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Impacts of electric-driven heat pumps on residential electricity consumption: An empirical analysis from Arizona, USA

Jing Liang [a], Yueming (Lucy) Qiu [b,*], Bo Xing [c]

[a] School of Public and International Affairs, Princeton University, 307 Robertson Hall, Princeton, NJ, 08540, USA
[b] School of Public Policy, University of Maryland College Park, 3135 Van Munching Hall, College Park, MD, 20742, USA
[c] Department of Forecasting, Resource Planning, and Development, Salt River Project, Tempe, AZ, 85281, USA

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ABSTRACT

Heat pumps play an important role in the electrification of the residential sector. The electrification of building energy consumption can have a significant impact on the load management of the electric grid. This study provides the first empirical investigation of the changes in hour-of-day loads after adopting heat pumps. We apply unique hourly electricity data for 13,010 residential consumers in Arizona during 2014–2019. Statistical matching, fixed effects regression, and difference-in-differences approach are applied to analyze electricity consumption. Contrary to the predictions from engineering models which indicate energy savings after heat pump adoption, our main analysis suggests that heat pumps do not necessarily save electricity for cooling and heating in Arizona. Besides, we also quantify the increase in electricity consumption when switching from natural gas furnaces to heat pumps. The increased environmental damages from electricity changes are estimated to be $0.59 per household during the summer and $1.64 during the winter. This also indicates an increase for electric loads by 8.8 (2.7) MW in the winter (summer) if all SRP utility consumers shifted to heat pumps. The findings have implications for the energy performance of heat pumps at households. The results could also help improve the sustainability of the electric sector, which can integrate more clean energy into a smarter grid.

1. Introduction

Residential energy consumption accounts for around 20% of the total energy consumption in the United States and is significant for the mitigation of energy-associated emissions (Pérez-Lombard et al., 2008; Aydin and Brounen, 2019). While it is difficult to capture emissions from small, distributed sources such as fossil-fuel-burning appliances in households, electrifying homes promotes deep decarbonization by replacing the fossil fuels with more renewable energy (National Research Council, 2010; Denis et al., 2015; Shen at al., 2021). Electrification of the residential sector has been widely supported by many countries and regions. For example, the Netherlands and California in the U.S. all plan to electrify the buildings and phase out the usage of natural gas in residential buildings.

Heat pumps are commonly used for heating and cooling in the United States, which takes over half of residential energy use (EIA, 2019). Therefore, they play an important role in the electrification of residential buildings given that with more electricity, fewer fossil fuels will be required for the buildings (Knobloch et al., 2020). Many studies have shown that heat pumps contribute to clean energy transition and greatly reduce carbon emissions and other pollutants (Huang and Mauerhofer, 2016; Xu et al., 2017). Heat pumps function by extracting heat from outside and transferring it into homes during the winter. The process is reversed to cool the houses in the summer. Heat pumps are energy efficient because the energy they transfer to heat is much more than that they require. Thus, they are promoted by many policymakers as an energy-efficient measure to reduce building energy consumption (Frontier Economics, 2013).

Existing studies generally indicate that heat pumps lead to savings of different magnitudes, ranging from about 10% to 54% (Kelly and Cockroft, 2011; Sivasakthivel et al., 2014; Morrone et al., 2014; Wu et al., 2015; Asaee et al., 2017). However, most of them rely on simulation or modeling methodologies, missing a thorough experimental and empirical examination of the energy performance. Pre-determined engineering parameters such as the Coefficient of Performance (COP), Energy Efficiency Ratio (Blum et al., 2010; Huang

* Corresponding author.
E-mail address: yqiu16@umd.edu (Y.(L. Qiu).

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and Mauerhofer, 2016; Xu et al., 2017), and Seasonal Performance Factors (SPF) are usually used to estimate the energy consumption and associated environmental impacts (Bayer et al., 2012; Greening and Azapagic, 2012). An empirical evaluation with empirical data is critical since the actual savings could be smaller than what models predict (Staffell et al., 2012; Liang et al., 2018), and few studies have been dedicated to such an empirical evaluation, probably due to data availability. Although one of the studies found that heat pumps save energy after heat pump installation (Xu et al., 2020), others have also shown that savings are not necessarily achieved (Gram-Hanssen et al., 2012; Raynaud et al., 2016). While the extant studies mostly rely on annual electricity data from a limited number of buildings, our study will use a unique dataset of hourly electricity consumption for a large sample of 13,010 households. We will provide the first empirical investigation of the change in hour-of-day loads after heat pumps. Knowledge of hour-of-day loads (i.e., 24 h during a day) is important for future smart grid management and electricity supply. The information could also help to integrate more variable energy sources (e.g., wind and solar) at the right time during a day, which could further improve the sustainability of the electricity sector (Corbett et al., 2018).

This study focuses on heat pump adoption in Arizona, which has the largest number of heat pumps in the U.S. (Sarbu and Sebarchievici, 2014), among which air source heat pumps are the most common electric-driven type. In this study, we will quantitatively compare the electricity consumption between households that have already adopted heat pumps (i.e., treated group) with those that have not adopted the technology (i.e., control group). To better compare the treated group with the control group, a statistical matching called propensity score matching is applied before running further analysis. Then, we apply the fixed effects regression to get the changes in hour-of-day loads. This way, we can mimic an experimental design using observational data, in which the only difference between the treated group and the control group is the treatment of heat pump adoption. Due to data constraints, this study applies a post-test-only design, which also belongs to quasi-experiment design (Tappen, 2016; Krishnan, 2021). We acknowledge that this post-treatment only analysis relies more on the comparison between heat pump homes with control ones, which might differ by some unobservables (Nair et al., 2010).

Using a sub-sample of the data, we also apply a difference-in-differences approach (DID), which is a special case of the fixed effects regression. The DID analysis helps further examine the causal relationship between electricity consumption and heat pump adoption. Although we have included all the possible household characteristics and building attributes, it is possible that the households may adopt other retrofits while installing a heat pump, then our estimates of electricity savings will be biased, and in that case, the results from this study can be seen as an upper bound of savings.

This paper is organized as follows. Section 2 describes the data and section 3 presents the methodology. Then, sections 4 and 5 show the results for the main analysis and the DID analysis. Finally, section 6 concludes and provides some policy implications.

2. Data

In this study, we use the smart meter data from a major utility company Salt River Project that contains hourly demand in kWh from January 2014 to April 2019 and it includes a total of 13,010 households in the Phoenix metropolitan area, Arizona. We also obtained the 2014 and 2017 Residential Equipment and Technology (RET) surveys conducted by the utility, which have information on energy appliances, housing characteristics and socio-demographics. The participants were selected randomly. The response rate was 19%. We obtained households' heating and cooling systems from questions "What is the primary type of heating equipment used to heat your home?" and "What type of cooling system do you have?" In this study, heating equipment mainly includes three types: gas furnaces, heat pumps, and electric heaters. Cooling systems are divided into air conditioning (AC) units and heat pumps.

Table 1
Number of heat pump consumers and control consumers.

	Cooling	Heating	
	Heat pump vs. AC	Heat pump vs. natural gas furnace	Heat pump vs electric heater
Heat pump consumers	6,447	8,913	8,913
Non-heat pump or control consumers	3,995	2,888	1,209
Total	10,442	11,801	10,122

The two RET surveys were conducted in July/August in 2014 and June/July in 2017. We do not have information on the exact dates of heat pump adoption since they were not reported. We can only be sure of the households' status of heat pumps after July/August in 2014 or June/July in 2017. Due to this constraint, we firstly conduct a fixed effects regression for the post-treatment period. This analysis uses the full sample data, including all households, but only data after RET survey submission are kept. However, although we do not know the exact treatment time, we can infer a time window of treatment. We, therefore, infer the time between two RET surveys as the time window of treatment. After that, we run a Difference-in-Differences (DID) analysis, using the sub-sample data that include fewer households, but it covers both pre-treatment and post-treatment periods. A DID analysis compares the changes in electricity consumption before and after the treatment and between the treated group and the control group.

For the fixed effects panel regression, we only include post-treatment data. The data before surveys were dropped.[1] For both the fixed effects analysis and DID analysis, the 2014 and 2017 surveys are merged with the smart meter data. After merging, there are 301 households from the 2014 survey and 12,709 households from the 2017 survey[2] (Table 1) for the fixed effects analysis while the DID analysis includes 370 households, as detailed in Table X1.

Since heat pumps can be used for both heating and cooling, we separate our analysis on them into heating in the winter months and cooling in the summer months. The summer months are defined as May–October and the winter months are November–April, following SRP's definition of seasons for billing purposes.

For cooling in the summer months, we compare the heat pump consumers with AC consumers (control group) (Table 1). For heating in the winter, consumers of different original heating systems are compared to heat pump consumers. The first comparison is between the heat pumps with natural gas. The second comparison is between the heat pumps and traditional electric heaters. Altogether, there are three types of comparisons.

Fig. 1 plots electricity consumption for cooling (panel a) and heating (panel b). The horizontal axis is the hour-by-day and the vertical axis is electricity consumption in kWh. Heat pump consumers (blue line) generally use less electricity than AC consumers (red line) for cooling, as shown in panel a. Panel b shows that for heating, heat pump consumers (blue line) have higher electricity consumption compared to gas furnaces (red line) or electric heater consumers (green line). These figures are only descriptive and do not control for housing characteristics and building attributes. In the next section, we will include housing characteristics and socio-demographics in a matching approach to ensure that heat pump consumers could be comparable to the control consumers.

[1] If a consumer appears both in the 2014 survey and the 2017 survey, data after the 2014 survey is kept. However, if a consumer reports different cooling or heating systems in two surveys, indicating changes between the 2014 survey and the 2017 survey, we keep the data after the 2017 survey.

[2] Due to limitation on identification information, 2017 survey are better merged with smart meter data than the 2014 one.

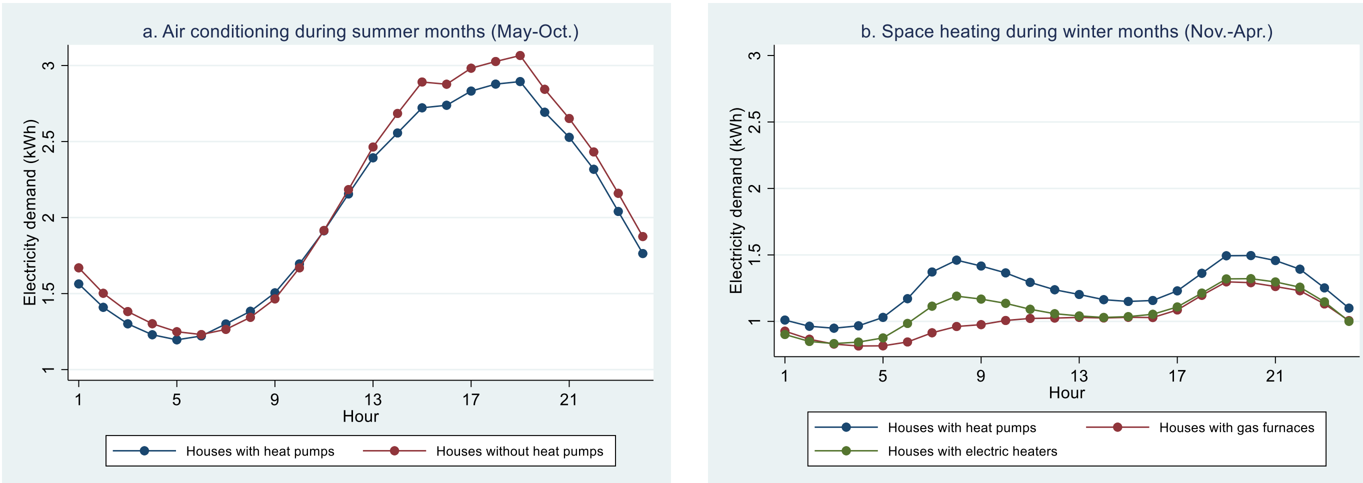

Fig. 1. Hour-by-day electricity consumption for cooling and heating.

3. Empirical strategies

3.1. The post-treatment fixed effects analysis

We apply propensity score matching (PSM) to help eliminate the systematic differences between heat pump consumers and control consumers so that the only difference between them is the adoption of heat pumps. The propensity score matching matches consumers on the probability of treatment (heat pumps adoption). For a heat pump consumer, we find a control consumer (without a heat pump) located within the same zip code area and also has similar housing characteristics and socio-demographics. The matching variables include household income, square footage, household size, the race of household head, story, vintage, age of household head, residence type (primary or seasonal residence), swimming pools, and dwelling type (single-family house, mobile house, or apartment). Then, we conduct the fixed effects regression on all the matched consumers. The propensity score of matched consumers on the common support is shown in Fig. X1. The balance checking is shown in Table X2, which indicates that after matching, the treated and control consumers are comparable to each other in terms of the matching variables.

The following fixed effects regression is applied:

$$Demand_{ihd} = \alpha_z + \sum_{h=1}^{24} \beta_1^h HP_{id} * hour\_of\_day_h + \beta_2 \boldsymbol{X}_{ihd} + \beta_3 Holiday_d + \beta_4 Weekday_d + \tau_y + \delta_m + \gamma_h + \varepsilon_{ihd} \quad (1)$$

In the regression, $Demand_{ihd}$ denotes the electricity consumption for consumer i during the hour h on day d; HP_{id} refers to the adoption of heat pumps and it is 1 for the heat pump consumers and 0 for the control consumers. As discussed beforehand, only the post-treatment data are included. β_1^h s are the coefficients on the interaction terms of the heat pumps and hour-of-day indicator. They measure the hour-of-day changes of electricity consumption due to heat pumps. $\boldsymbol{X}_{ihd}$ is a vector of covariates. It includes electricity price, CDD (Cooling Degree Days), and HDD (Heating Degree Days). The electricity prices are the average hourly per kWh charges for SRP residential consumers on different rate plans, as listed in Table X3. CDD and HDD are obtained based on hourly temperatures from the National Oceanic and Atmospheric Administration (NOAA). α_z is zip-code fixed effects, which control for the time-invariant variation at the zip code level such as local energy programs and residents' environmental awareness. The time fixed effects include year fixed effects τ_y, month-of-sample fixed effects δ_m, and hour-of-day fixed effects γ_h. These time fixed effects capture the time-varying factors across different times such as seasonal patterns, economic development, and changes in local policies.

3.2. The DID analysis

Among the households that participate in both in 2014 and 2017 RET surveys, there are 16 (15) treated consumers without heat pumps in 2014 but installed heat pumps in 2017 for cooling (heating). These treated households are compared to control consumers, as those in the fixed effects analysis. For these treated households, we dropped their metering data that fall in the time window because we are uncertain of their exact installation time.

We use the following regression for the DID analysis:

$$Demand_{ihd} = \alpha_i + \sum_{h=1}^{24} \beta_1^h HP_{id} * hour\_of\_day_h + \beta_2 \boldsymbol{X}_{ihd} + \beta_3 Holiday_d + \beta_4 Weekday_d + \tau_y + \delta_m + \gamma_h + \varepsilon_{ihd} \quad (2)$$

where HP_{id} is equal to 1 only for the treated consumers after treatment and is 0 all otherwise. α_i is the individual fixed effects, which controls for the time-invariant variation at the household level, such as housing characteristics and socio-demographics. All the other variables share the same definition as those in equation (1).

4. Post-treatment fixed effects results

4.1. Cooling in the summer

Fig. 2 plots the 24 h-by-day changes in electricity consumption based on equation (1). The horizontal axis is the hour-by-day and the vertical axis shows the change in electricity consumption in kWh. The propensity score matching is used before running the regression. Regressions include zip-code fixed effects and year, month-of-year, and hour-of-day fixed effects. Electricity price, CDD, HDD, holiday, and weekend are also incorporated as covariates.

Our results indicate that no electricity savings are detected after heat pump adoption in the summer. Instead, hour 7 and hour 9 have slightly increased demand by about 0.08 kWh per household ($p<0.10$). The detailed coefficients are shown in column (1) in Table X4. All the other covariates (e.g., electricity prices, CDD, HDD) have expected signs.

The reason for no savings from heat pumps may be that some energy technologies experience quality issues and also have inadequate commissioning in practice (Liang et al., 2018). Thus, the energy savings predicted by engineering models are not realized (Graff Zivin and Novan, 2016; Fowlie et al., 2018; Qiu and Kahn, 2019). This is consistent with the results of (Gram-Hanssen et al., 2012), which also show that there is no reduction in electricity consumption after heat pump adoption.

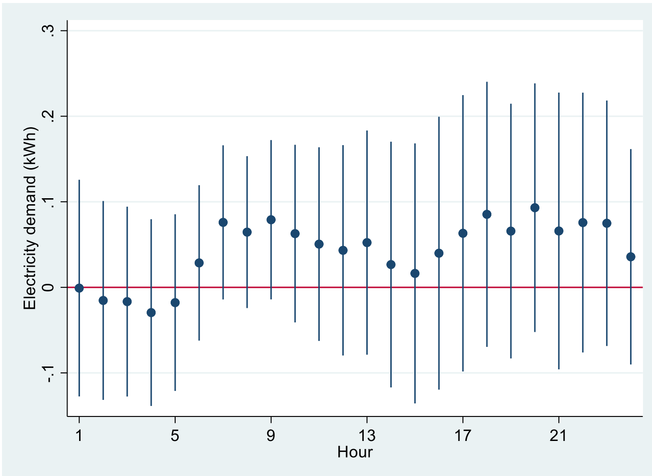

Fig. 2. Hour-of-day changes in electricity consumption from cooling (May–Oct.) after heat pump adoption. Notes: Each plot has 24 coefficients with the 95% confidence intervals. Standard errors are clustered at the consumer level.

Other possible reasons for the slight increase in consumption are as follows. (1) ACs and heat pumps function in very similar ways. Therefore, it is not surprising that no savings are detected from heat pumps if they are compared to high-performance ACs. (2) The rebound effects may exist, indicating that potential savings are reduced by behavioral changes (Greening et al., 2000). A rebound effect of 20% is observed due to increased comfort and behavioral changes (such as a longer operation time) (Gram-Hanssen et al., 2012). (3) We only rely on data of the post-treatment periods, and are primarily comparing heat pump homes with control ones. They might differ by some unobserved variables such as consumers' preferences (Nair et al., 2010). These unobserved variables also make the comparison between two types of homes suffer from some self-selection issue.

4.2. Heating in the winter

4.2.1. Heat pumps vs. gas furnaces

In this section, we compare heat pump consumers with gas furnace consumers based on equation (1). The results (Fig. 3) indicate that there is an evident increase in electricity consumption, which is intuitive given that heat pumps are electric-driven. There are two peaks, the larger one happens at 8 a.m., with an increase of 0.68 kWh per consumer while the lower one is at 9 p.m., with an increase of 0.37 kWh. This implies that more electricity will be demanded, especially during these peak hours. Consequently, with the wider electrification of buildings, this will pose challenges for the electric grid management on the supply side. All the other covariates show expected signs. The details of coefficients are seen in Table X4.

4.2.2. Heat pumps vs. electric heaters

In this section, heat pumps are compared to electric heaters. The results (Fig. 4) again show that there are no electricity savings after heat pump installations. Electricity consumption increases by 0.20 kWh both at 6 a.m. and 7 a.m. ($p<0.10$). The details of coefficients are seen in Table X4. The reasons for no savings are similar to those for cooling, as discussed earlier in the former section. It may be that heat pumps are no more efficient than traditional electric heaters, which can be turned on when needed. Other possibilities also include unpredictable operational practices and the rebound effects.

As a robustness check, we also run the analysis for data in 2018 only, because the year 2018 is certain to be post-survey year with determined adoption status while we are uncertain of the adoption status of heat pumps before the 2014 survey and also between the 2014 and 2017 surveys. Fig. X2 shows that the results for cooling (panel a), and space heating (panels b and c) are quite similar to those in the main analysis (Figs. 2–4).

It is also possible that the adoption of heat pumps correlates with switching electricity price plans (Liang et al., 2020). If this correlation is high, then our estimate is biased in that it also captures the impacts of price changes on electricity demand. Thus, our estimates can be seen as an upper bound of the real effects. However, it is also likely that only a small proportion of consumers will adopt heat pumps and switch price plans simultaneously and the correlation between the two may be low (0.03 in this study).

4.3. Emission and load impacts

Based on the hour-by-day demand changes, we provide a more precise estimation of the environmental damages from electricity generation. Because the marginal environmental emissions depend on the marginal fuel used to generate electricity, the marginal environmental emissions from the electric grid could vary by hour-of-day. We provide a

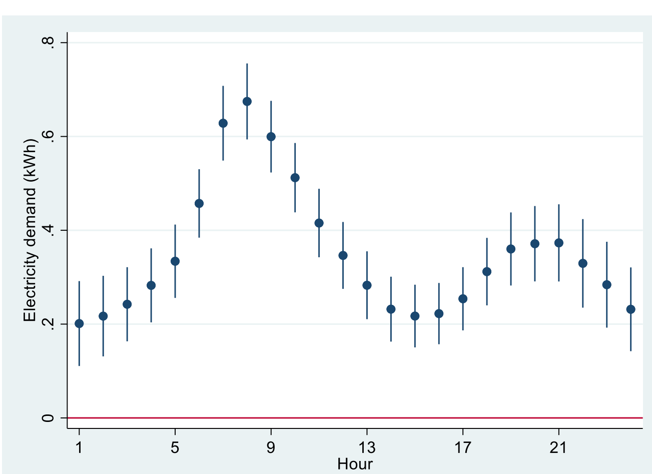

Fig. 3. Hour-of-day changes in electricity consumption (Nov.–Apr.) after heat pumps (compared to gas furnace consumers). Notes: Each plot has 24 coefficients with the 95% confidence intervals. Standard errors are clustered at the consumer level.

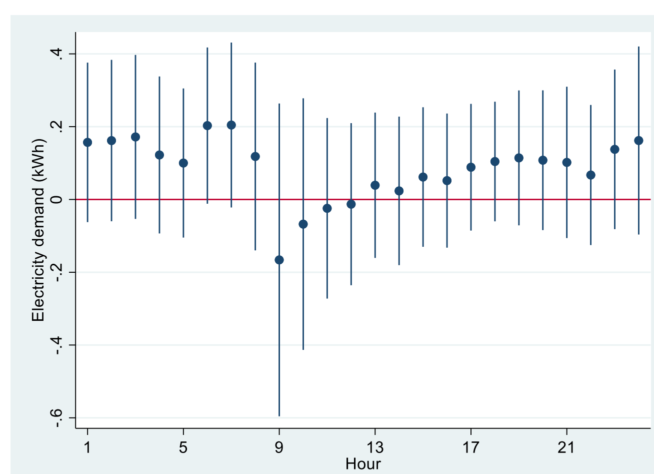

Fig. 4. Hour-of-day changes in electricity consumption (Nov.–Apr.) after heat pump adoption (compared to traditional electric heating consumers). Notes: Each plot has 24 coefficients with the 95% confidence intervals. Standard errors are clustered at the consumer level.

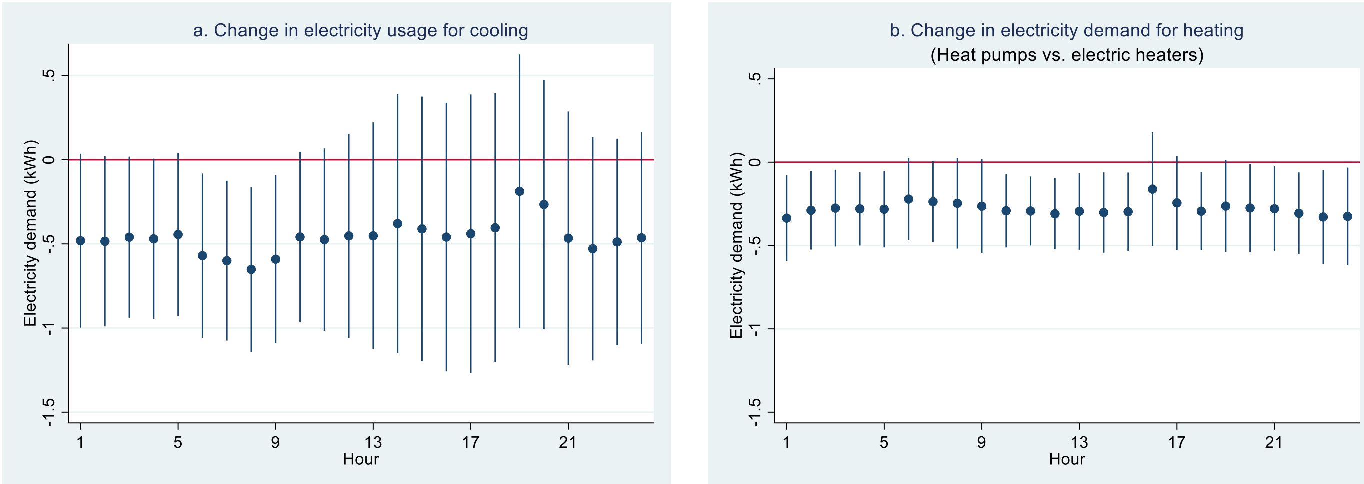

Fig. 5. Hour-of-day changes in electricity consumption by using DID analysis. Notes: Each plot has 24 coefficients with the 95% confidence intervals. Standard errors are clustered at the consumer level.

monetized valuation of environmental emissions with the current electricity generation mix.

We include the following emissions: CO_2, SO_2, NO_X, and particulate matter. The daily environmental damages per household are estimated by $\sum_h \beta_1^h MD_h$, where β_1^h is taken from our previous estimates of hour-by-day electricity changes. MD_h denotes hour-by-day marginal damage factors of different emissions for Western Electricity Coordinating Council (WECC) region, where Arizona belongs (Holland et al., 2016).

Our estimation shows that environmental damages increase by $0.59 per household after heat pump adoption in the summer. During the winter, the increase in environmental damages is $1.64 for heat pumps relative to traditional heaters. When compared with natural gas furnaces, the increase in environmental damages is $32.59 per household. However, if the decrease in natural gas usage is considered, which also generates emissions, the environmental damage is then reduced by $9.39. More details of estimation can be found in Table X5. This is in line with the findings of (Hanova and Dowlatabadi, 2007; Vaishnav and Fatimah, 2020) that a shift to heat pumps from natural gas could even lead to an increase in environmental damages under the current electricity generation mix.

The finding of slightly increased electricity consumption also has implications for load management of electric grids. Higher demand means a higher load for the power sector. If all SRP consumers shifted to heat pumps, according to our estimates, the load during peak hours of 5–9 pm would increase by 8.8 MW in the winter.[3] The hourly load would increase by 2.7 MW at a maximum in the summer. Given that the average capacity of a generating station of SRP utility in Arizona is around 600 MW, this amount of increase equals an increase by 1.5% (0.5% for the summer), which could power around 2000 houses.[4] The monetary cost of such an increase in peak load is estimated at $24,129, including capacity costs (Novan and Smith, 2018; Liang et al., 2021), delivery costs (EIA, 2017) and generation costs. The details of the estimation are seen in Table X6. The increase in electricity demand indicates that the grid operators need to add extra generating capacity. Under current situation, it is very likely this increase will be met by natural gas, which could further add to greenhouse gas burdens (Howarth et al., 2011).

5. DID results

Fig. 5 plots the hour-by-day changes in electricity consumption, using a DID analysis. Propensity score matching is also applied, and households are matched on socio-demographics and housing characteristics. The consumer fixed effects and various time (year, month-of-sample, and hour-of-day) fixed effects are also included in the regression. The DID results differ from the previous main results in section 4.2 and they indicate some electricity savings from heat pumps.

Fig. 5 (panel a) indicates that there is reduced electricity consumption from cooling during 1 a.m.–11 a.m. The hourly reduced demand (or savings) is 0.52 kWh for a household, on average. The largest electricity savings (0.65 kWh) occur at 8 a.m. Figure panel b shows that for heating, relative to traditional electric heaters, heat pumps have decreased electricity consumption almost all across the day. The largest savings are 0.34 kWh. The larger daily savings during the winter may be related to the fact that with a mild winter in Arizona, space cooling could still be needed in part of November, March, and April although these months are conserved as the winter months by the utility company SRP (Fig. X3). The details of coefficients are in Table X7.

The discrepancy on energy savings from heat pumps using different methods or in different studies may be due to factors such as heat pump efficiency, current household consumption condition, heating/cooling systems, local climate, etc. (Gram-Hanssen et al., 2012; Nadel and Kallakuri, 2016; Raynaud et al., 2016; Xu et al., 2020). It is also possible that the resulted electricity changes also depend on the types of consumers that are sampled in the study. Different consumers may be subject to different levels of behavioral changes (i.e., the rebound effects) such as setting of temperatures for heating/cooling (Greening et al., 2000; Brännlund et al., 2007).

Therefore, one of the reasons why our DID analysis is not in line with the main analysis is probably small groups of households involved in the analysis and consequentially restricted representativeness. This caveat is complicated by the self-selection bias that usually happens for energy efficiency programs (Gans et al., 2013). In this study, it is possible that the conventional DID analysis is not able to fully control for the selection bias, although propensity score matching is applied to partially soak up this bias.

6. Conclusion and policy implications

Heat pumps are important for the electrification of the residential buildings. While many studies rely on engineering energy efficiency parameters and assume that higher efficiency leads to energy savings (Xu et al., 2017), this study employs empirical data to provide the estimates

[3] It is calculated as 13010 (number of all residential consumers) *0.68 (largest kWh increase)/1000 = 8.8 MW.

[4] One MW could power on average 225 houses in Arizona: https://media.srpnet.com/srp-customers-set-records-for-energy-demand-over-weekend/

of the changes in hour-of-day load profiles after heat pump adoptions for households in Arizona. Our findings of hour-by-day changes in electricity consumption provide information for the electric sector when the electric grid is integrating more renewable energy, and thus improving the sustainability of energy generation.

Our primary analysis indicates that heat pumps have a limited effect on saving electricity. One of the reasons is that they do not perform well in the field. Their performance is highly dependent on the quality of installation and operational conditions. Energy performance will be compromised if they are set up incorrectly, operate in sub-optimal modes, or suffer from problems such as poor airflow and leaky ducts (Staffell et al., 2012; Deng et al., 2019; Shen et al., 2021).

Given the energy performance of heat pumps, one of the policy implications is that energy policymakers should be careful in terms of program design and target setting for heat pump replacements. This implication is also confirmed by studies on other energy efficiency retrofits (Graff Zivin and Novan, 2016; Fowlie et al., 2018). In addition, to improve the performance of energy retrofits, quality assurance and commissioning should be implemented to ensure the proper function of appliances (Mills, 2011; Liang et al., 2019).

Secondly, the results have implications for the grid load management. As the electrification of the residential sector is becoming an important pathway of decarbonization (Shen et al., 2021), we should ensure that increased load requirements are met by the electricity supply system. Long-term policy support for the electricity supply system is also needed for the transition to a low carbon future (Wei et al., 2013) when more clean and sustainable energy will be integrated into the grid.

Thirdly, because of the large behavioral changes after the upgrade, effective behavioral intervention programs could be implemented in conjunction with efficiency technologies (Stern, 2020; Khanna et al., 2021). The combination of behavioral changes (such as information provision, demand response program, and incentives) and technology updates could have greater potential of emissions reduction.

In this study, we apply a post-test-only design and rely primarily on the comparison between heat pump homes with control ones, which might suffer from the impacts of some unobservables. Meanwhile, we are also unable to establish a profound causal inference of heat pump adoption on electricity demand using DID analysis. A key limitation of this DID analysis is that we only have a small number of treated houses. The current results should be taken with caution when it comes to results interpretation and causal inference. The difference between the main analysis and DID analysis implies that most consumers who voluntarily adopt heat pumps are probably larger electricity users compared to non-heat pump homes, indicating the evidence of self-selection. To fully examine the causal impacts, better data with clearer installation time that enables robust DID analysis could contribute more to the studies on heat pumps. In future work, we possibly are able to conduct a more robust analysis that better investigates the causal impact of switching to heat pumps.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table X1
Number of consumers that appear in both in 2014 survey and 2017 survey

		No heat pumps in 2017	Heat pumps in 2017
Cooling	No heat pumps in 2014	114	16
	Heat pumps in 2014	38	202
Heating	Heat pumps in 2014	114	15
	Heat pumps in 2014	23	218

Notes: Total = 370.

Table X2
The balance checking after propensity score matching

Variables	Treatment	Obs	Mean	Std. Dev.	Min	Max
Household income	Control consumers	1,272	100.513	81.931	7.5	300
	Heat pump consumers	1,732	89.174	74.134	7.5	300
Square footage	Control consumers	1,272	2.100	1.103	0.5	8
	Heat pump consumers	1,732	1.954	1.070	0.5	8
Household size	Control consumers	1,272	2.617	1.413	0	12
	Heat pump consumers	1,732	2.466	1.330	0	10
White	Control consumers	1,272	0.797	0.402	0	1
	Heat pump consumers	1,732	0.812	0.391	0	1
Stories	Control consumers	1,272	1.228	0.434	1	3
	Heat pump consumers	1,732	1.192	0.407	1	3
Vintage	Control consumers	1,272	22.079	14.486	5	50
	Heat pump consumers	1,732	25.612	13.720	5	50
Household head age	Control consumers	1,272	53.979	15.410	21	80
	Heat pump consumers	1,732	55.164	15.540	21	80
Primary house	Control consumers	1,272	0.902	0.298	0	1

(*continued on next column*)

Table X2 (*continued*)

Variables	Treatment	Obs	Mean	Std. Dev.	Min	Max
	Heat pump consumers	1,732	0.904	0.294	0	1
Swimming pool	Control consumers	1,272	0.313	0.464	0	1
	Heat pump consumers	1,732	0.277	0.448	0	1
Single family home	Control consumers	1,272	0.886	0.318	0	1
	Heat pump consumers	1,732	0.859	0.348	0	1

Notes: A treated consumer is matched to a control consumer in the same zip code area, as well as on the above features.

Table X3
Salt River Project tariffs in Arizona

Pricing plan	Name	Hours	Summer rates	Summer peak rates	Winter rates
E−21	Price plan for residential super peak time-of-use service	On peak	$0.3013	$0.3568	$0.1205
		Off peak	$0.0820	$0.0844	$0.0748
	On-peak hours year-round consist of those hours from 3 p.m. to 6 p.m.; All other hours are off-peak.				
E−22	Experimental plan for residential super peak time-of-use service	On peak	$0.3013	$0.3568	$0.1205
		Off peak	$0.0820	$0.0844	$0.0748
	On-peak hours year-round consist of those hours from 4 p.m. to 7 p.m.; All other hours are off-peak.				
E−23	Standard price plan for residential service	≤700 kWh	$0.1082	$0.1148	$0.0793
		701-2,000 kWh	$0.1101	$0.1160	$0.0793
		All Additional kWh	$0.1206	$0.1311	$0.0793
E−25	Experimental plan for residential super peak time-of-use service	On-peak	$0.3013	$0.3568	$0.1205
		Off-peak	$0.0820	$0.0844	$0.0748
	On-peak hours year-round consist of those hours from 2 p.m. to 5 p.m.; All other hours are off-peak.				
E−26	Standard price plan for residential time-of-use service	On-peak	$0.1937	$0.2206	$0.1010
		Off-peak	$0.0718	$0.0721	$0.0701
	Summer on-peak hours consist of those hours from 1 p.m. to 8 p.m.; winter on-peak hours consist of hours from 5 am to 9 am and from 5 p.m. to 9 p.m.				

Table X4, Change in electricity consumption by hour-of-day from the adoption of heat pumps (post-treatment analysis)

Variables	Cooling	Space heating (HP vs. gas furnace)	Space heating (HP vs. electric heater)
Hour1*HP	-0.001(0.065)	0.201***(0.046)	0.157(0.112)
Hour2*HP	-0.015(0.059)	0.217***(0.044)	0.162(0.113)
Hour3*HP	-0.017(0.057)	0.242***(0.040)	0.172(0.115)
Hour4*HP	-0.029(0.056)	0.283***(0.040)	0.122(0.110)
Hour5*HP	-0.018(0.053)	0.334***(0.040)	0.100(0.104)
Hour6*HP	0.029(0.046)	0.457***(0.037)	0.203*(0.109)
Hour7*HP	0.076*(0.046)	0.628***(0.041)	0.205*(0.115)
Hour8*HP	0.065(0.045)	0.675***(0.041)	0.118(0.131)
Hour9*HP	0.079*(0.047)	0.600***(0.039)	-0.166(0.219)
Hour10*HP	0.063(0.053)	0.512***(0.038)	-0.068(0.176)
Hour11*HP	0.051(0.058)	0.416***(0.037)	-0.024(0.126)
Hour12*HP	0.043(0.063)	0.346***(0.036)	-0.013(0.113)
Hour13*HP	0.052(0.067)	0.283***(0.037)	0.039(0.102)
Hour14*HP	0.027(0.073)	0.232***(0.035)	0.024(0.104)
Hour15*HP	0.016(0.078)	0.217***(0.034)	0.062(0.098)
Hour16*HP	0.040(0.081)	0.222***(0.033)	0.052(0.094)
Hour17*HP	0.063(0.082)	0.254***(0.034)	0.089(0.089)
Hour18*HP	0.085(0.079)	0.312***(0.037)	0.104(0.084)
Hour19*HP	0.066(0.076)	0.360***(0.040)	0.114(0.094)
Hour20*HP	0.093(0.074)	0.371***(0.041)	0.108(0.098)
Hour21*HP	0.066(0.082)	0.373***(0.042)	0.102(0.106)
Hour22*HP	0.076(0.077)	0.329***(0.048)	0.067(0.098)
Hour23*HP	0.075(0.073)	0.284***(0.047)	0.138(0.112)
Hour24*HP	0.036(0.064)	0.232***(0.046)	0.162(0.132)
CDD	0.030***(0.001)	0.024***(0.001)	0.024***(0.001)
HDD	0.056***(0.003)	0.024***(0.001)	0.034***(0.002)
Electricity price	-4.352***(0.195)	-4.962***(0.369)	-4.502***(0.850)
Weekend	0.047***(0.006)	0.072***(0.004)	0.091***(0.009)
Holiday	0.052***(0.006)	0.047***(0.003)	0.056***(0.008)
-cons	1.652***(0.198)	0.859***(0.131)	0.431**(0.192)
Zip-code fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Month-of-sample fixed effects	Yes	Yes	Yes
Hour-of-day fixed effects	Yes	Yes	Yes
N	14,671,906	14,362,303	5,166,449
R^2	0.272	0.096	0.097

Table X5
Monetary valuation of emission impacts per household from heat pump adoption

	Cooling	Heating		
		Natural gas furnaces as controls		Electric heaters as controls
		Due to increased electricity consumption	Due to decreased natural gas use	
Annual environmental damages	$0.59	$32.59	-$9.39	$1.64

Notes: We assume that heat from 1 kWh electricity is equal to 3.2 cubic feet of natural gas with equal energy content (https://www.engineeringtoolbox.com/energy-content-d_868.html).
The average emission coefficient is 0.054 kg for CO_2 emission, and 0.0001 g for NOx per cubic foot of natural gas (https://www.epa.gov/sites/production/files/2020-04/documents/ghg-emission-factors-hub.pdf). Social cost of carbon is $35/ton (Holland et al., 2016) and social cost of nitrogen is $1.19 per pound (https://www.cibotechnologies.com/blog/nitrogen-fertilizer-farming-necessity-and-environmental-challenge). Amounts of SO_2 and PM are negligible from natural gas combustion (https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf).

Table X6
Maximum monetary costs of adding electric loads

	Winter	Unit cost
Capacity costs	$23,408	$2.66/kW
Delivery costs	$281.6	3.2 cents/kWh
Generation costs	$440	5 cents/kWh
Total	$24,129	

Table X7, Change in electricity consumption by hour-of-day from the adoption of heat pumps (DID analysis)

Variables	Cooling	Space heating (HP vs. electric heater)
Hour1*HP	-0.481*(0.263)	-0.336**(0.131)
Hour2*HP	-0.485*(0.257)	-0.289**(0.120)
Hour3*HP	-0.460*(0.244)	-0.275**(0.117)
Hour4*HP	-0.470*(0.242)	-0.280**(0.112)
Hour5*HP	-0.444*(0.247)	-0.282**(0.116)
Hour6*HP	-0.570**(0.248)	-0.221*(0.125)
Hour7*HP	-0.600**(0.242)	-0.237*(0.123)
Hour8*HP	-0.651***(0.249)	-0.246*(0.138)
Hour9*HP	-0.591**(0.254)	-0.264*(0.144)
Hour10*HP	-0.458*(0.258)	-0.291***(0.112)
Hour11*HP	-0.474*(0.276)	-0.293***(0.105)
Hour12*HP	-0.452(0.309)	-0.309***(0.108)
Hour13*HP	-0.452(0.343)	-0.295**(0.117)
Hour14*HP	-0.379(0.391)	-0.302**(0.123)
Hour15*HP	-0.410(0.400)	-0.297**(0.119)
Hour16*HP	-0.459(0.406)	-0.162(0.174)
Hour17*HP	-0.439(0.421)	-0.244*(0.144)
Hour18*HP	-0.404(0.407)	-0.294**(0.119)
Hour19*HP	-0.187(0.414)	-0.263*(0.141)
Hour20*HP	-0.266(0.377)	-0.275**(0.135)
Hour21*HP	-0.466(0.383)	-0.279**(0.130)
Hour22*HP	-0.528(0.338)	-0.307**(0.125)
Hour23*HP	-0.488(0.312)	-0.329**(0.143)
Hour24*HP	-0.464(0.320)	-0.325**(0.149)
CDD	0.040***(0.004)	0.019***(0.002)
HDD	0.098***(0.013)	0.016***(0.002)
Electricity price	-3.343***(0.843)	-2.064**(0.875)
Weekend	0.042**(0.016)	0.053***(0.017)
Holiday	0.027(0.017)	0.054***(0.013)
-cons	0.931***(0.140)	0.896***(0.086)
Individual-consumer fixed effects	Yes	Yes
Year fixed effects	Yes	Yes
Month-of-sample fixed effects	Yes	Yes
Hour-of-day fixed effects	Yes	Yes
N	4,800,001	5,297,044
R^2	0.345	0.099

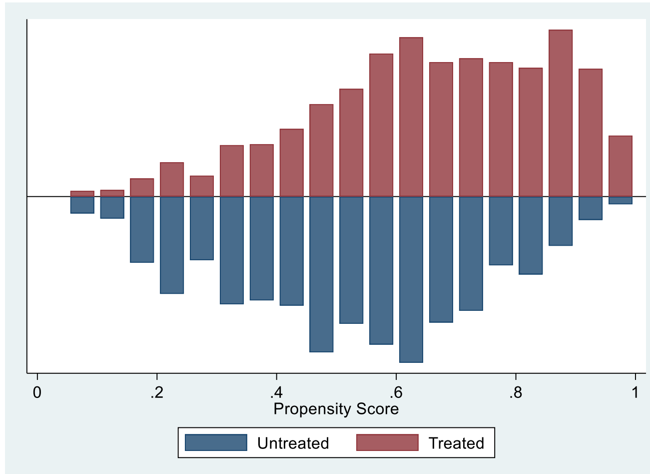

Fig. X1. Common support after propensity score matching for cooling.

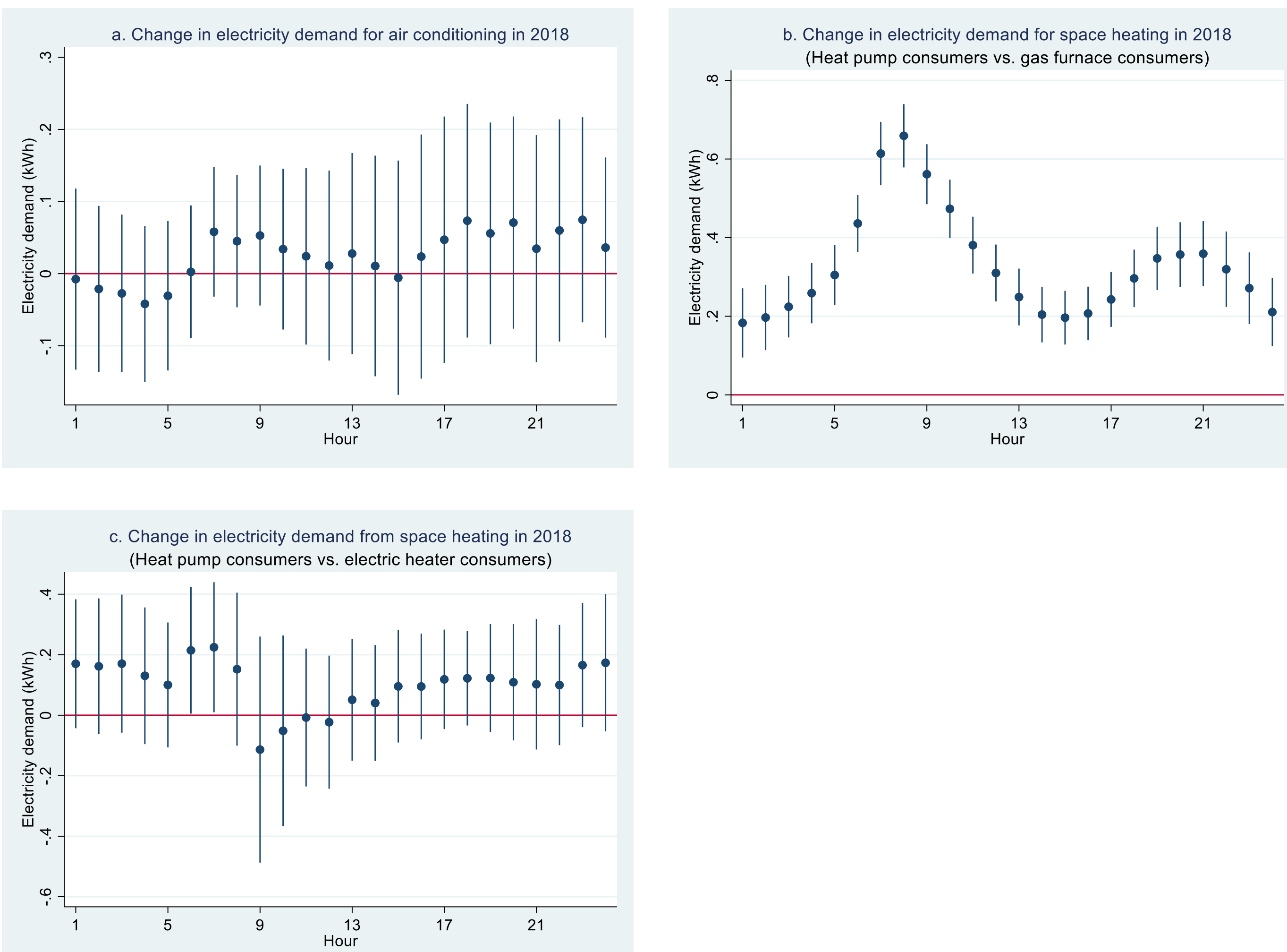

Fig. X2. Changes in electricity consumption by hour-of-day from cooling and space heating after heat pump installation using data in 2018 onl. Notes: Propensity score matching is applied, and households are matched on socio-demographics, housing characteristics, and zip codes. The zip fixed effects and various time fixed effects (year, month-of-sample, and hour-of-day) are included. Standard errors are clustered at the individual consumer level..

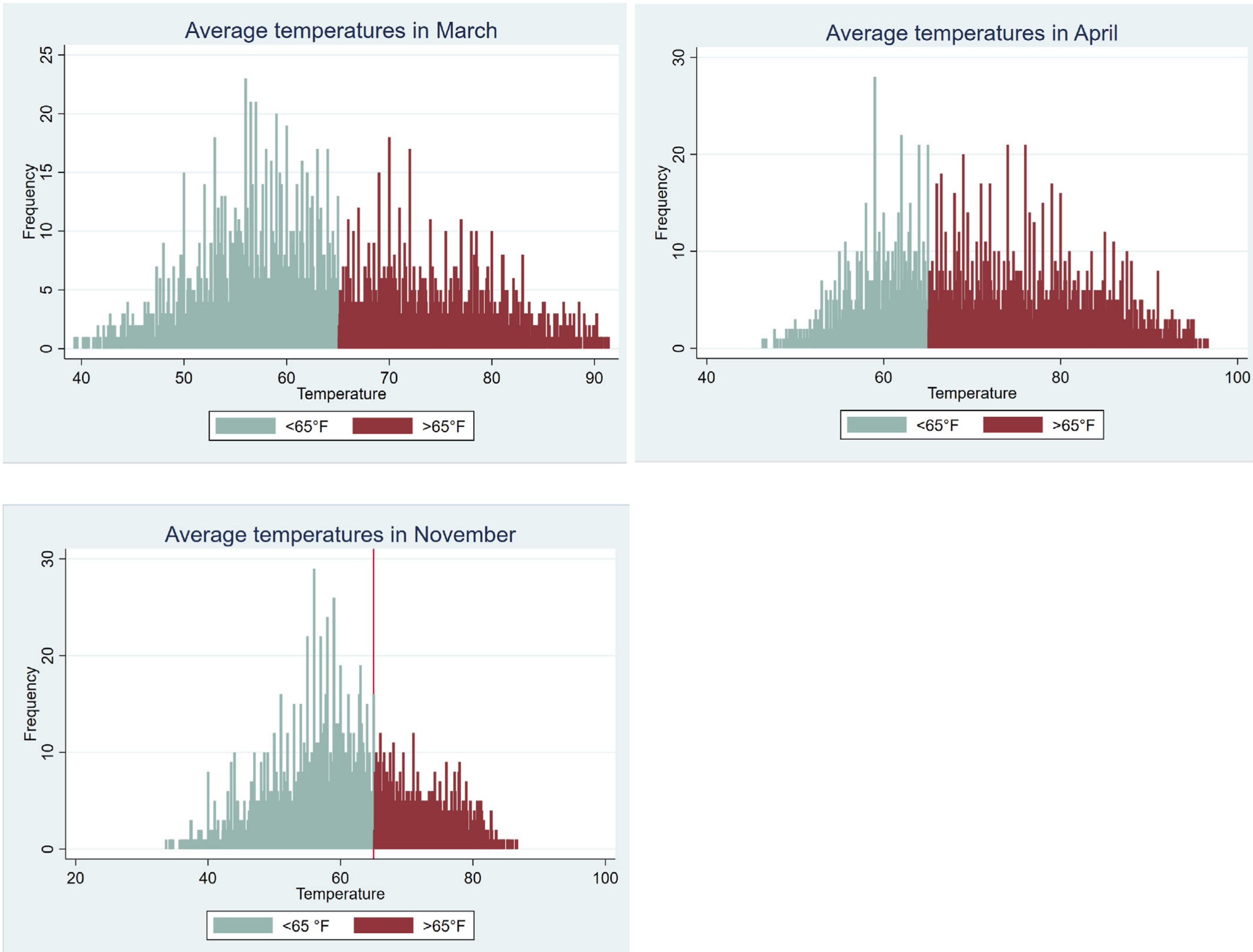

Fig. X3. Average temperatures in March, April, and November in Arizona. Notes: Temperatures over 65 °F indicate cooling is needed while below 65 °F indicate heating is needed. The figures show that even in the winter billing months, cooling is still needed in Arizona.

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