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Estimation of change in house sales prices in the United States after heat pump adoption

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Electrifying most fossil-fuel-burning applications provides a pathway to achieving cost-effective deep decarbonization of the economy. Heat pumps offer a feasible and energy-efficient way to electrify space heating. Here, we show a positive house price premium associated with air source heat pump installations across 23 states in the United States. Residences with an air source heat pump enjoy a 4.3–7.1% (or US$10,400–17,000) price premium on average. Residents who are environmentally conscious, middle class and live in regions with mild climate are more likely to pay a larger price premium. We find that estimated price premiums are larger than the calculated total social benefits of switching to heat pumps. Policymakers could provide information about the estimated price premium to influence the adoption of heat pumps.

The increase in global average temperature must be kept below 1.5 °C above the pre-industrial level to avoid irreversible environmental damage, which requires carbon dioxide emissions to be reduced or captured and sequestered[1]. Electrifying most fossil fuel-burning applications by using renewable sources provides a pathway to achieving cost-effective deep decarbonization of the economy[2,3]. Although it is economically and technologically easier to sequester emissions from large sources such as electric power plants, reducing emissions from small widely distributed sources, including the tens of millions of natural gas furnaces used to heat homes and offices, is more difficult. Without the electrification of space heating, large amounts of carbon emissions will continue to be generated from burning natural gas for space heating even if we achieve a cleaner electricity grid.

Studies have typically identified the use of air source or ground source heat pumps as a technologically straightforward way to electrify space heating and replace fossil fuel-burning furnaces or boilers[4–7]. An increasing number of national, state and municipal decarbonization plans are reliant on the diffusion of heat pumps. For instance, the Dutch government plans to electrify buildings and fully phase out natural gas by 2050. The Irish government plans to install 600,000 highly efficient heat pumps by 2030. Finland has set a target to be carbon neutral by 2035, which includes a shift to electric heating by heat pumps. Massachusetts in the United States offers incentive programmes for switching to heat pumps from furnaces. From a social planner's perspective, promoting heat pumps to electrify space heating will help achieve deep decarbonization with a clean electricity grid. Further advantages of heat pumps include energy-efficient space cooling, given the huge potential demand for air conditioning in developing countries[8], they can help to balance electricity demand through demand-side smart management, given the high penetration of renewable energy in the grid in the future, and also relieve the problem of natural gas infrastructure constraints in the winter when there is peak demand for natural gas for heating in the northern United States.

Residential installations of air source heat pumps have increased in recent years in the United States. However, the distribution across states is not balanced. The Pacific, Mountain, South Atlantic and West North Central regions enjoy a higher penetration of air source heat pumps, while other regions have a much lower penetration, which implies a large potential for further growth (Fig. 1). The heterogeneous growth of air source heat pump installations begs the question of whether this new technology has been recognized in the housing market. In this study we have investigated how the installation of air source heat pumps affects house prices in the United States, and whether the presence of a heat pump increases house values (that is, a heat pump-induced price premium). The heat pump-induced price premium provides useful information for sellers and buyers to better assess house values as well as the technological value. More importantly, a positive price premium associated with the presence of air source heat pumps will be useful for policymakers to design information programmes to influence the adoption and diffusion of heat pumps. For instance, the government could highlight the positive price premium induced by heat pumps and put a certified 'energy-efficient heat pump' label on homes with heat pumps in an information campaign.

Several studies[9–12] have provided evidence of the price premiums of residential properties after installing solar panels or solar water heaters, with the premiums ranging from 3.5 to 17%. Other studies[13–18] looked at the capitalization of residential energy efficiency investment into property values and found that the property price premiums with energy efficiency rating or green building labelling range from 2 to 10%. Studies of commercial properties[19–21] also found that green-certified office buildings enjoy a premium on transaction prices or rents. Existing studies of price premiums from energy efficiency mostly focus on green certification or energy efficiency ratings, not on specific technologies such as heat pumps. Despite the benefits of energy efficiency investments, there is a persistent gap between the level of energy efficiency investment that is projected to save money and the investment that actually occurs[22]. Common explanations focus on market failures, such as imperfect information, capital market failures, split incentive problems and consumer behaviour[23–25]. Fowlie et al.[22] and Liang et al.[26] found that the actual energy savings are lower than the predictions of engineering models.

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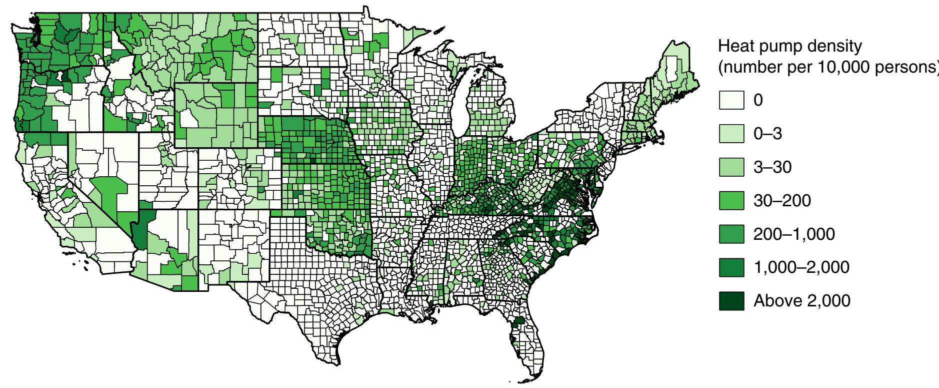

Fig. 1 | The distribution of air source heat pumps by county level in the United States in 2018. The map shows the number of air source heat pumps per 10,000 population in the United States in 2018. The data are taken from the ZTRAX database[27] (Supplementary Note 1).

This paper contributes to the literature using hedonic pricing methods to value energy technologies and energy efficiency investment. This study provides empirical evidence for the house price premium induced by air source heat pumps and its heterogeneity by different influencing factors. This paper also contributes to the literature on the 'energy efficiency gap'. In this research we have found a large house sales price premium induced by air source heat pumps, providing a strong incentive for installing heat pumps. The positive house sales price premium can be regarded as a substantial private benefit in energy efficiency investment that helps close the 'energy efficiency gap'. This study has produced three key findings. First, we estimated the house sales price premiums induced by air source heat pumps using observations across 23 states of the United States and found that residences with an air source heat pump enjoy a 4.3–7.1% (US$10,400–17,000) price premium on average. Second, we explored the heterogeneity of the price premium by investigating its relationship with other factors. The results show that residents who are environmentally conscious, middle class and live in regions with mild climate are more likely to pay a larger price premium. Third, we compared the price premium with the benefit and cost of switching from a traditional heating, ventilation and air-conditioning (HVAC) system to an air source heat pump and found that the estimated price premiums are larger than the installation costs of heat pumps and larger than the calculated total social benefits of switching to heat pumps.

House price premium induced by air source heat pumps

We estimated the house sales price premium induced by air source heat pumps using the difference-in-differences (DID) approach with exact matching at the county level based on property data from the Zillow Transaction and Assessment Database (ZTRAX)[27]. The data consist of two types: building characteristics for each house in the United States from six assessments from 2016 to 2018, and historical transaction records across the United States. The treatment group consists of houses with installed heat pumps. Based on the heat pump installation dates, we categorized the transaction prices as pre- or post-treatment prices. The control group consists of the houses using the same types of heating and cooling systems other than heat pumps across all the assessments and sold at least twice during a similar data window. The transaction records in our final analysis are from 2000 to 2018 (not just during the period 2016–2018). Details of the data can be found in the Methods.

In our DID approach, we matched treated houses and control houses in the same county. We removed the houses that were remodelled after the year 2000 (about 4% of the total sample) from our sample to exclude the influence of remodelling on the estimation of a price premium. This gave 14,211 houses in the treatment group and 440,168 houses in the control group across the country covering 23 states.

We ran a DID specification (two-way fixed effects model) by regressing the natural logarithm of transaction prices on a dummy variable of installing a heat pump, controlling for building age, county-by-year fixed effects, month-of-year fixed effects and individual property fixed effects to capture building, neighbourhood, regional and intertemporal confounding factors. Details of the sample restriction and DID modelling can be found in the Methods. The coefficient of the heat pump installation dummy variable measures the average treatment effect on the treated (ATT). Our estimated ATT is 7.1%, meaning that the installation of air source heat pumps induces a positive price premium, suggesting that houses with air source heat pumps enjoy an additional 7.1% (or US$17,000) sales price premium on average compared with houses with other heating and cooling systems holding other factors fixed (for the full statistical estimation results see Supplementary Note 2, Supplementary Tables 2–5 and Supplementary Fig. 2).

DID specifications rely on panel intertemporal variation and may fail to measure the slope of the hedonic function of price. The DID estimates could be biased if the hedonic gradient changes over time[28,29]. We conducted alternative analyses using cross-sectional data in conjunction with nearest-neighbour matching as a robustness check (Supplementary Note 3 and Supplementary Tables 6 and 7). The results of the robustness checks are consistent with our main results and show positive price premiums.

The lower bound of the price premium

Contemporaneous energy efficiency and building upgrades may also be captured by the dummy variable of the heat pump in our model and cause the price premium to be overestimated. If these upgrades are counted as remodelling in the data, our results are unbiased because we dropped all houses remodelled after the year 2000. We conducted additional analyses to further eliminate the influence of contemporaneous upgrades.

First, we show that the difference in energy efficiency investments other than the heat pump is minor between houses with and without heat pumps. The ZTRAX[27] data show that treated houses did not have non-heat-pump energy-efficient space heating and cooling technologies. Also, we used the 2015 Energy Information Administration Residential Energy Consumption Survey Data[30] to compare the adoption of non-heat-pump energy efficiency measures of houses with and without heat pumps. We found that houses with installed heat pumps are more likely to have other Energy Star qualified appliances compared with houses without heat pumps, but the marginally increased probabilities are small at about 8–15% (Fig. 2a). We also found that there is no significant difference in the

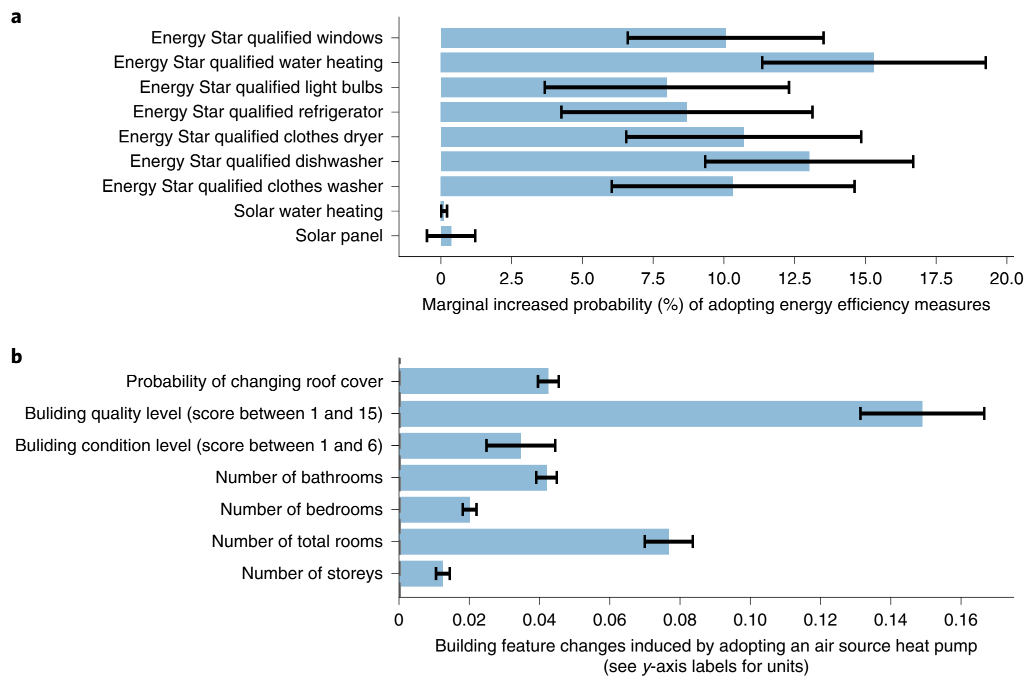

Fig. 2 | Contemporaneous energy efficiency and building upgrades correlated with air source heat pump adoption. a, The marginally increased probability of adopting other energy efficiency measures of houses with heat pumps against other houses without heat pumps. **b**, The building feature changes induced by the adoption of an air source heat pump. The data are taken from the 2015 Energy Information Administration Residential Energy Consumption Survey[30] and ZTRAX data[27]. The error bars show 95% confidence intervals.

installation of a solar panel or a solar water heater between houses with and without heat pumps (Fig. 2a).

Second, we show that the correlation between other contemporaneous building retrofits (for example, adding rooms, improving building quality) and the adoption of air source heat pumps is small in our sample. The correlation may lead to a biased coefficient of the treatment dummy in the DID approach. We regressed the dummy variable of heat pump adoption on building feature changes using the observations of six assessments of ZTRAX[27] data from 2016 to 2018, including both the treated and control houses of our DID analysis. All the coefficients have small, although significant magnitudes due to the large sample size, suggesting that the adoption of an air source heat pump entails a small probability of other building retrofits. On average, the adoption of an air source heat pump is correlated with an increase of 0.03 levels of building condition (score between 1 and 6), 0.15 levels of building quality (score between 1 and 15), 0.01 storeys, 0.08 total rooms, 0.02 bedrooms, 0.04 bathrooms and 4% probability of changing the roof cover (Fig. 2b). Our main conclusion of positive price premiums still holds even after accounting for the market values of these minor impacts (changes of 0.64–2.04% from the average building features).

To further eliminate the concern over contemporaneous energy efficiency and building retrofits, we multiplied the unit monetary value of the energy efficiency measures and building features by the estimated marginal increase correlated with heat pump installation. We then subtracted the sum of the products from the previously estimated price premium to obtain a lower bound of the price premium, which is 4.3% (US$10,400). We used the average prices of the Energy Star qualified measures to estimate their values. We applied a cross-sectional hedonic model by regressing house prices on building features to estimate the values of the building features (for the detailed estimation of the lower bound of the price premium see Supplementary Note 4, Supplementary Tables 8–11 and Supplementary Figs. 3–5). The ATT of 7.1% (US$17,000) estimated in the previous section can be treated as an upper bound.

The heterogeneity of the price premium

The house sales price premium induced by air source heat pumps may differ across different regions and demographic groups. We examined the heterogeneity of the price premium by investigating the correlation of the price premium with several other important factors, including residents' environmental awareness at the county level, air source heat pump adoption rate at the county level, personal income per capita at the county level, average annual heating degree days and annual cooling degree days[31] from 1981 to 2010 at the meteorological station level. We used the percentage of people who believe global warming is happening in a county to measure the residents' environmental awareness, based on the Yale Program on Climate Change Communication[32]. None of the above factors is strongly correlated with another except for heating degree days and cooling degree days (Supplementary Fig. 6).

We applied a flexible semiparametric approach using the partially linear varying coefficient fixed effects panel data model. This approach allows for linearity in some variables and non-linearity in others, where the effects of these regressors on the outcome variable vary non-parametrically on the basis of low-dimensional variables[33], which shows advantages in estimating non-linear heterogeneity. For details of the model specifications see Methods.

Figure 3 shows the estimated relationships between the price premium and other factors. The data reveal that residents who are environmentally conscious, middle class or live in regions with a mild climate are most likely to pay a higher price premium for houses with air source heat pumps. The price premium induced by heat pumps is not statistically significant for people in regions with too low or too high levels of environmental awareness, heat pump penetration rate, income, heating degree days and cooling degree days. When residents care more about the environment, they are

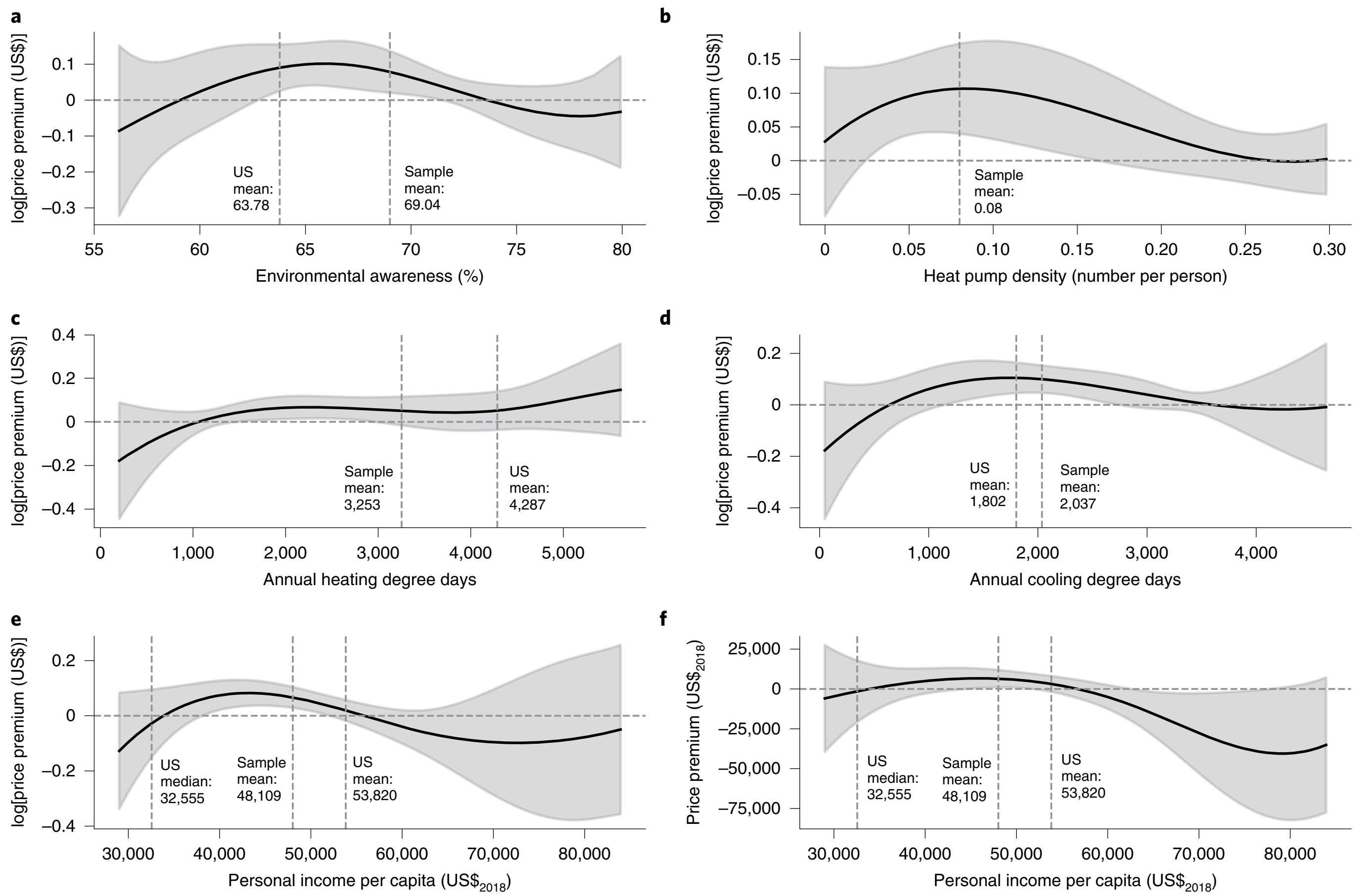

Fig. 3 | The heterogeneity of the price premium induced by air source heat pumps. a, The relationship between price premium and residents' environmental awareness. We used the percentage of people who believe that global warming is happening in a county to measure the residents' environmental awareness, based on the Yale Program on Climate Change Communication[32]. **b**, The relationship between price premium and heat pump penetration rate. **c**, The relationship between price premium and annual heating degree days. **d**, The relationship between price premium and annual cooling degree days. **e**, The relationship between price premium (log) and personal income per capita (US$$_{2018}$). **f**, The relationship between price premium (US$$_{2018}$) and personal income per capita (US$$_{2018}$). We fitted these curves on the basis of a partially linear varying coefficient fixed effects panel data model. The grey shaded areas represent 95% confidence intervals.

more willing to pay extra money for the 'environmentally friendly' air source heat pumps. However, as environmental awareness further increases, residents may favour other green technologies that are more visible to others, such as solar panels, home energy storage and electric vehicles, to show the environmental status of the owners. This leads to an inconspicuous price premium when environmental awareness is high. The insignificant and lower price premium when the penetration rate is very low can be explained by uncertainty in the adoption of novel technologies. During the very early stages of technology adoption, consumers have little knowledge about how to use the technology, its performance and future return[34]. In this case, consumers tend to observe the behaviour of another person who has used the novel product to infer the usefulness of this product[35,36]. Thus, the first user will have much less incentive to adopt the new product[24], which leads to a lower/insignificant price premium when the penetration rate is very low. The house price premium shows a downward trend when the penetration rate is larger, which could be due to lower installation costs, information searching costs and transaction costs with increasing penetration rate (see the detailed explanation in Supplementary Note 6). The relationship between price premium and heating degree days or cooling degree days is consistent with the physics of heat pumps (for a detailed explanation see Supplementary Note 6 and Supplementary Figs. 7 and 8). When the income level is low, households cannot afford to upgrade their homes, which leads to an insignificant price premium. High-income households may spend a large amount of money on other house retrofits. Thus, home buyers will pay more attention to these other distinguished and salient house features, and the heat pump will be overlooked among high-income residents.

Because house prices are higher among high-income residents, the percentage of the price premium induced by heat pumps will be diluted by the high house price if we use only the log of price as the outcome variable. Thus, we also used the absolute price as the outcome variable and deleted the observations for the top and bottom 1% sales prices to reduce the influence of extreme values. We reran the model and found that the new estimated relationship is consistent with our previous findings (Fig. 3e,f). The price premium still declines when the income level increases above the average level and the inverted 'U' relationship still holds.

Residents' environmental awareness may also be related to political affiliation or racial background. Due to the data limitation and the scope of the paper, we have only explored the correlation between price premium and other factors. Although our research only demonstrates potential correlation, future research may explore the causal mechanism channels (for example,

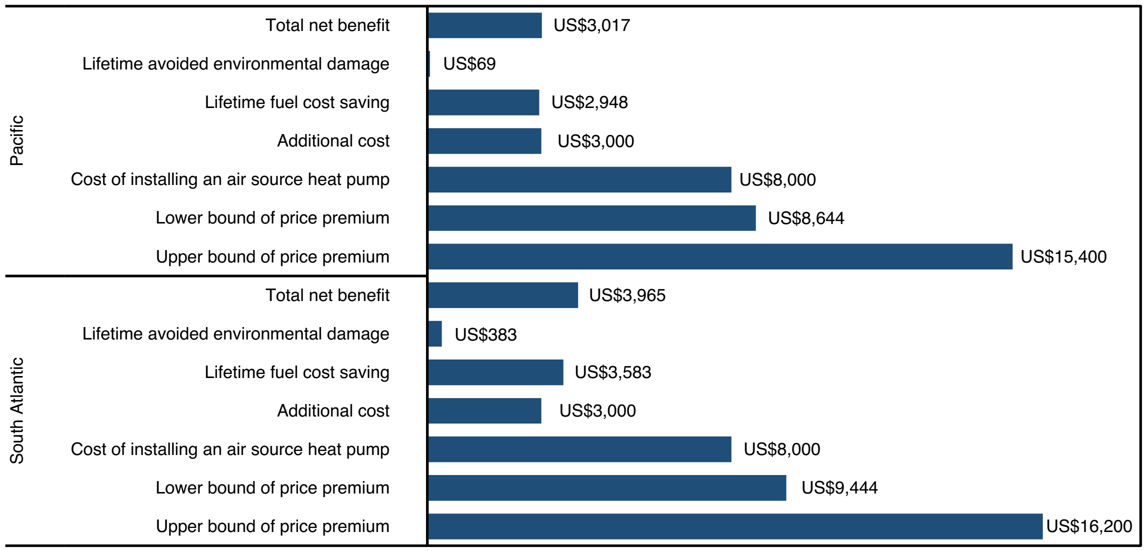

Fig. 4 | Comparing the price premium with the cost and benefit of replacing a traditional HVAC system with an air source heat pump. The lifetime fuel cost saving, lifetime avoided environmental damage, the total net benefit of switching to an air source heat pump from a traditional HVAC system with the current power grid, the cost of installing an air source heat pump and the additional cost are compared with the house price premium induced by the installation of air source heat pumps in the Pacific and South Atlantic regions of the United States (the values are US$ from 2018). The costs of installing an air source heat pump and a traditional HVAC system depend on the size of the home and type of equipment. The cost of installing an air source heat pump typically ranges from US$4,000 to US$12,000. The cost of installing a traditional HVAC system typically ranges from US$3,000 to US$7,000. The extra cost of installing an air source heat pump compared with an HVAC system is about US$3,000. The upper bound of the price premium was estimated directly from the DID model. The lower bound of the price premium is the upper bound minus the product of the values of contemporaneous energy efficiency and building upgrades and the probability of conducting these other upgrades together with installing heat pumps.

political affiliation, demographics) that impact the willingness to pay for heat pumps.

We also conducted a robustness check using a traditional method based on interaction terms between the treatment variable and a set of dummies for different quantiles of the distribution of other influencing factors. The estimated results, which are consistent with the results obtained using the partially linear varying coefficient model, are presented in Supplementary Table 15.

Discussion

We have provided here empirical evidence on the effect of air source heat pump adoption on residential property values. Houses with an air source heat pump enjoy on average a 4.3–7.1% (US$10,400–17,000) sales price premium in 23 states of the United States.

To better understand the estimated price premium, we compared the price premium with the installation cost of an air source heat pump and the additional cost and net benefit of replacing a traditional HVAC system with an air source heat pump. The additional cost is the extra cost of installing an air source heat pump compared with a traditional HVAC system and the net benefit includes lifetime fuel cost saving and lifetime avoided environmental damage, including reduced emissions of CO_2 and other hazardous pollutants. The procedures used to estimate the costs and benefits are presented in Supplementary Note 7. We made these comparisons in two regions (the census divisions of South Atlantic and Pacific) as we can only provide precise estimates of the price premium for the divisions of the South Atlantic and Pacific with enough observations for the DID approach (Supplementary Note 5 and Supplementary Tables 12–14).

We found that, in both the Pacific and South Atlantic regions, the upper bound of the price premium (US$15,400 and US$16,200, respectively) and the lower bound of the price premium (US$8,644 and US$9,444, respectively) are larger than the average installation cost of an air source heat pump (the average installation cost is about US$8,000). The additional cost is close to the lifetime fuel cost saving (US$2,948 and US$3,583, respectively) as well as the total net benefit (US$3,017 and US$3,965, respectively) associated with a switch from a traditional HVAC system to an air source heat pump. The results of these comparisons are presented in Fig. 4.

The relatively high price premium (compared with the installation cost) can be explained by the transaction cost, information searching cost and cognitive cost. In an equilibrium resale market, the house price premium approximates the sum of the installation cost, transaction cost, information searching cost and cognitive cost. If the house price premium is larger than the sum of these costs, people will buy a house without heat pumps and install one themselves assuming that the value of dismantled old HVAC equipment is close to zero. First, a resident may be willing to pay to avoid complications such as removing the old heating system, doing necessary upgrade work and having to wait at home for the complete installation work (all of which can be thought of as transaction costs)[24]. These costs, including the opportunity cost of lost time, can be quite high for some homeowners or certain types of houses (or certain existing heating systems). Moreover, given the low penetration rate of heat pumps, inexperienced installers may increase the time, cost and risk of installation[37,38], contributing to even higher transaction costs. Second, there are information searching costs[38] for consumers who need to spend time and effort gathering and comparing different information on the price and performance of heat pumps between different installers. Currently, there is no one-size-fits-all heat pump in the United States. The costs and capacity needed for different homes vary. It is not straightforward to obtain price information on heat pumps for a specific building, because a good estimate may require the installer to visit the home. Third, there are cognitive costs for consumers who need knowledge literacy and to expend effort to understand a new technology (for example, heat pumps) and the financial aspects (upfront cost versus future benefits) and then make a decision to adopt it. Complex information may impede some consumers' understanding and rational behaviour[39,40]. Literacy could be a important determinant of investment in energy efficiency[41]. Some consumers may not think of the option of heat pumps when their HVAC systems break and need to be replaced.

Divergence between installation cost and house price premium has also been observed for other energy technologies using housing characteristics and transaction data. For example, two recent studies[10,12] found a positive house sales price premium induced by solar panels ranging from US$23,000 to US$28,000 in 2012 and 2014. This price premium is also larger than the installation cost of solar panels, which was US$14,400 for an average-sized 3.6 kW photovoltaic system in 2014[42].

Figure 4 shows that the lifetime fuel cost savings associated with a heat pump compared with a traditional HVAC system are large enough to compensate homeowners for the additional cost of installing an air source heat pump, and also that the house resale price premium is large enough to compensate the installation cost of the heat pump. Nonetheless, the penetration rate of air source heat pumps in the United States is still low. There may be several explanations for this 'energy efficiency gap'. First, most home buyers do not know whether and when they will sell their homes in the future. Uncertainties can lower house owners/buyers' willingness[43] to adopt new energy technologies. Second, imperfect and asymmetric information[24] on the benefits of heat pumps could impede adoption. Third, liquidity constraints also matter given that the median American household only has about US$12,000 in savings[44]. Fourth, a heat pump may not be attractive for some consumers (for example, for homes without new or robust electrical wiring, or households that do not use space heating and cooling very often) even though it is attractive for the average consumer given the 'consumer heterogeneity'[23].

Nevertheless, our results show that the value of the heat pump is recognized by the housing market and home buyers. Our estimated price premium is larger than the cost of installing an air source heat pump, which is valuable information for homeowners who are deciding whether to install heat pumps. A significant positive price premium reduces consumer risk of not being able to recover their investments when selling their houses[43]. This is an important contribution to the literature on the 'energy efficiency gap', as studies typically compare fuel cost savings with the initial cost of installation. The significant positive house price premium is an important incentive for energy efficiency investment. Policymakers could use the information on potential price premiums to influence consumer choice in addition to traditional energy guides, which typically focus on fuel costs. For instance, the government or other authorities could spread information on heat-pump-induced price premium and put a certified 'energy-efficient heat pump' label on homes with heat pumps to encourage adoption.

Many nations, states and cities have introduced decarbonization plans that rely on the conversion to heat pumps as discussed earlier in the introduction. Given the increasing importance of electrification, our study adds a new dimension to quantifying the benefit of installing heat pumps. There are significant house price premiums and net social benefits associated with a switch to heat pumps in the Pacific and South Atlantic regions of the United States. Three types of factors may influence the full social benefits of heat pumps, including the net fuel cost savings and net environmental savings associated with the electrification of space heating and cooling, the evolution of the electric grid in the future and other potential benefits associated with the heat pump. More studies are needed to systematically quantify the social benefits of switching to heat pumps to better assist policymaking.

Methods

Data. The ZTRAX[27] data were provided by Zillow. The 4 TB of data covers more than 150 million homes in 51 states with building characteristics (for example, heating types, rooms, area, view, land value, building quality, year built) for each house from six assessments conducted between 2016 and 2018, as well as historical transaction records since 1900 across the United States. We identified heat pump installations by comparing the difference in heating types between two consecutive assessments. If the heating types differed in two consecutive assessments and in the later assessment the heating type was a heat pump, a house installed a heat pump during the time window between the two assessments. Based on the heat pump installation dates, we categorized the transaction prices as pre- or post-treatment prices. Details of the data structure can be found in Supplementary Note 1, Supplementary Table 1 and Supplementary Fig. 1. The control group consisted of the houses using one traditional heating system (gas, coal, hot water, none, oil, radiant, steam and wood burning) and one air-conditioning system (central air conditioning, packaged air-conditioning unit, evaporative cooler, ventilation and none) that were sold at least twice during a similar data window. To make the sales dates of the control group close to those of the treatment group, we limited the second sales dates of the control group to be after 2016. All the transaction records in our analysis were from 2000 to 2018. We also removed the houses that were remodelled after the year 2000 from our sample to rule out the influence of remodelling on the estimation of the price premium. These houses remodelled after 2000 only account for a small portion (4%) of our full sample. Finally, we matched treated houses and control houses in the same county to obtain 14,211 houses in the treatment group and 440,168 houses in the control group across 23 states.

Empirical strategy. We applied the DID method with exact matching at the county level to compute the ATT of the installation of air source heat pumps on house prices based on the ZTRAX[27] data across the United States. We also used cross-sectional data in conjunction with the nearest-neighbour matching approach as a robustness check.

There are three common challenges to estimating ATT, namely the selection bias, omitted variable bias and model dependence. Many cross-sectional studies have applied the outcome of units in the control group as the counterfactual, which potentially leads to selection bias[45]. In the context of the housing market, the price of a house with a heat pump if it had not installed the heat pump may be different from the price of a comparable house in the control group. The second major concern is that the assignment to the treatment group may be correlated with unobservable variables that also influence the outcome of interest[46]. The treatment variable then becomes endogenous. For instance, the level of education in a region could be an unobservable variable that influences residents' environmental protection awareness and further influences the installation of heat pumps. The level of education also affects personal income and house prices. Another major concern is model dependence. The actual relationship between variables may not be consistent with the assumed models. For instance, most studies applied a hedonic linear regression model to estimate house values. The conditional expectation function could be non-linear and lead to biased estimation. To address these concerns, we used the DID method (two-way fixed effect model) to estimate the ATT of adopting a heat pump on the house sales price. We also adopted nearest-neighbour matching using cross-sectional data as a robustness check. Below we describe each method in detail.

DID model. To address the concern of selection bias and omitted variable bias, in this study we applied the DID method to obtain the treatment effect based on the following equation[47]:

$$\text{Treatment effect} = (E[Y_{ist}|s = \text{treated}, t = \text{post}] - E[Y_{ist}|s = \text{treated}, t = \text{pre}]) \\ -(E[Y_{ist}|s = \text{control}, t = post] - E[Y_{ist}|s = \text{control}, t = \text{pre}])$$

where E is the expectation function, Y_{ist} is the outcome of unit i in the group s at time t, 'post' represents the time after receiving the treatment and 'pre' is the time before the treatment. The DID approach can rule out the influences of neighbourhood and community, natural environment, building-specific fixed features, consumer-specific fixed characteristics and other unobserved time-invariant factors. To obtain a causal treatment effect, the parallel trend assumption is required between the treatment group and the control group to control for the influence of time-variant factors. We matched treated houses with control houses at the county level for our national estimation (covering 23 states) and matched at the city level for a regional estimation. In most places in the United States, the house property tax is calculated at the county level. We assume that the treated houses and control houses share a common macro time trend in the same county or city. We matched at the county level for the national estimation to obtain observations covering as many areas across the United States as possible. Matching at the city level in a national dataset will remove more regions from our sample. To justify the parallel trend assumption, we regressed the log of house prices on interaction terms between an indicator for being in the treatment group and the year of the transaction, controlling for county-by-year fixed effects, month-of-year fixed effects, property fixed effects and building age using only pre-treatment data. We found that all the coefficients on the interaction terms are insignificant, which is consistent with the parallel trend assumption (for the results of the test see Supplementary Note 2).

We adopted the following two-way fixed effect model, which can be regarded as a generalized DID model:

$$\ln Y_{ict} = \beta D_{it} + \alpha B_{it} + \delta \mathbf{V}_{it} + \varphi_i + \sigma_c \times \vartheta_t + \mu_t + \varepsilon_{ict}$$

where $\ln Y_{ict}$ is the natural logarithm of the sales price of house i at time t in county c. The price was converted into 2018 dollars adjusted for inflation rates. D_{it} is the treatment variable, which takes a value of one when house i has received the treatment (that is, installed the heat pump) at time t. In our regression model, D_{it} takes a value of one only if house i is in the treatment group and the post-treatment period. φ_i controls individual fixed effects, capturing all the time-invariant individual building-specific characteristics. $\sigma_c \times \vartheta_t$ represents county-by-year fixed effects, capturing unobservable common features in each year of each county, such as changing local housing market conditions. μ_t represents month-of-year fixed effects, absorbing variation over the annual cycle in the housing market. Moreover, B_{it} is the building age since it was built or remodelled (whichever is later). ε_{ict} is an idiosyncratic error term. We clustered our standard errors at the house level, allowing for arbitrary correlations between any two observations within the same house. Remodelling a house can greatly influence the house value. We can only observe the remodelling date for each house in our dataset but cannot observe the degree of remodelling. Thus, we removed the houses that were remodelled after the year 2000 from our sample to ensure no houses were remodelled between two transactions in our sample, which can help to rule out the influence of remodelling on the estimation of the price premium. Houses remodelled after 2000 only account for a small portion (4%) of our full sample. We further included a vector of control variables $\mathbf{V}_{it}$ to control other time-variant factors, namely federal fund rates, demographic features by county level[48] and state-level prices of electricity and natural gas[49]. These variables will be dropped when we include county-year fixed effects although we include these variables in other model specifications when the county-year fixed effects are not present. We obtained a robust causal effect of heat pump systems on house prices where there were no other unobservable time-variant differences between the control and treatment groups.

We conducted an additional robustness check by restricting the sample to transactions that occurred between 2016 and 2018 to directly control for the time-variant building features in our DID model. We still observed a price premium for the heat pump (Supplementary Note 8 and Supplementary Table 16).

Cross-sectional data with nearest-neighbour matching. The DID approach relies on intertemporal price variation. However, the estimates would be biased if the hedonic gradient shifts over time[28]. To address this issue, we employed an alternative approach that uses cross-sectional data in conjunction with the nearest-neighbour matching technique following Muehlenbachs et al.[29]. To reduce the selection bias, we needed to ensure that both groups (treatment and control groups) were almost identical except for the treatment variable. The nearest-neighbour matching is based on the conditional independence assumption[45], which controls the selection bias conditional on observed features or covariates. However, the matching covariates in our dataset cannot cover all house features. The DID is therefore our preferred specification and the cross-sectional estimation with matching serves as a robustness check.

We first applied an exact match in the time dimension (transaction year) to control for unobservable time-variant factors and in the geographic dimension (city) to control for unobservable neighbourhood factors. We then applied propensity score matching to find the three nearest neighbours in the control group for each treated house based on the covariates of time-invariant building characteristics[10]. The covariates for matching were the key house characteristics, including year built, number of storeys, number of rooms, number of bedrooms, building area and land assessed value. After the matching procedure, we ran an ordinary least squares model by regressing the log of the house sales prices on a treatment dummy variable and the house feature covariates. The treatment dummy variable takes a value of one for treated houses, otherwise it takes a value of zero. The coefficient of the treatment variable is our estimated ATT. The ATT estimated using cross-sectional data with matching (Supplementary Note 3) is consistent with the results of the DID approach.

We also conducted a robustness check by focusing on new buildings using the cross-sectional data. We still found a positive price premium, which is consistent with our main findings (Supplementary Note 9 and Supplementary Table 17).

The heterogeneity of the price premium. We explored the heterogeneity of the price premium by applying a flexible semiparametric approach, namely the partially linear varying coefficient fixed effects panel data model[33]. This method allows for linear funcation in some variables and non-linear function in others, where the effects of these non-linear regressors on the outcome variable vary based on low-dimensional variables non-parametrically[33], which has advantages for estimating non-linear heterogeneity. The model has been widely used previously[50–52]. We adopted the following model:

$$\ln Y_{it} = D_{it} \times g(U_{it}) + \beta \mathbf{V}_{it} + \varphi_i + \vartheta_t + \mu_t + \varepsilon_{it}$$

where Y_{it} is the sales price of house i at time t. U_{it} is a continuous variable of an influencing factor associated with the house i at time t. D_{it} is a treatment variable with functional coefficient $g(U_{it})$. $\mathbf{V}_{it}$ is a vector of control variables to control for other time-variant factors, namely federal fund rates, demographic features by county level and the price of electricity and natural gas by state level. φ_i represents individual fixed effects, ϑ_t denotes year fixed effects and μ_t represents month-of-year fixed effects. We used a linear combination of sieve basis functions to approximate the unknown functional coefficient $g(U_{it})$.

The historical federal fund rate data were obtained from the online database of Macrotrends[53]. The population density and personal income per capita data by county were obtained from the Bureau of Economic Analysis, US Department of Commerce[54]. The monthly natural gas price[55] and annual electricity price[56] data by state were obtained from the US Energy Information Administration. The residents' environmental awareness data were obtained from the Yale Program on Climate Change Communication[32]. The local adoption rates of air source heat pumps by county were calculated on the basis of ZTRAX[27] data. The data on heating degree days and cooling degree days were obtained from the National Oceanic and Atmospheric Administration[57]. The heating degree days and cooling degree days were computed on the basis of a base temperature of 18.33 degrees Celsius.

Data availability

Individual property data were provided by Zillow through the Zillow Transaction and Assessment Database (ZTRAX). More information on accessing the data can be found at https://www.zillow.com/research/ztrax/. The data are proprietary and are not publicly available under a non-disclosure agreement with Zillow. Interested readers can submit a request to Zillow for approval to obtain the data. Other data used for this analysis are available from the publicly available sources cited or from the authors upon reasonable request. Source data are provided with this paper.

Code availability

The custom code of the data processing and analysis is deposited and managed on GitHub (https://github.com/willshen21/heat-pump-house-price-premium).

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X.S., P.L. and Y.Q. designed the study and planned the analysis. X.S. conducted the data analysis and drafted the paper. P.L., Y.Q. and P.V. edited the paper. P.V. provided initial calculations on private and social benefits. All authors offered revision suggestions and contributed to the interpretation of the findings.

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The authors declare no competing interests.

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