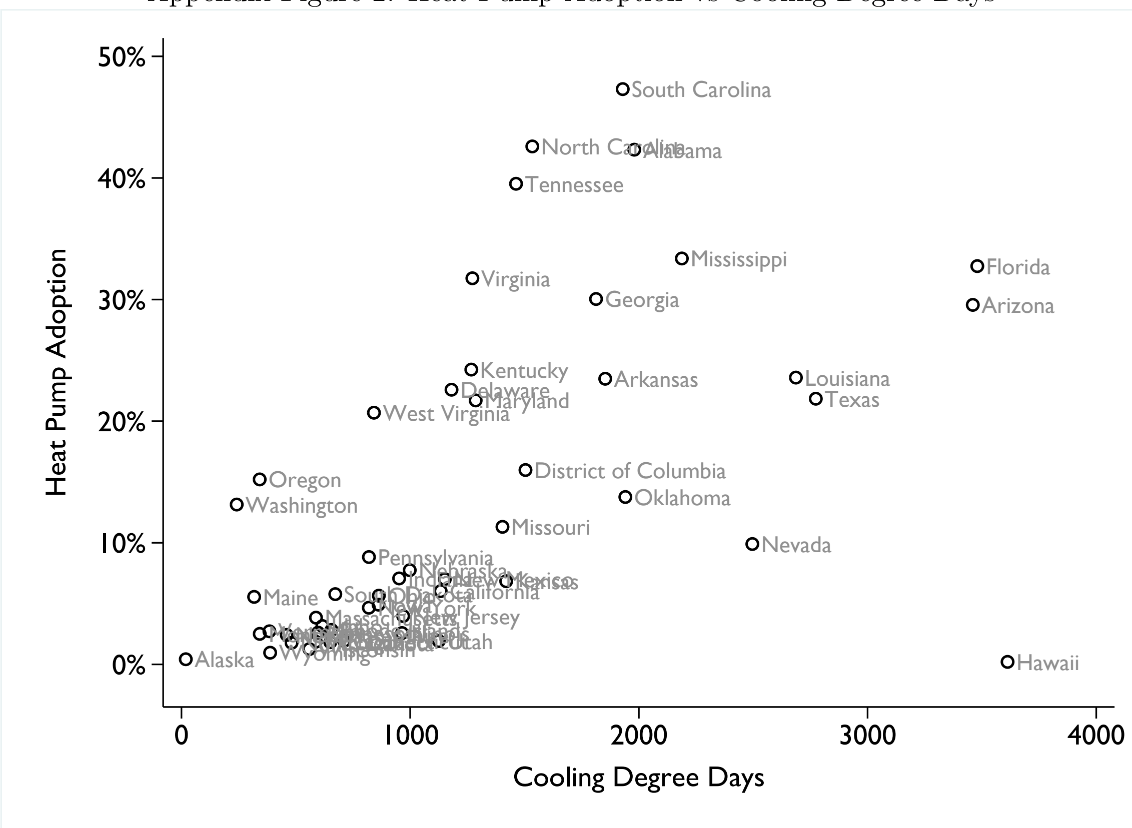
Note: This table reports calculated lifetime carbon abatement in tons for a $2000 electric vehicle subsidy. Under the baseline assumptions, 25% of subsidy recipients are additional, households otherwise would have used a gasoline-powered vehicle that gets 30 miles-per-gallon and is driven 10,000 miles per year, vehicles have a 15-year lifetime, and there is a 5% annual discount rate. Abatement is rounded to the nearest ton.

Appendix Figure 1: Cooling Degree Days By State



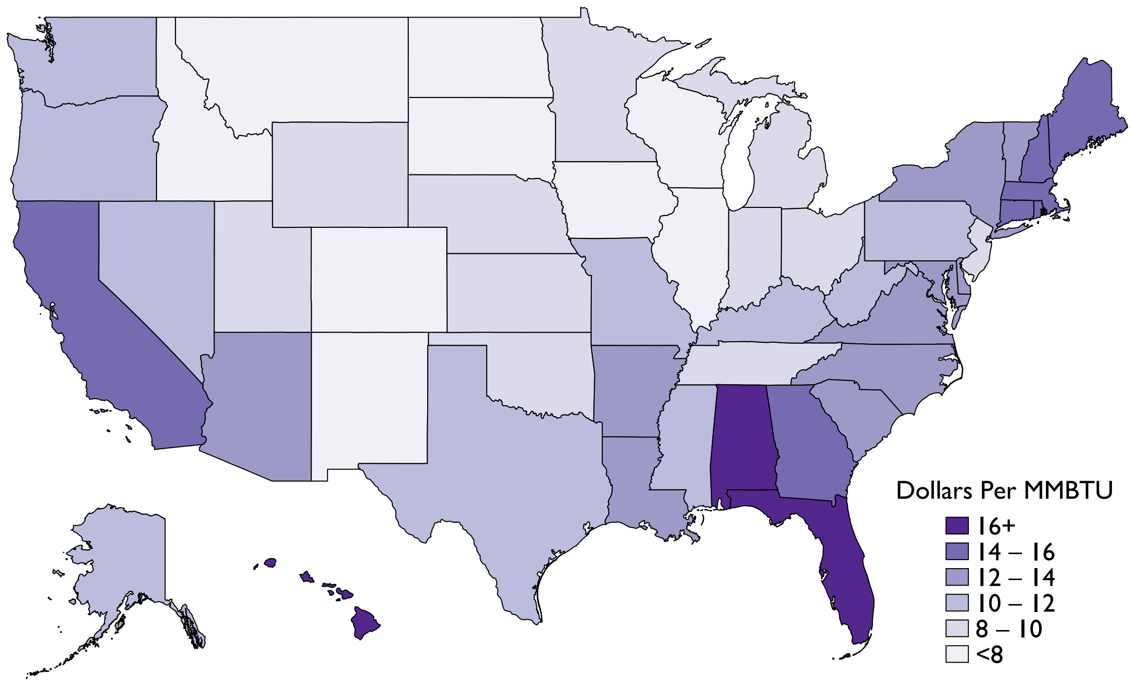
Note: This map plots cooling degree days (CDDs) by state. CDDs are a widely used measure of cooling demand that reflects the number of days with hot weather as well as the intensity of heat on those days. These data come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020* and are 30-year annual averages 1981-2010, relative to a base temperature of 65°F. Households are weighted using RECS sampling weights.

Appendix Figure 2: Heat Pump Adoption vs Cooling Degree Days



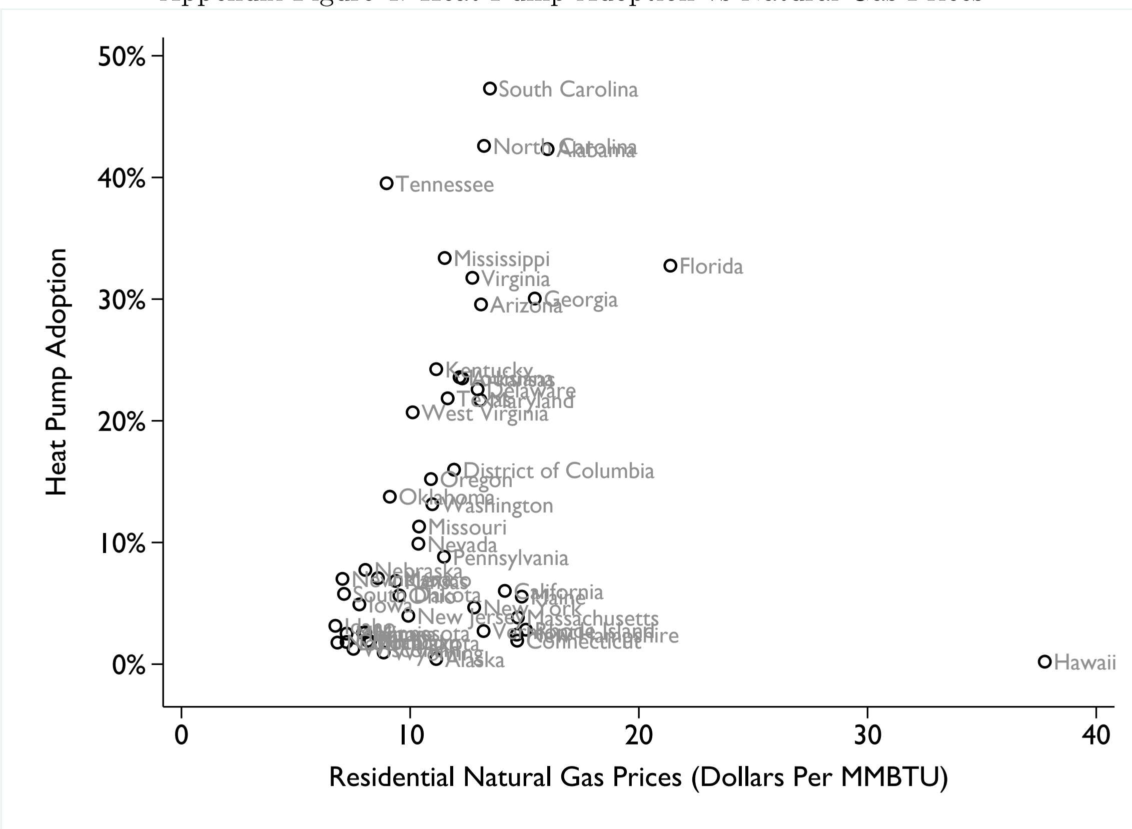
Note: This scatterplot shows the percent of households with heat pumps versus annual cooling degree days. Both variables come from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020*. Households are weighted using RECS sampling weights. The correlation between the two variables is positive (0.55) and strongly statistically significant (p-value .00).

Appendix Figure 3: Average Residential Natural Gas Prices



Note: This map plots average residential natural gas prices in 2020. These data come from the U.S. Department of Energy, *Energy Information Administration* and include all relevant taxes and delivery charges. See `https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm`.

Appendix Figure 4: Heat Pump Adoption vs Natural Gas Prices



Note: This scatterplot shows the percent of households with heat pumps versus residential natural gas prices. The percent of households with heat pumps by state comes from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020* and was calculated using RECS sampling weights. Average residential natural gas prices by state come from the U.S. U.S. Department of Energy, *Energy Information Administration* and include all relevant taxes and delivery charges. See `https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_a.htm`. The correlation between the two variables is positive (0.18) but not statistically significant (p-value .20).

Appendix Table 1: Heat Pump Adoption By State, Ranked By Percentage

	Percent	Total (Millions)		Percent	Total (Millions)
1. South Carolina	47%	0.9	26. Kansas	7%	0.1
2. North Carolina	43%	1.7	27. California	6%	0.8
3. Alabama	42%	0.8	28. South Dakota	6%	0.0
4. Tennessee	40%	1.1	29. Ohio	6%	0.3
5. Mississippi	33%	0.4	30. Maine	6%	0.0
6. Florida	33%	2.6	31. Iowa	5%	0.1
7. Virginia	32%	1.0	32. New York	5%	0.4
8. Georgia	30%	1.2	33. New Jersey	4%	0.1
9. Arizona	30%	0.8	34. Massachusetts	4%	0.1
10. Kentucky	24%	0.4	35. Idaho	3%	0.0
11. Louisiana	24%	0.4	36. Rhode Island	3%	0.0
12. Arkansas	23%	0.3	37. Vermont	3%	0.0
13. Delaware	23%	0.1	38. Minnesota	3%	0.1
14. Texas	22%	2.2	39. Illinois	3%	0.1
15. Maryland	22%	0.5	40. Montana	3%	0.0
16. West Virginia	21%	0.1	41. New Hampshire	2%	0.0
17. Oregon	15%	0.3	42. Connecticut	2%	0.0
18. Oklahoma	14%	0.2	43. Utah	2%	0.0
19. Washington	13%	0.4	44. Michigan	2%	0.1
20. Missouri	11%	0.3	45. Colorado	2%	0.0
21. Nevada	10%	0.1	46. North Dakota	2%	0.0
22. Pennsylvania	9%	0.5	47. Wisconsin	1%	0.0
23. Nebraska	8%	0.1	48. Wyoming	0%	0.0
24. Indiana	7%	0.2	49. Alaska	0%	0.0
25. New Mexico	7%	0.1	50. Hawaii	0%	0.0

Note: This table reports by state the percent of households with heat pumps and the implied total number of household with heat pumps. This information comes from the U.S. Department of Energy, *Residential Energy Consumption Survey 2020* and was calculated using RECS sampling weights. Percentages are rounded to the nearest percent and totals are rounded to the nearest 100,000.