Decarbonizing Heat: The Impact of Heat Pumps and a Time-of-Use Heat Pump Tariff on Energy Demand*

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Abstract: Heat pumps have been proposed as the leading technology in the electrification of domestic heat and therefore could play a crucial part in decarbonizing energy systems. However, there is limited causal evidence on how they affect energy demand and how price per kWh can optimize their use. Leveraging a staggered roll-out of heat pumps by a large energy supplier in Great Britain, we show: (1) heat pumps reduce average household gas use by 98% and increase electricity use by 50%, leading to a 72% reduction in carbon emissions over a typical asset lifetime; (2) a time-of-use tariff (a retail electricity pricing plan) designed for heat pumps can halve electricity demand during the evening peak to enhance grid flexibility; (3) the marginal value of public funds for the current heat pump subsidy in Great Britain is £1.23 per £1 of government spending. Overall, we find that heat pumps can effectively decarbonize heat and subsidies can be welfare-enhancing.

> *"The reversed-cycle heat engine (or heat pump) is described, and it is shown... that where heat at a comparatively low temperature is required, heating efficiencies of the order of from 300 to 500 per cent or even more may be obtained."*
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> — Graeme Haldane, *1930, p. 666.*

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1 Introduction

Heating buildings accounts for nearly one-fifth of global energy-related carbon emissions, much of which comes from residential gas boilers in industrialized countries (International Energy Agency, 2023). Replacing boilers with electric heat pumps powered by low-carbon electricity is a key element of decarbonization strategies recommended by international institutions such as the IEA (2021) and IPCC (2022).

Heat pumps have long been recognized for their potential engineering energy efficiency advantage in converting energy into useful indoor heat. Engineering analyses dating back to Haldane (1930) highlight that, relative to electric resistance heating, heat pumps can deliver about three times as much heat per unit of energy consumed. At the same time, residential heating in the UK remains overwhelmingly reliant on gas, with the vast majority of households using gas boilers as the incumbent technology. While gas and electricity have similar marginal carbon intensities in the UK today, energy efficiency gains from switching from gas boilers to electric heat pumps have the potential to substantially reduce the carbon dioxide equivalent (CO_2e) emissions from domestic heating. This reduction in emissions will increase further if, as projected, the marginal carbon intensity of electricity declines as the grid decarbonizes. However, there remains little causal evidence on their realized performance and how their widespread use could affect energy systems. Empirical evidence is crucial for electricity system operators and for many governments around the world considering or using a heat pump subsidy.

This paper provides the first large-scale evidence on how heat pumps affect household energy demand, using detailed consumption data from a large utility in Great Britain. We exploit a staggered roll-out of installations driven by supply constraints to identify impacts using a difference-in-differences design (Callaway and Sant'Anna, 2021). Our setting offers rare conditions for identification: all households in the sample eventually receive a heat pump, but adoption occurs at different times for reasons unrelated to energy use.

Our contribution is threefold.

First, we offer the first evidence of the impact of heat pump adoption on household energy demand. From a sample of 1,308 households, we find that adopting a heat pump caused an 8,744 kWh (98%) reduction in household gas consumption and a 2,551 kWh (50%) increase in electricity use. These impacts are in the context of a policy regime mandating removal of households' previous heating system, such as their gas boiler, in order to access the heat pump subsidy. The electricity and gas results together imply that real-world heat pump energy efficiency meets engineering predictions. We find lower-than-expected energy efficiency at colder temperatures and higher-than-expected energy efficiency at warmer temperatures; these may reflect behavioral or operational factors not captured in engineering models and represent the largest divergences between our empirical results and model-based predictions. Overall, we believe these results are the first credible validation that the theoretical energy efficiency gains of heat pumps translate into realized energy and carbon savings at scale.

We did not find evidence of a rebound, for example due to the heat pump's high engineering energy efficiency lowering the marginal cost of comfort and inducing increased heating demand. We believe this is because the heat pump operates primarily through a mechanical rather than behavioral channels, with households maintaining similar heating practices while switching fuels. However, it is also relevant that operating costs remained similar after heat pump adoption, as electricity prices were approximately three times higher per unit of energy than gas prices during our analysis period.

This near-parity in operating costs, despite heat pumps' higher energy efficiency, largely reflects broader mispricing across fuels. Retail electricity prices embed a disproportionate share of fixed network and policy costs relative to gas, while gas prices exclude climate externalities. We show that correcting these distortions can lead heat pumps to deliver meaningful savings on operating costs.

For our second contribution, we show that time-of-use tariffs can materially shift demand, offering a pathway for cost-effective grid integration of electrified heat. Such tariffs are designed to shift electricity consumption away from times of grid constraints and higher wholesale energy costs. From a sample of 6,631 households, we analyze the introduction of a time-of-use tariff designed specifically for heat pump users. Heat pump adopters not facing a time-of-use tariff increase electricity consumption in all hours of the day, with higher increases in the morning. Adoption of the time-of-use tariff halves peak-period electricity consumption and doubles off-peak use. We see this load shifting even on the coldest days of the year and from all building types in our sample. These results indicate that, although heat pumps substantially shift heating demand onto the electricity grid, where marginal social costs fluctuate over time, time-of-use pricing can incentivize households to adjust the timing of consumption in ways that reduce congestion and exposure to high-cost periods. We also find that time-of-use pricing can reduce households' private operating costs substantially.

Third, we present evidence that the heat pump subsidy in Great Britain (the Boiler Upgrade Scheme) is welfare-enhancing. Using our empirical estimates of the heat pump's impact on electricity and gas consumption, we evaluate the welfare implications of the subsidy based on computing its marginal value of public funds (Hahn et al., 2024, Hendren and Sprung-Keyser, 2020). This calculation requires several assumptions — including the additionality of subsidy recipients (i.e., the share who would not have adopted a heat pump absent the subsidy) and the value placed on avoided carbon emissions — which we discuss, along with their sensitivity, in Section 3. Subject to these assumptions, our calculations suggest that the subsidy is welfare-enhancing. The main welfare benefit is a reduction in CO_2e emissions of around 39% in 2024, rising to approximately 72% over an assumed 20-year lifetime of the heat pump as the electricity grid decarbonizes (UK Government, 2024). Under our preferred assumptions, we estimate that the heat pump subsidy generates roughly £1.23 in societal benefits for the £1 in net government cost, rising to £1.65 if we include estimated learning-by-doing benefits.

It is important to note that our analysis takes place within the specific policy and technological context of the United Kingdom. In the UK, heat pump adoption has largely occurred through air-to-water systems designed to work with existing water-based radiators, and all of the heat pumps in our sample are of this type. These systems typically replace a household's gas boiler entirely. In many other settings, including much of continental Europe and the United States, air-to-air heat pumps are more prevalent. Air-to-air systems can also provide space cooling during the summer, a function that air-to-water systems generally do not offer. This difference helps interpret some of our results. For instance, the absence of increased electricity consumption during summer months reflects the fact that the systems in our sample do not provide cooling. In addition, the subsidy program we use for identification requires that the heat pump replace the household's previous heating system, whereas in other contexts heat pumps may be installed alongside existing heating technologies rather than fully displacing them.

Beyond these contextual and technological differences, our samples are not necessarily representative of the broader population of British households that have not yet adopted a heat pump or the heat pump tariff. Heat pump adopters are likely those for whom heat pumps are most desirable or best suited, so the observed effects here need not reflect population treatment effects. We expect our heat pump results to translate reasonably well beyond this sample, however, to the extent that the response we estimate is largely mechanical, driven by outdoor temperature and house size (Section 2.1.3), rather than by idiosyncratic characteristics of early adopters. The issue is more consequential for the heat pump tariff, where selection into treatment by structural winners or low-shifting-cost households is likely: our sample skews toward larger homes and technologically engaged households well placed to shift load at low cost, which likely explains why our estimated demand response (Section 2.2.2) is large relative to the time-of-use pricing literature. As tariff adoption extends beyond early adopters, who may be more likely to be structural winners, to the early majority, who may be more likely to have smaller and less automated homes, we expect smaller absolute load-shifting effects, although still meaningful ones relative to heat pump and home size.

Our findings relate to the energy economics literature on household responses to technological change and energy efficiency investments (Allcott and Greenstone, 2017, Christensen et al., 2023, Fowlie et al., 2018). In contrast to much of this literature where realized energy savings from efficiency investments fall short of ex ante predictions due to behavioral responses, installation quality, or rebound, we find that heat pump adoption delivers reductions in fossil fuel use that are closely aligned with engineering expectations. Unlike many retrofits studied previously, heat pump installations in our setting are subject to technical standards and previous heating system removal under the boiler subsidy, limiting scope for under-performance driven by household or installer behavior. This divergence is policy-relevant: many decarbonization pathways rely heavily on modeled projections of heat pump performance. Our results suggest that, at least in this setting, such projections may be more reliable than those for other energy efficiency investments.

Our analysis also situates heat pump adoption within broader questions of policy effectiveness, household behavior, and energy system impacts. We extend work on the welfare analysis of energy subsidies (Hahn et al., 2024, Hendren and Sprung-Keyser, 2020) and on household responses to time-varying electricity prices (Borenstein, 2007, Imelda et al., 2024, Ito et al., 2023). Finally, we complement recent research on the determinants of heat pump adoption and diffusion (Anderson and Kirkpatrick, 2024, Davis, 2024), showing how adoption translates into concrete changes in household energy use and emissions.

The remainder of the paper proceeds as follows. Section 2 presents the empirical strategy and results for the impact of heat pumps and the time-of-use tariff. Section 3 evaluates welfare implications, and Section 4 concludes. Full robustness checks, heterogeneity analyses, and methodological details are reported in the Online Appendix.

2 Empirical Analysis

Our empirical analysis focuses on two related channels through which heat pump adoption affects energy use and system outcomes. First, we study how installing a heat pump alters households' energy consumption, focusing on the substitution from gas to electricity and the resulting implications for heating efficiency. Second, we examine how electrified heating interacts with retail electricity pricing by analyzing the effects of a time-of-use tariff designed for heat pump users. This tariff varies prices across the day to encourage load shifting away from high-cost periods, allowing us to assess whether time-varying prices can reallocate heat-pump demand within the day, mitigating peak load and system congestion, without materially changing average energy consumption.

Table 1 reports summary statistics for the electricity and gas consumption data used in both of the analyses, separately for the pre- and post-treatment periods. Observations are defined at the household–week–period level (for example, average weekly electricity consumption during the morning off-peak period). For ease of interpretation, these outcomes are scaled to annualized kWh equivalents, although the underlying variation exploited in the estimation is at the weekly level. The table shows that households that adopt the heat pump tariff consume, on average, more electricity than households in the heat pump installation sample, consistent with adopters tending to live in larger dwellings with higher baseline energy demand (see Table A.19 for a comparison of our samples). For the tariff adoption sample, average electricity consumption is higher in the post-adoption periods; however, these level differences are not reflected in the Callaway and Sant'Anna (2021) estimates reported below, which exploit within-household changes over time. This pattern is consistent with the possibility that households adopt other low-carbon technologies or undertake energy-related investments during the sample period. We conduct a range of robustness checks and balance tests to ensure that such compositional changes do not bias the estimated treatment effects (see Section A.4.5).

Table 1: Summary statistics before and after adoption

	Period	Obs	Mean	SD
Panel A: Heat Pump Adoption Sample				
Electricity consumption	Pre	77,348	5,049.45	4,148.30
	Post	25,033	8,612.40	5,547.98
Gas consumption	Pre	64,429	10,097.86	9,922.03
	Post	21,668	483.50	2,415.04
Panel B: Tariff Adoption Sample				
Overall (all 24 hours)	Pre	235,857	6,629.36	6,381.11
	Post	200,505	8,602.01	6,799.14
Morning off-peak (04:00–07:00)	Pre	235,703	795.45	987.18
	Post	200,491	2,258.98	2,244.23
Afternoon off-peak (13:00–16:00)	Pre	235,716	696.64	802.26
	Post	200,493	1,549.87	1,644.41
Peak (16:00–19:00)	Pre	235,712	960.85	1,019.52
	Post	200,493	684.68	836.04
Standard rate, all other hours	Pre	235,857	4,193.73	4,059.93
	Post	200,505	4,107.67	4,039.33

Note: This table reports summary statistics for the two estimation samples. All figures are annual consumption in kWh, obtained by annualizing the weekly consumption (panel A) and half-hourly (panel B) used in the difference-in-differences models. "Pre" is the period before adoption and "Post" the period after; weeks within the anticipation window are excluded. *Obs* is the number of household–period observations, and Mean and SD are computed across those observations. *Panel A* is the heat pump adoption sample and reports household electricity and gas use. *Panel B* is the heat-pump time-of-use tariff adoption sample: two cheap off-peak windows in the morning (04:00–07:00) and the afternoon (13:00–16:00), a peak window (16:00–19:00) priced above the standard rate, and the standard rate that applies in all other hours (07:00–13:00 and 19:00–04:00); "Overall" covers all 24 hours.

2.1 Impact of Heat Pump Installation on Energy Consumption

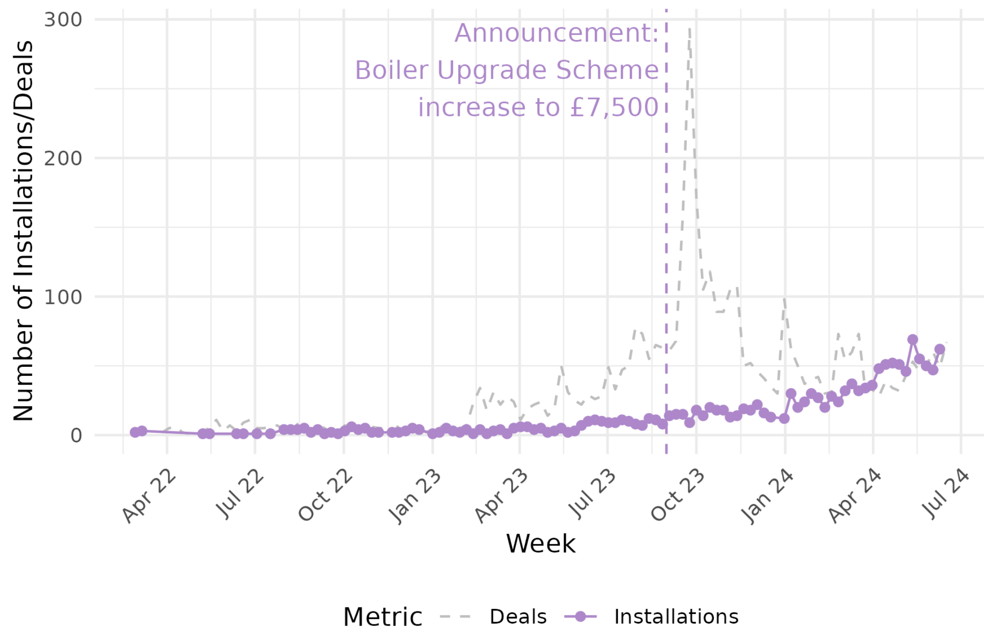
2.1.1 Set-up and Identification Strategy

This section outlines our approach to identifying the effects of heat pump installation. Simply comparing adopters to non-adopters risks bias, since households that adopt may differ in unobservable ways correlated with their potential outcomes. We instead exploit the staggered adoption of heat pumps across Great Britain among households that purchased directly from a large energy supplier, using households that adopt later as a counterfactual control group. While it is unusual for a utility to sell and install heat pumps, this one has pursued vertical integration—installation, maintenance, and tariff provision—as part of its broader commercial and decarbonization strategy. It began taking orders in December 2021 and installing in February 2022. Figure 1 shows the rollout over time, where a deal is a household paying a refundable deposit to obtain a heat pump.

A delay between households making a deal for the heat pump and installation, due to installation constraints, provides us with a natural experiment to understand the impact of heat pumps on energy demand for those who want a heat pump. We see evidence that deals increased markedly in September 2023, when the Government announced its plan to increase the level of the main subsidy for heat pumps (the Boiler Upgrade Scheme), from £5,000 to £7,500 per air-source heat pump. However, because of the delay between deal and installation, we see a slower and steadier increase in heat pump *installations* both before and after September 2023.

We use the universe of households that adopted a heat pump with the partner utility as their

Figure 1: Weekly Deals and Installations



Note: The solid purple line and dots show weekly heat pump adoptions, comprising our sample of 1,308 adopters. The hashed gray line shows *deals* — reservations made by paying a refundable deposit — over the same period. The heat pump subsidy increased from £5,000 to £7,500 in October 2023, following an announcement in September 2023.

installer. There are 1,308 such households who adopted a heat pump as early as 28 February 2022 or as late as 15 June 2024, and who have sufficient consumption data for analysis. Households who have a deal but no installation as of 15 June 2024 are akin to never treated in our sample; we exclude these 634 households from our main analysis but include them in a robustness check we present in Table A.2. We examine consumption from 13 December 2021 through 15 June 2024.

Almost all households in our sample took advantage of the heat pump subsidy. On average, it was worth £6,800 to the households in our sample — this is a weighted average of the £5,000 subsidy level and the later, more generous, £7,500 level. The average cost of an air-source heat pump installation since the subsidy increased to £7,500 in October 2023 is £12,713, based on MCS's monthly average costs from November 2023 to June 2024 (Microgeneration Certification Scheme (MCS), 2024). Because MCS certification is required for subsidy eligibility, these figures cover all eligible installations, implying an average private cost of £5,213 after the subsidy. Heat pumps in our sample have an average size of 8 kW, which is typical of domestic heat pumps in the UK.

Callaway and Sant'Anna (2021) in This Context: Staggered difference-in-differences models may produce biased estimates if treatment effects are heterogeneous across units and over time (Callaway and Sant'Anna, 2021, Goodman-Bacon, 2021). This might happen in our setup because: (a) households may get better at using their heat pump over time; and (b) households could also adopt more low-carbon technologies to complement their heat pump usage. With this in mind, we calculate Callaway and Sant'Anna (2021) (CS) difference-in-differences estimators. We do this by aggregating the data at weekly level. Our cohorts are divided by their week of heat pump adoption, and the unit of observation is the average consumption for household i in the week of installation (cohort) g in week t.

In settings with staggered adoption and time-varying treatment effects, conventional summaries, such as simple average treatment effects or event-time dynamic average treatment effects on the treated (ATTs), can be difficult to interpret. These summaries often conflate true treatment heterogeneity with variation in cohort composition and exposure length. In our setting, where treatment effects are strongly seasonal, this issue is particularly acute: for example, the simple ATT depends mechanically on how much of the post-adoption period households spend in colder versus milder months, rather than capturing a stable annual impact of heat pump adoption. As a result, commonly reported estimates can vary substantially across samples or horizons even when underlying behavioral responses are unchanged.

To address this problem, we apply what we believe is a new and practically important aggregation approach that has not previously been used to summarize treatment effects in staggered adoption settings with pronounced seasonality. Specifically, we exploit calendar-time ATTs as a constructive aggregation device that preserves the seasonal structure of treatment effects. By estimating impacts at each point in calendar time and then aggregating over a full annual cycle, we recover yearly effects on electricity and gas consumption that are interpretable and comparatively stable, up to natural variation in winter severity. This approach separates seasonality in treatment effects from differences in exposure timing across cohorts, yielding annual estimates that more closely reflect the policy-relevant impact of heat pump adoption. Our main results use the most recent 12 months of data, which provide the greatest precision in our setting. As a robustness check, we also report 12-month rolling averages constructed from calendar-time ATTs in Figure A.1.

We believe this approach offers a practical solution for many empirical settings characterized by staggered adoption and pronounced seasonal responses — common in energy, environmental, and climate policies — where the object of interest is an annual or long-run impact rather than an exposure-weighted average over event time. In such contexts, calendar-time aggregation provides a transparent way to summarize heterogeneous treatment effects without obscuring their underlying seasonal structure.

The validity of our identification strategy rests on four assumptions. First, we have irreversible treatment, so once a household installs a heat pump, it does not revert to its previous heating system, which is a highly plausible assumption given that subsidy receipt requires the removal of any existing gas boiler. Second, we have random timing of treatment driven by installation constraints, so selection into receiving a heat pump earlier versus later is not correlated with underlying trends in energy use; the average waiting time in our sample is 28 weeks, creating a natural experiment in which households awaiting installation — who nonetheless *want* to adopt — form a credible counterfactual. Third, we have no anticipation, so households do not change their behavior in anticipation of heat pump installation, or if they do, this anticipation is limited to a clearly defined period; we use an anticipation period of four weeks.[1] Last, we assume unconditional parallel trends based on "not-yet-treated" groups, ensuring that the comparison between treated and untreated groups is valid, as the trends in outcomes would have been parallel in the absence of treatment.

2.1.2 Dynamic ATTs

We begin by examining the dynamic effects of heat pump adoption on electricity and gas consumption using an event-study framework. We show dynamic ATTs of heat pump installation on electricity and gas consumption in Figure 2. We find that the impact of heat pump adoption is effectively immediate, with a sharp reduction in gas consumption and a corresponding increase in electricity use at the time of installation. There is little evidence of differential trends prior to adoption. We use a universal base period with four weeks anticipation period; as discussed in Section 2.1.1, we see evidence of an anticipation period of up to one month before adoption (Figure A.4).

The dynamic ATTs exhibit flat pre-trends, reducing concerns about pre-treatment divergence and increasing our confidence in our overall identification strategy. Notably, our large sample gives high power to detect modest pre-trend differences, mitigating low-power critiques (e.g. Freyaldenhoven et al., 2019, Roth, 2022).

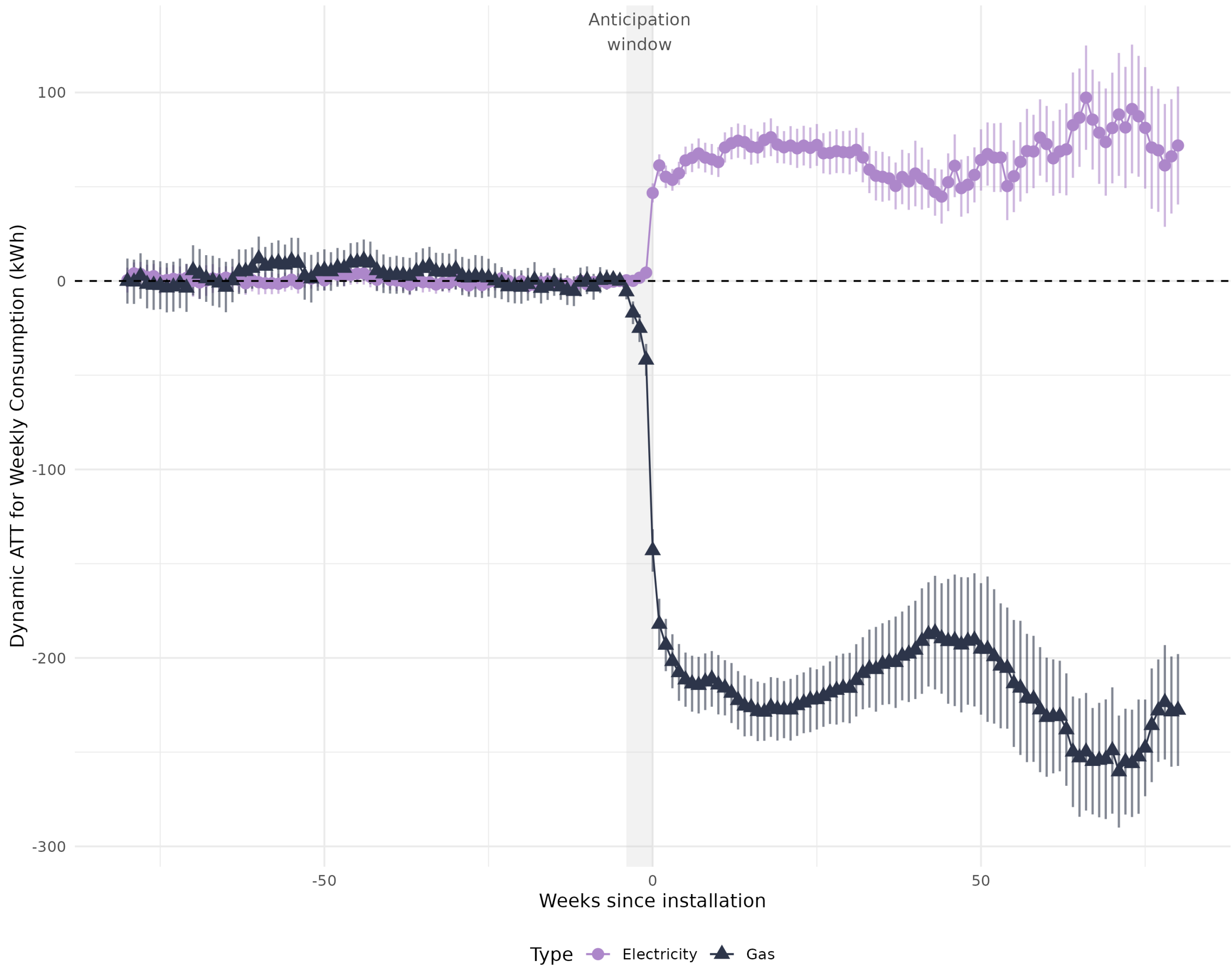
In a staggered-adoption setting with heterogeneous effects, event-time patterns can reflect cohort composition and exposure timing as much as true post-adoption dynamics. In our setting, seasonality is a key driver of this issue: event-time estimates may embed seasonal variation because cohorts adopt at different times of the year. Since the largest cohorts tend to adopt at the beginning of winter (see Figure A.7), the early post-adoption weeks predominantly reflect outcomes from these groups, embedding a systematic seasonal pattern into the event study results even though later cohorts may adopt in different seasons.

A related concern is that installation timing may not be random across households. In practice, installations could occur earlier for reasons such as equipment failure, property characteristics, or household readiness, which may themselves correlate with energy use patterns. Our difference-in-differences design partly mitigates this issue by comparing households relative to their own pre-treatment outcomes and to contemporaneous controls that also adopt during the sample period but at different times. The flat pre-trends in Figure 2 provide further reassurance, although unobserved factors correlated with installation timing cannot be ruled out entirely.

It is useful to clarify why the event-study pre-trends exhibit little seasonality. Under the not-

[1] We see evidence of an anticipation period up to a month, as can be seen in Figure A.4. Specifically, heat pump impacts increase slightly when we use longer anticipation periods. This is especially the case for the extent to which heat pumps cause a reduction in gas consumption. We hypothesize that this pattern may be due to people removing their gas meters more than one week before heat pump installation, even up to a month before heat pump installation. Households might then use portable electric heaters as temporary substitutes during this period.

Figure 2: Gas and Electricity Dynamic ATTs



Note: This figure shows how the estimated effect of heat pump adoption on energy consumption evolves over time. Electricity (purple) and gas (dark gray) effects are shown separately. The y-axis shows the weekly consumption effect in kWh; the x-axis shows weeks relative to installation, with week 0 the first full week after installation. The gray box marks a four-week anticipation window running from four weeks before installation through the installation week. Estimates come from a Callaway and Sant'Anna (2021) event-study design comparing treated and not-yet-treated households; no additional controls are included.

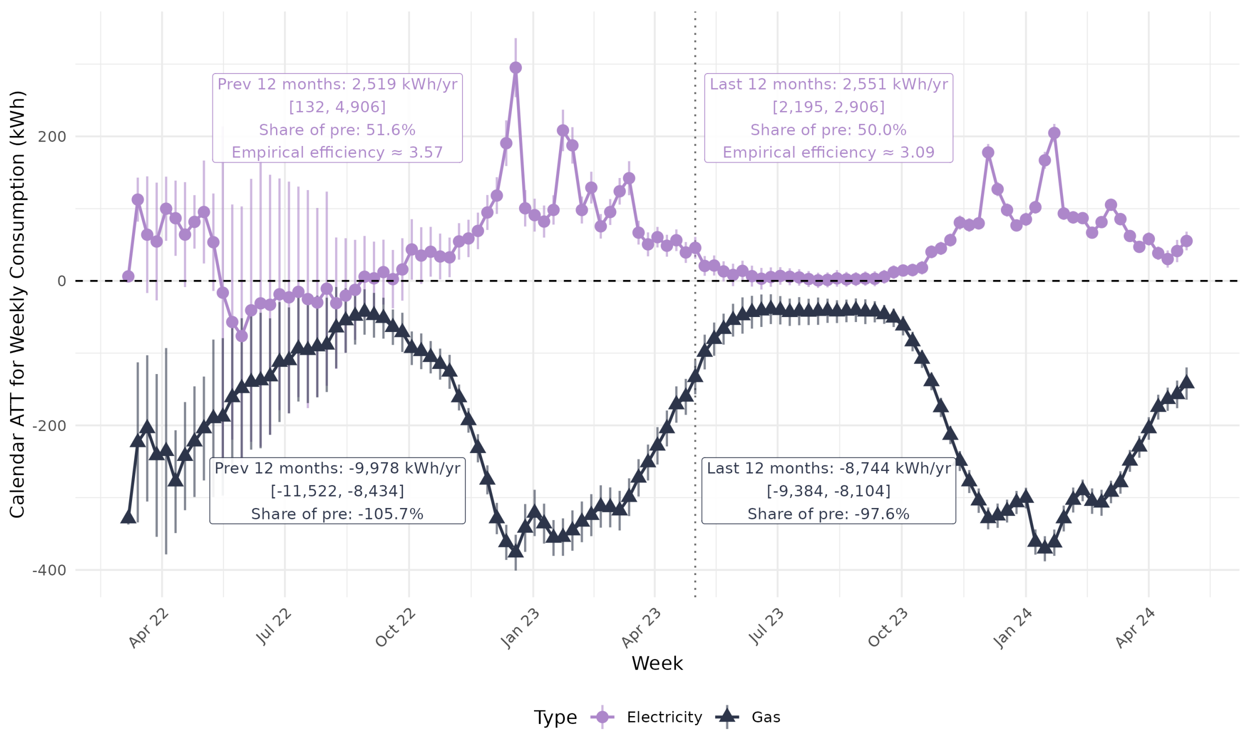
yet-treated estimator, comparisons are always made within the same calendar week between units that are treated in that week and units that have not yet been treated. In the pre-adoption periods for a given cohort, both the "earlier" and "later" adopters are untreated in the relevant weeks, so any seasonal patterns in the outcome, such as fluctuations in energy use, are common across groups and difference out mechanically. The control principle is the same in every calendar week; what changes over time is whether a given cohort has begun treatment. After adoption, the same comparison rule applies, but treated units are now exposed to the policy while the not-yet-treated units remain untreated. If the treatment effect itself varies over calendar time, for example because the policy interacts with seasonal demand conditions, then the estimated post-adoption average treatment effects can display seasonal patterns. This reflects seasonally heterogeneous treatment effects and the weighting of different cohorts and exposure lengths, rather than differential seasonality in untreated outcomes or a violation of parallel trends.

2.1.3 Seasonal Variation

To directly capture the seasonal nature of heat pump impacts, we next examine treatment effects in calendar time. Calendar-time ATTs measure the effect of heat pump adoption at each point in the year, pooling across all cohorts that are treated in that period. This perspective is particularly informative in our setting, where space-heating demand, and thus both electricity increases and gas reductions, varies sharply with outdoor conditions.

We show calendar ATTs in Figure 3. During winter, the calendar ATT increase in electricity consumption reaches over 200 kWh per week. Meanwhile, it drops to almost zero between April and October. The decrease in gas consumption is larger in magnitude, but shows similar seasonal patterns, with very little decrease during warm months and a large decrease during the winter.

Figure 3: Gas and Electricity Calendar ATTs



Note: This figure shows how the estimated effect of heat pump adoption on energy consumption varies across weeks of the year. Electricity (purple) and gas (dark gray) effects are shown separately. The y-axis shows the weekly consumption effect in kWh; the x-axis shows the week of the year.

2.1.4 Main Results

To construct annual impacts of heat pump adoption on electricity and gas consumption, we aggregate calendar-time ATTs (shown in Section 2.1.3). As discussed in Section 2.1.1, we sum weekly calendar ATTs over a 12-month window, yielding annualized changes in energy use that preserve the seasonal structure of treatment effects while avoiding distortions arising from cohort composition and time spent in treatment. We focus on the most recent 12 months of data, which provide the most precise estimates in our setting.

We find that heat pump adoption increases electricity consumption by 2,551 kWh per year and reduces gas consumption by 8,744 kWh per year. To aid interpretation, we also examine these effects relative to pre-installation energy use, measured as a 12-month rolling average of electricity and gas consumption among not-yet-treated households observed in the same calendar weeks. Relative to this baseline, the electricity increase corresponds to 50% of pre-installation electricity consumption (5,099 kWh), while the reduction in gas consumption corresponds to 98% of pre-installation gas use (8,963 kWh).

The results remain consistent across different choices of rolling average windows, indicating the robustness of the annualized impact estimates. For example, aggregating the preceding 12 months yields similar magnitudes (electricity: 2,519 kWh/yr; gas: -9,978 kWh/yr), with variation mainly driven by winter severity. Twelve-month rolling averages of these annual impacts are shown in Figure A.1 and demonstrate smooth, stable annual estimates over time.

Simple ATTs and Estimator Comparisons: To complement the annualized estimates from rolling average calendar-ATTs, we also report simple average treatment effects from the CS estimator and their two-way fixed-effects (TWFE) equivalents in Table A.1. These estimates summarize impacts on weekly electricity consumption for all households in our sample, and on weekly gas consumption for the subset of households with natural gas service. For ease of interpretation, coefficients and standard errors are scaled to annual units by multiplying weekly estimates by 52.

As noted above, these simple ATTs average treatment effects across cohorts and post-adoption periods and therefore mix observations from different seasons and different lengths of exposure. As a result, they are not our preferred estimates of annual impacts in a setting with strongly seasonal and heterogeneous treatment effects. Instead, we use them as a diagnostic benchmark and as a point of comparison with alternative estimators and samples.

These estimates nonetheless are similar to our preferred specification. Heat pump adoption is associated with higher electricity consumption and a large reduction in gas use, consistent with the substitution patterns documented using calendar-time ATTs. The magnitude of these simple averages falls within the range implied by our annual calendar-based estimates, once differences in weighting and exposure are taken into account.

Gas Consumption and Sample Coverage: Most households in our sample replace a gas boiler when installing a heat pump, as confirmed by administrative survey data collected at the time of installation. We therefore examine gas consumption for households that had an active gas account prior to installation and at least four weeks of observed gas use in the pre-treatment period.

Gas consumption data are unavailable for households supplied by other retailers or without a gas connection, and gas smart meter readings are more frequently missing than electricity readings. As a result, the gas analysis relies on a smaller sample. Reassuringly, when we restrict the electricity analysis to this subsample, estimated electricity impacts remain very similar to those in the full sample, indicating that sample selection is unlikely to drive the results (see Table A.3 and Figure A.2).

Relative Impacts Across Fuels and Emissions: The reduction in gas consumption is roughly three times as large as the increase in electricity consumption in absolute kWh terms. While final energy use does not translate one-to-one into primary energy — electricity generation involves conversion losses, whereas gas boilers convert fuel to heat at higher efficiencies — the marginal carbon intensities of electricity and natural gas in Great Britain are currently of a similar order of magnitude (Department for Energy Security and Net Zero, 2023*b*, UK Government, 2024). As a result, the observed substitution from gas to electricity translates into an immediate and substantial reduction in CO_2e emissions from residential heating.

We find little evidence that these patterns are driven by increased reliance on secondary heating sources. Only around 10% of surveyed heat pump tariff adopters report using a backup heating system (Section A.4.5), compared with 39% in the general population (Department for Business, Energy and Industrial Strategy, 2021). That said, this evidence is based on self-reported survey responses and may be subject to response bias, and the sample is slightly different from the heat pump adopters.

Moreover, we acknowledge that some forms of backup heating may be imperfectly observed in our data. Electric resistive backup heating would be mechanically included in measured electricity consumption, biasing estimated electricity increases upward and implied energy efficiency downward, while non-electric backup heating (e.g., gas or solid fuels) would reduce observed electricity demand, biasing estimated electricity increases downward and implied energy efficiency upward. If reliance on backup heating rises on very cold days, these channels could affect implied energy efficiency estimates at the cold end of the temperature distribution, although our survey evidence suggests such effects are unlikely to be large.

Operating Costs: Because electricity prices per kWh exceed gas prices in the UK, heat pump adoption is associated with modestly higher operating costs under standard tariffs. Using contemporaneous retail prices[2], we estimate an increase of around £97 per year relative to gas boiler heating, falling to a £10 *saving* per year if we assume the household disconnects from the gas network and thus avoids gas standing charges. These figures should be interpreted as indicative, as operating costs depend on tariff choice. In particular, heat pump–specific time-of-use tariffs can substantially reduce electricity costs, an issue we explore in more detail in the heat pump specific tariff analysis (Section 2.2). In addition, we discuss the impact of policy and regulatory choices on these operating costs in Section 3.2.

2.1.5 Temperature Interactions

To understand the mechanisms behind the seasonal patterns documented above, we next examine how treatment effects vary with outdoor temperature. For this and other heterogeneity analyses, we use TWFE models, since the CS estimator does not readily accommodate finely binned treatment–temperature interactions. As in our CS analyses, we estimate separate models for weekly electricity and gas consumption.

In these models, we interact heat pump installation status with weekly average outdoor temperature, measured at the GSP Group level and rounded to the nearest degree Celsius. Temperature is treated as a categorical variable and bounded between 0°C and 25°C. GSP Groups are geographic zones commonly used in the Great Britain energy sector, and we assign each household the temperature recorded at the highest-quality weather station in its group. All specifications include household and week fixed effects, and standard errors are clustered at the household level.

By interacting heat pump installation status with temperature, while also controlling for temperature on its own, we isolate how the impact of heat pump adoption varies across outdoor conditions. In this specification, treatment effects are identified through these interaction terms rather than through a single average installation effect. The resulting TWFE estimates characterize the shape of the temperature-response relationship but not its absolute magnitude, since staggered adoption can introduce modest bias (around 7% for electricity and gas; see Table A.1). For this reason, our preferred treatment effects remain our CS estimates.

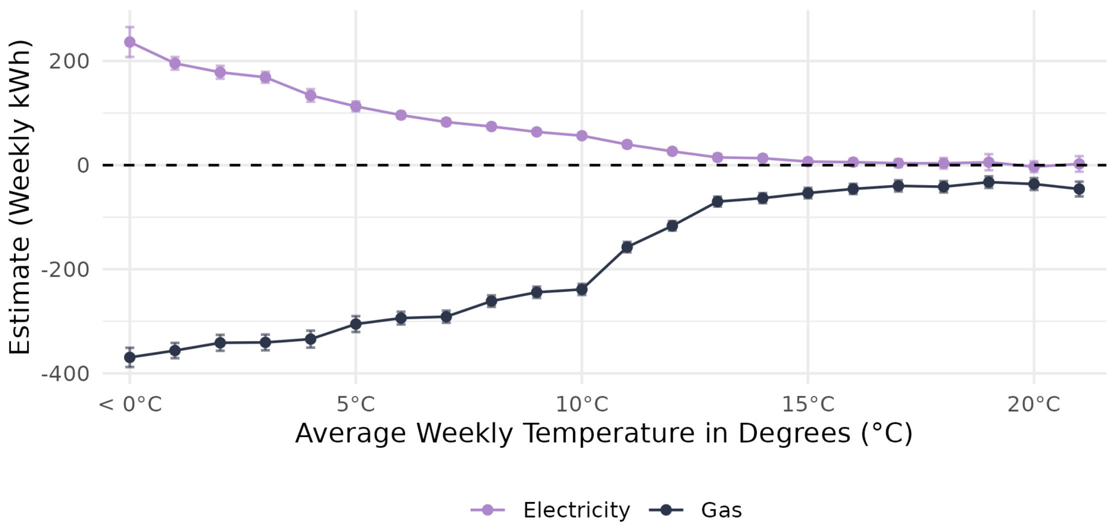
We plot these temperature-varying effects in Figure 4. Electricity impacts rise sharply as temperature falls below 15°C, and are close to zero in warmer weeks, consistent with air-to-water heat pumps operating on the space-heating margin. Gas reductions display a similarly winter-peaked pattern. This is natural in the UK context, where air-to-water heat pumps typically replace gas boilers in "wet" central heating systems and do not provide active cooling: electricity use increases over the heating-relevant range, with no corresponding summer cooling effect. The persistent reduction in gas use at higher temperatures likely reflects broader technological and behavioral changes associated with adoption — such as electrification of domestic hot water via a hot water cylinder

[2] As of 15 June 2024, the average electricity price per kWh was £0.2450 versus a gas price per kWh of £0.0604 using the utility's standard tariff (Octopus Energy, 2024). UK Government (2024) retail price estimates show similar differences in fuel prices, although electricity and gas price per kWh are both higher than the utility's own prices.

and reduced reliance on gas appliances — rather than space heating *per se*.

These temperature profiles also clarify the external validity of our results. They speak most directly to settings where heat pump adoption entails a near-complete switch from fossil fuel boilers to air-to-water systems in a heating-dominated climate with limited cooling demand (e.g., the UK and other countries with hydronic radiator systems). In settings dominated by air-to-air heat pumps that jointly provide heating and cooling — often alongside continued fossil heating — one would expect weaker winter substitution away from gas or oil and stronger electricity increases on hot days due to cooling. Our findings should therefore be interpreted as evidence on whole-system electrification of heating in cold and temperate climates, rather than on the joint heating-and-cooling margin relevant in warmer regions.

Figure 4: Heat Pump Impacts on Gas and Electricity Demand, by Outside Temperature



Note: This figure shows how the estimated effect of heat pump adoption on energy consumption varies with outside temperature. Estimates come from a TWFE model interacting heat pump installation status with average weekly outside temperature in °C (binned into 0–25°C, with tails grouped). The dependent variable is electricity or gas consumption in kWh. We control separately for temperature and include household and time fixed effects, so interaction terms capture the additional impact of heat pump installation at each temperature level. Standard errors are clustered at the household level. The sample includes 1,308 households for the electricity analysis and 1,110 for the gas analysis.

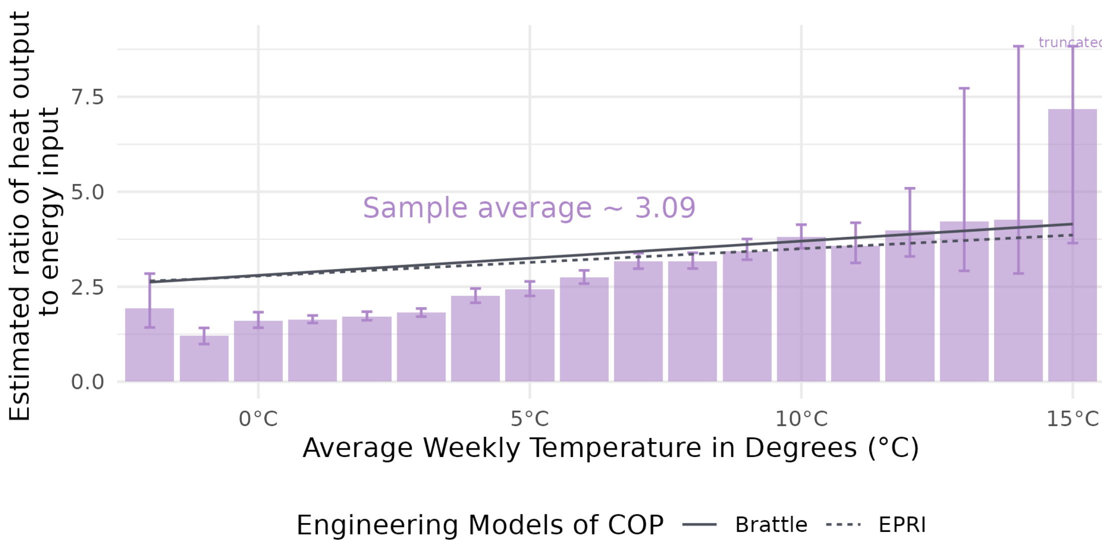
We show in Figure A.8 that this relationship holds true across different times of day using daily electricity data (note that the temporal nature of this analysis is slightly finer grained than the main temperature interactions, which are based on weekly averages), including the peak time (which is between 4pm and 7pm in the UK).[3] Lower outside temperatures drive higher electricity usage due to increased heating demand.

[3]For convenience, we show these impacts by the different rate periods of the heat pump specific tariff investigated in Section 2.2.2, but it should be noted that the majority of our heat pump adopting households are on tariffs other than the heat pump time of use tariff analyzed later.

2.1.6 Empirical Heat Pump Energy Efficiency

We can also calculate an empirical estimate of heat pump efficiency by comparing how adoption changes annual gas and electricity consumption. In engineering terms, the Coefficient of Performance (COP) is the ratio of useful heat output to electricity input. Because we do not observe heat output directly, we cannot estimate a physical COP. Instead, we infer an empirical energy efficiency measure from observed fuel substitution: we take the absolute ratio of the annual gas reduction to the annual electricity increase implied by our calendar-time ATT aggregation, and multiply by 0.9 to adjust for the fact that gas boilers convert fuel to useful heat with roughly 90% energy efficiency (typically 78–97%; see Department of Energy and Climate Change, 2009, U.S. Department of Energy, 2023).

Figure 5: Estimated Gas (kWh Reduction) to Electricity (kWh Increase) Energy Demand Ratio



Note: This figure compares the estimated real-world energy efficiency of heat pumps at different temperatures with engineering predictions. Temperature interactions are estimated using TWFE because the CS estimator does not support treatment–temperature interaction terms. Headline annual impacts and the annual implied empirical heat pump energy efficiency are constructed separately from calendar-time ATTs. The figure is restricted to temperatures at or below 15°C to avoid unstable ratios when interaction coefficients approach zero. We do not observe households with weekly average temperature below -2°C in our dataset. Error bars denote 95% clustered bootstrap confidence intervals.

This empirical ratio captures two components: (i) the relative energy efficiency of heat pumps versus gas boilers in delivering heat, and (ii) any behavioral responses to adoption (e.g., changes in heat demand) that affect observed energy use. Using the CS-based annual impacts in Figure 3, we obtain an implied empirical heat pump energy efficiency of 3.09$(8{,}743.756/2{,}550.681 \times 0.9)$. This value is consistent with expected performance of air-to-water heat pumps in the UK, and falls between seasonal performance factors (SPF) reported via HeatpumpMonitor.org (average SPF 3.86), noting that this data is shared by highly engaged households, and participants in the UK Government's Electrification of Heat trial (average SPF 2.81) (see Rosenow et al., 2026 for discussion of why these two averages differ). Note that the UK Climate Change Committee uses the latter energy efficiency, 2.81, as its main assumption for heat pump energy efficiency in its Seventh Carbon Budget modeling (Committee on Climate Change, 2025, p. 170).

As discussed previously, our main results are based on a 12-month rolling average of calendar ATTs, and thus our empirical energy efficiency estimate is as well. As shown in Figure A.1, 12-month rolling averages of the annual impacts — and the implied empirical energy efficiency — remain consistent over time.

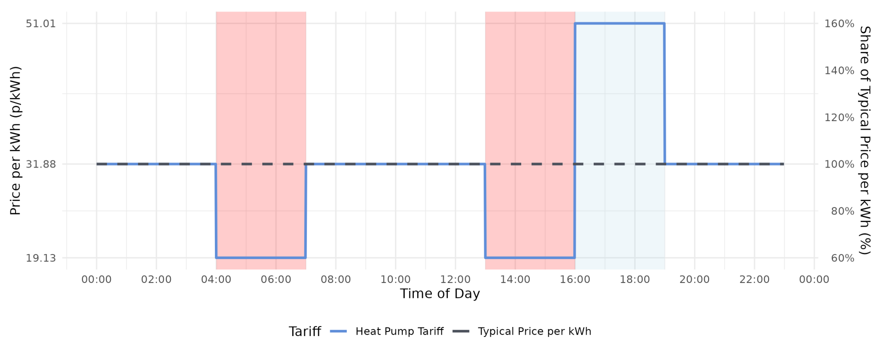
We can also use the temperature-interaction estimates from Section 2.1.5 to construct a *temperature-varying* empirical energy efficiency, shown in Figure 5. We focus on temperatures at or below 15°C, where coefficients are stable and the ratio is well-behaved. The empirical energy efficiency is lowest in very cold weather and rises as temperatures become milder, remaining above 1.15 even at 0°C. The lowest observed mean weekly temperature is -2°C.

Overall, our empirical energy efficiency estimates are broadly consistent with engineering projections in Electric Power Research Institute (2018) and Sergici et al. (2023). These estimates, and the empirical pattern we document, are consistent with the basic thermodynamics of heat pumps: when outdoor temperatures are lower, the system must move heat across a larger temperature gap, which mechanically reduces energy efficiency. That said, we find somewhat lower energy efficiency in very cold weather and higher energy efficiency at milder temperatures. A likely explanation lies in how installed heat pump systems are actually operated, rather than in the basic thermodynamics described above. Most systems use a *weather compensation* curve: as outdoor temperature falls, the controller automatically raises the flow (water) temperature delivered to radiators to maintain the target indoor temperature, rather than relying solely on a room thermostat to react after the fact. Because a higher flow temperature itself reduces the coefficient of performance — independent of the indoor-outdoor temperature gap — weather compensation causes efficiency to decline faster in cold weather than a model based on temperature gap alone would predict. Engineering coefficient-of-performance estimates are typically reported at a fixed flow temperature and therefore do not capture this effect. Households may compound this further by raising thermostat setpoints during especially cold spells to maintain comfort. Our findings also partially align with Watson et al. (2023), who directly measure heat output from the heat pump divided by all electricity input to the heat pump to compute COP using the conventional definition. While their approach isolates device-level performance, our empirical measure additionally reflects behavioral adjustment following adoption. Similar to our results, they document a non-linear relationship between outdoor temperature and energy efficiency; however, whereas they find lower energy efficiency at higher temperatures, we observe higher implied energy efficiency in milder conditions.

2.2 Impact of Heat Pump Specific Tariff on Electricity Consumption

Having established the impacts of heat pump installation on electricity and gas demand, we now turn to our second main analysis: the effect of heat pump–specific electricity pricing on household electricity consumption. We study *Cosy Octopus*, a time-of-use tariff introduced in 2022 that targets heat pump households and is designed to incentivize load shifting away from peak periods, when electricity generation is most CO_2e-intensive. This section evaluates whether targeted pricing can meaningfully reshape consumption patterns among electrified-heating households, complementing the technology adoption effects documented above.

Figure 6: Price per kWh by Rate Period



Note: We show the price per kWh for heat pump specific tariff adopting households by time of day (blue line) compared to the typical price per kWh of the utility's standard tariff in North West England. The tariff was first made available to households on 13 December 2022. Unless otherwise noted, price levels in the paper use the North West England tariff schedule as of 15 June 2024. The two off-peak 40%-reduction periods relative to the typical price per kWh are shaded light red, while the peak period with 160% of the typical price per kWh is shaded light blue. Prices per kWh vary slightly by region; there are 14 tariff-pricing regions in Great Britain. In all 14 regions, the overall structure of the heat pump specific tariff is similar: 40% lower than the typical price per kWh for the off-peak periods, 60% higher than the typical price per kWh for the peak period, and the typical price per kWh for all other hours of the day. Prices can also change over time; but, again, the overall structure of the tariff remained as in Figure 6 during the period of our analysis, except in the final two months of our analysis period when the peak was 151% of the standard price per kWh and off-peak was 45% lower. (See Section A.4.2 for further detail.)

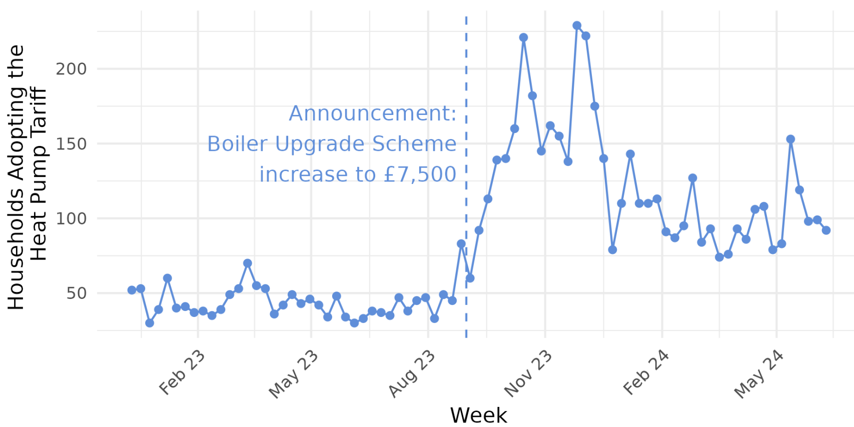
The price per kWh faced by adopting households differs by hour of the day, as we show in Figure 6. Specifically, the heat pump tariff features two off-peak periods and one peak period. All remaining hours are charged at the utility's standard price per kWh. For most of the trial period, off-peak prices are set at 60% of the standard tariff, while the peak period is priced at 160% of the standard rate. We show average wholesale prices across the two off-peak and peak periods in 2022, 2023, and the first half of 2024 in Table A.8 based on data from LCP Delta (2024). The first off-peak period is in the morning, from 4am to 7am, and the second in the early afternoon, from 1pm to 4pm. The peak period is from 4pm to 7pm. The design of the tariff with respect to prices varying within a day is designed to broadly correlate with wholesale market prices. The tariff structure is also designed to align with how households use heat pumps. In particular, the two off-peak periods allow households to pre-heat their homes ahead of the morning and evening periods of higher prices, while the peak period imposes additional costs on electricity use during the evening.

We use the full universe of households who switched to the heat-pump tariff: 6,631 households who adopted the tariff between 13 December 2022 and 15 June 2024. Note that most households in this sample are not the same as the sample of heat pump adopters. Many households had their heat pumps installed before 2022 or used a third-party installer, and therefore did not obtain their heat pump through the utility.

Our analysis covers the same time period as the heat pump adoption analysis, focusing on consumption data from 13 December 2021 through to 15 June 2024. Our analysis measures households' consumption for on average seven months after adoption, not just the weeks immediately before and after adoption. Many households in our sample have two winters of data on the tariff.

2.2.1 Timeline of Heat Pump Tariff Adoption

Figure 7: Weekly Adoption of the Heat Pump Specific Tariff



Note: We show weekly switches among the 6,631 households in our heat pump tariff analysis sample.

As with our heat pump analysis, we employ CS models to assess the impact of the tariff on consumption during different periods of the day. Again, our identification strategy relies on the parallel trends assumption: in particular, that the electricity consumption of households that adopted earlier would have followed a parallel trend to control households (in this case, those who adopted later) in the absence of adoption of the tariff. We also assume that once households adopt the tariff, they do not leave. This assumption is not as strong in the case of tariff adoption as for heat pump installation; we conduct robustness checks on leavers in Table A.13.

2.2.2 Main Results

Switching to the heat pump–specific tariff induces large and persistent shifts in electricity use across the day. To summarize these effects in a way that is directly comparable to the heat pump adoption results, we report 12-month average calendar-time treatment effects, computed over the final year of available data (June 2023–June 2024). As shown in Table 2, households substantially increase electricity consumption during incentivized off-peak periods and reduce demand during peak and standard-rate hours, while leaving total daily electricity use essentially unchanged.

On average over this 12-month window, households increase electricity consumption by 0.43 kWh per half hour during the early-morning off-peak period (4am–7am), corresponding to a 123% increase relative to the mean consumption level of not-yet-treated households in these hours. Electricity use also rises during the afternoon off-peak window (1pm–4pm), by 0.26 kWh per half hour on average, equivalent to a 79% increase relative to the non-treated baseline. In contrast, electricity demand during the peak period (4pm–7pm) falls by 0.21 kWh per half hour — around 47% of baseline consumption — while usage during standard-rate hours declines by 0.10 kWh per half hour, a reduction of approximately 28%. Averaged across the day, overall electricity consumption is statistically indistinguishable from zero, suggesting that the tariff primarily induces load shifting rather than changes in overall energy demand. For comparison, we report corresponding simple ATTs and TWFE estimates in Table A.9, which yield similar qualitative patterns.

The tariff-induced reallocation of electricity demand is highly persistent, rather than a short-lived behavioral response. Aside from the seasonal variation discussed in Section 2.2.3, we observe little attenuation in the magnitude of these effects over time (see Figure A.20). This durability is consistent with a substantial role for automated or easily scheduled responses to prices: tariff survey evidence in Section A.4.5 indicates that 64% of households respond to the tariff through some form of automation. That said, we cannot rule out that tariff adoption coincides with increased attention to electricity use, marketing, or other salience effects at the time of switching. Our estimates should therefore be interpreted as reduced-form treatment effects that reflect the combined influence of price incentives, automation, and any contemporaneous shifts in household attention.

Consistent with this interpretation, heterogeneity analysis in Section A.4.10 shows larger absolute responses among households that report owning flexible low-carbon technologies, such as electric vehicles or home batteries, which can more easily automate load shifting. Among households without these technologies, the absolute magnitude of the tariff response is roughly half as large (comparing the `Contract Active = 1` coefficients in Table A.9 and Table A.11). Because ownership of such technologies is correlated with other household characteristics (e.g., home size or baseline electricity demand), these differences should be interpreted as descriptive rather than causal evidence on mechanisms.

The magnitude of this load-shifting response is large relative to much of the existing time-of-use and dynamic pricing literature (e.g., Borenstein, 2007, Ito et al., 2023, Wolak, 2011). That said, some studies show similar large demand response — especially when pairing incentives with technology; see Bailey et al. (2025), Blonz et al. (2025), Bollinger and Hartmann (2020), Gillan (2017), Jessoe and Rapson (2014). We acknowledge that our results may reflect selection into treatment by structural winners, and even more so by low-shifting-cost households: those who adopted the tariff so far have larger homes and may have more technologically engaged members of the household, well placed to automate load shifting. As tariff adoption extends beyond these earlier adopters to the early majority — including smaller homes and those with less familiarity with automation — we expect the absolute magnitude of load shifting to fall, though the response should remain meaningful once scaled to heat pump and home size.

Table 2: Heat Pump Tariff Adoption on Half Hourly Electricity Consumption in kWh

Rate period	Mean ATT (se)	NYT baseline	Share (ATT/NYT)
Morning Off-peak	0.434 (0.013)	0.353	123.0%
Afternoon Off-peak	0.258 (0.009)	0.329	78.6%
Peak Rate	-0.207 (0.010)	0.443	-46.8%
Other	-0.103 (0.007)	0.371	-27.9%
Overall	0.001 (0.007)	0.371	0.3%

Calendar window: June 2023 to June 2024.

Note: This table summarizes calendar-time average treatment effects on the treated (ATT) for the heat pump tariff adoption analysis over June 2023 to June 2024. Weekly calendar ATTs are obtained from the Callaway–Sant'Anna estimator aggregated to calendar time. For each rate period, we report the *mean* calendar ATT over this period ("Mean ATT"). The standard error in parentheses is computed as $\sqrt{w'\Sigma w}$, where Σ is the covariance matrix of weekly calendar ATT estimates (from the did influence-function/cluster bootstrap covariance) and $w_t = 1/T$ over the selected window. "NYT baseline" is the mean outcome among not-yet-treated households over the same weeks. "Share (ATT/NYT)" reports the ratio of the mean ATT to the NYT baseline, expressed as a percentage. Outcomes are measured in kWh per half-hour.

The within-day shifts imply substantial changes in electricity consumption across hours in response to the tariff's relative prices. However, these responses should not be interpreted as extremely large price elasticities in the conventional sense, which measure the response of total electricity use to a single marginal price (Ito, 2014). Instead, our setting is more relevant to measures of interhour elasticity of substitution (Imelda et al., 2024): households reallocate electricity use across hours in response to a vector of simultaneously changing prices, while total daily consumption remains essentially unchanged.

This distinction matters because a back-of-the-envelope elasticity computed as $\varepsilon \approx (\Delta q/q)/(\Delta p/p)$ within a given period, such as an implied elasticity of about -3.1 in the morning off-peak period and -0.78 in the peak period, does not isolate a structural own-price elasticity. Rather, it reflects a reduced-form within-period response that combines (i) the own-price response for that period, (ii) cross-period substitution toward or away from other hours whose prices also change, and (iii) mechanical re-timing of flexible end uses (notably automated heat pump control). A useful way to think about our estimates is therefore as evidence of a high *within-day interhour elasticity of substitution*, reflecting a strong willingness/ability to shift usage from high-price to low-price hours rather than as evidence that overall electricity demand is highly price elastic.

Overall, households that also adopt the heat pump time-of-use tariff achieve meaningful reductions in their electricity bills. On average, these households save around £321 per year (18% of annual electricity expenditure), compared to if they were on the standard tariff from the same utility. Roughly one-quarter of these savings (around £76) arise from the tariff's structural price advantage — that is, the lower average price per kWh compared with the standard tariff even if consumption patterns do not change. The remaining three-quarters (about £245) stem from behavioral responses to the time-of-use price schedule, such as shifting heating and appliance use to cheaper off-peak periods.

Next, we explore how responses to the heat pump–specific tariff vary across household and property characteristics. Households with higher annual electricity consumption, larger floor areas, or living in higher-income areas exhibit larger absolute reductions in peak-period use, although these differences largely disappear when normalizing by each household's pre-period consumption profile. Energy efficiency bands show little systematic variation. We also find that households previously on time-of-use tariffs respond more strongly in the peak period, though they represent less than 10% of our sample and excluding them leaves our main estimates unchanged. Overall, these patterns indicate that while some groups shift more in absolute terms, the underlying behavioral response to the tariff is broadly similar across households. See Section A.4.10 for full heterogeneity plots.

2.2.3 Seasonal and Temperature Effects

We examine how the impact of the tariff on electricity consumption varies across the year and with outside temperature. In Figure A.21, we plot dynamic average treatment effects by calendar time across the four main periods of the day. We observe substantial load shifting into the morning and afternoon off-peak periods during colder months (October to March), with effects nearly disappearing in warmer months. Peak and "Other" period consumption fall correspondingly, indicating that off-peak increases are driven by substitution. Interestingly, the peak and "Other" reductions persist into summer, suggesting that some non-heating appliance usage is also being shifted.

Overall daily consumption increases moderately during winter but falls slightly in summer. These effects offset each other over the year, resulting in a near-zero average change. We hypothesize that in warmer months, the observed reduction in peak demand reflects some demand destruction (rather than pure shifting), whereas in colder months, some additional demand is created due to increased heating in off-peak hours.

A plausible mechanism is that households program their thermostats with higher setpoints during off-peak periods and lower setpoints during the peak period. Once set, this behavior is likely to persist over time and explains why shifting is strongest when the thermostat's setpoint is more likely to be binding — that is, when outdoor temperatures are low.

To further examine this hypothesis, we estimate the interaction between tariff adoption and daily average outside temperature, shown in Figure A.32. We control for household and day fixed effects and isolate the marginal impact of temperature after adoption. We find that the treatment effect nearly doubles during the coldest days relative to the average effect reported in Table A.9. Off-peak usage increases sharply when temperatures are below 14°C, consistent with heat demand being shifted from peak to cheaper hours. In the peak period, consumption decreases more steeply as temperature falls.

We do not observe a clear ceiling to shifting at very low temperatures, although very cold days (below 0°C) are rare in our data. This increasing responsiveness during colder weather may seem surprising, as one might expect households to resist lowering heating during peak hours when it is especially cold. However, since total heat demand is also higher in colder conditions (Section 2.1.3), the absolute opportunity for shifting increases. Furthermore, heat pumps employ load compensation: as the gap between indoor and outdoor temperatures widens, flow temperatures rise to maintain comfort. If households adopt lower peak-period thermostat setpoints under the heat pump tariff, this compensation mechanism amplifies the shifting effect.

Finally, outside temperature has little effect on consumption during non-heating periods, reinforcing the conclusion that most of the observed flexibility under the tariff relates to heating load.

2.3 Economic Implications of Heat Pump Adoption

Heat pump adoption generates two conceptually and economically distinct effects, each of which can be interpreted as concerning separate market imperfections. The first is an energy efficiency effect: heat pumps convert energy to useful indoor heat more efficiently than conventional gas boilers. This is reflected in substantial substitution from gas to electricity, with reductions in gas consumption roughly three times larger, in absolute terms, than the corresponding increase in electricity use. The second is a fuel-switching or congestion effect: by moving heating demand from energy sources whose timing is largely economically irrelevant (for example, due to pressurized gas systems) onto the electricity grid, households create new marginal costs that vary over time and are not fully captured by flat or weakly time-varying retail prices.

The first effect naturally raises the classic rebound question. If the implicit marginal cost of delivered heat falls, households may consume more heat, partially offsetting the engineering energy efficiency gains. In our setting, however, British electricity prices remain substantially higher per kWh than gas, meaning that the marginal cost of heating does not decline materially. For this reason, the scope for rebound is limited, and the observed energy efficiency gains are largely realized. Moreover, adopters in our sample may be early, higher-income households who already manage their heating to achieve desired comfort levels, further constraining potential rebound. The large gas reductions relative to electricity increases, combined with comparable marginal carbon intensities for the two fuels, imply that heat pump adoption delivers substantial CO_2e reductions. This carbon abatement increases as the grid becomes less carbon-intensive in the future (see Section 3). This finding contrasts with much of the residential energy-efficiency literature (for example, Fowlie et al. (2018)), where ex post savings have often fallen short of engineering projections. In our setting, it may be that the fuel switching impacts are mostly mechanical and do not interact strongly with behavioral adjustments. In addition, the absence of a substantial operating cost reduction may limit rebound. Both mechanisms would help explain why realized performance aligns closely with ex ante expectations. With that said, we acknowledge that we lack data from households' thermostats, so we cannot comment directly on comfort taking.

The second effect concerns grid congestion and temporal mispricing. Electrifying heating exposes demand to the structure of the electricity grid, where the marginal social cost of consumption varies across hours due to both congestion and emissions intensity. In this sense, electrified heating inherits a familiar second-best problem in electricity markets: even when upstream policies (such as carbon pricing) raise wholesale prices, distorted retail tariffs prevent consumers from efficiently adjusting demand across hours (Borenstein and Bushnell, 2022*a*,*b*). Our results illustrate how time-of-use pricing can mitigate this problem: Figure A.22 shows that households on the heat pump specific tariff shift electricity demand toward off-peak hours (early morning and afternoon) while reducing consumption during peak periods, with little effect on total daily usage. This demonstrates that tariffs primarily correct intra-day pricing distortions and congestion externalities, rather than inducing large reductions in overall consumption.

Taken together, these two channels highlight distinct policy considerations. The engineering energy efficiency gains from electrification are substantial. However, without time-varying prices, electrified heating may impose higher congestion costs or emissions at peak times than necessary. Time-of-use pricing therefore emerges as a natural complement to heat pump adoption, allowing the energy efficiency gains from electrification to translate into welfare improvements on the power system.

3 Welfare Analysis

3.1 Marginal Value of Public Funds

We use the estimates of energy demand from heat pump adoption to evaluate the welfare effects of the UK's heat pump subsidy, the Boiler Upgrade Scheme. Our approach follows the marginal value of public funds (MVPF) framework of Hendren and Sprung-Keyser (2020), which compares the total social benefits of a policy to its net fiscal cost. In this framework, the reference point for overall economic efficiency is the marginal cost of public funds for raising the revenue for that subsidy, so that a given MVPF implies lower economic efficiency when the opportunity cost of public expenditures is higher. We account for the fiscal and environmental components of the subsidy alongside transfers to households who would have adopted regardless. A key limitation of our design is that we cannot directly estimate the additionality rate — the share of subsidy recipients who were induced to adopt by the subsidy, as opposed to those who would have adopted without it. Relatedly, because eligibility for the subsidy is not randomized, our design does not identify an intention-to-treat effect of the subsidy itself; our estimates are effects of realized heat pump adoption, and moving from them to the welfare impact of the subsidy requires the additionality assumption we adopt below. We follow Hahn et al. (2024) in assuming that half of all recipients are *subsidy-induced* (those who adopt only because of the subsidy; referred to as 'marginal' in the MVPF literature) and half are *non-additional* (those who would have adopted regardless; 'inframarginal' in the MVPF literature). This is broadly consistent with empirical evidence from comparable residential energy efficiency programs (Boomhower and Davis, 2014, Davis, 2024, Hahn et al., 2024), though additionality rates vary substantially across programs and this assumption represents a meaningful source of uncertainty in our welfare estimates.

Under a linear adoption demand curve, a subsidy-induced adopter's private cost of adopting is distributed uniformly between zero and the subsidy amount, so on average the subsidy splits evenly: half compensates the household's private cost of adopting, and half is retained as consumer surplus. Induced households therefore value the subsidy at roughly half its face value, while non-additional recipients — who would have adopted regardless — value it at the full amount as a pure transfer. Sensitivity to this assumption is shown in Table 3.

The social benefits comprise reductions in carbon dioxide and local air pollutants arising from the observed fall in gas use and rise in electricity consumption. The fiscal and resource costs include the subsidy expenditure, the average installation cost, avoided operating costs on a counterfactual gas boiler, and associated changes in government revenue such as VAT on appliances and energy bills. Private operating benefits beyond fuel switching, such as potential savings from time-of-use electricity tariffs or other complementary technologies, are not modeled separately in the MVPF calculation. To the extent that such factors increase the private value of adopting a heat pump, they are implicitly captured in our reduced-form assumption about the share of marginal versus inframarginal adopters.

Under a range of parameter choices, our estimated MVPF remains above unity, though the estimate is sensitive to underlying assumptions, particularly the additionality of subsidy recipients and the chosen value of avoided carbon (see Table 3). We find that the average household reduces gas use by 8,744 kWh per year and increases electricity consumption by 2,551 kWh per year. Using UK Government emissions factors for end-use electricity consumption, which account for upstream efficiency losses in electricity generation and transmission, this corresponds to a reduction of approximately 1.16 tonnes of CO_2e per household per year at 2024 Great Britain grid intensities, rising to around 1.74 tonnes per year by 2043 as the Great Britain electricity grid decarbonizes. Over an assumed 20-year lifetime of a heat pump, this implies a cumulative reduction of roughly 31 tonnes of CO_2e per household.

Under the UK Government's approach, carbon values are derived by first specifying the quantity of CO_2e reductions required to meet future emissions targets and then reading off the corresponding cost from the marginal abatement cost curve. This procedure yields a carbon value of around £280 per tonne of CO_2e (Department for Energy Security and Net Zero, 2023*a*). This method differs from the approach used in some other countries, such as the United States, where the social cost of carbon is typically estimated using integrated assessment models that quantify the marginal damages from an additional tonne of CO_2e (EPA, 2022).

Combining these carbon valuations with the fiscal cost of the £7,500 subsidy, the average installation cost of £12,713, and associated tax and spending effects, we estimate a marginal value of public funds (MVPF) of 1.23, suggesting that each £1 of public expenditure on the subsidy generates approximately £1.23 in social benefits, driven primarily by avoided carbon emissions. This estimate should be interpreted with the assumptions above in mind (see Table 3), but it compares favorably with the estimated returns to other policies aimed at reducing CO_2e emissions (Hahn et al., 2024). Table 3 presents a sensitivity analysis illustrating how our estimates change under alternative assumptions about discount rates and the definition of costs and benefits. Section A.6.5 extends this to a joint sensitivity over the full range of additionality and social-cost-of-carbon assumptions.

Further, we calculate an MVPF that accounts for dynamic efficiency effects from learning-by-doing. Evidence from other heating technologies suggests cost declines of roughly 14% for each doubling of cumulative installations (Weiss et al., 2009). Applying a similar learning rate to heat pumps increases the MVPF to about 2.1, reflecting the long-run social value of accelerated cost reduction and adoption. Figure 8 illustrates the components of the MVPF calculation, showing how social benefits, fiscal costs, and externalities interact to generate net welfare gains.

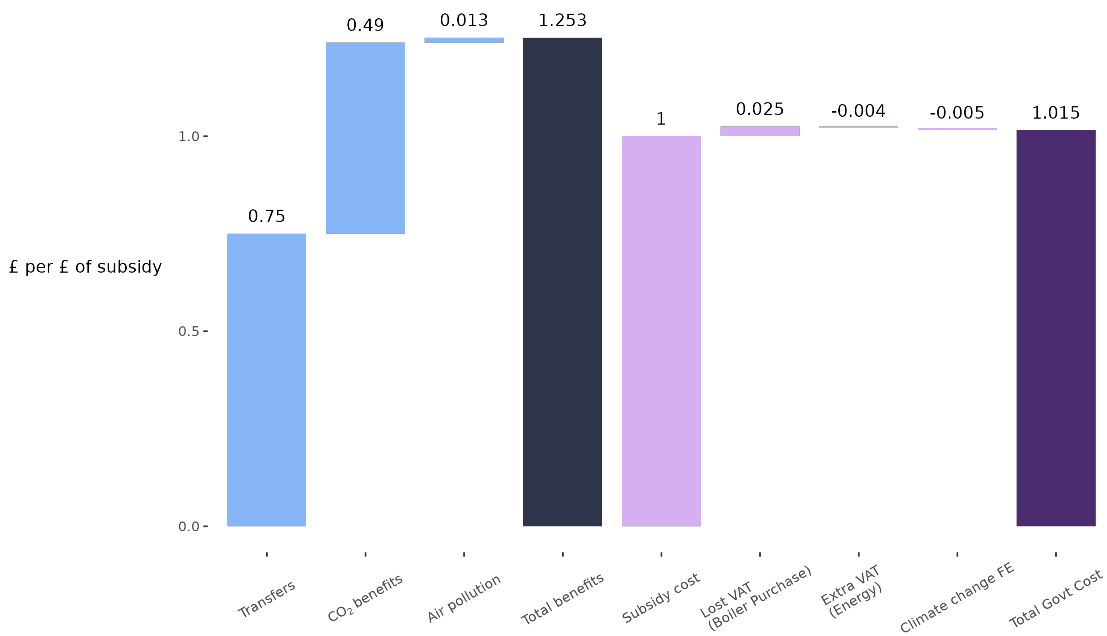
Table 3: MVPF and Other Measures of Cost Effectiveness

			MVPF			Cost per tonne		
	Discount Rate	Additionality Rate	Average	First £	First £ w/ LBD	Resource	Government	Social
MAC-based SCC	3.5%	50%	1.230	1.65	2.10	£86	£487	£329
MAC-based SCC	3.5%	25%	1.120	1.65	2.10	£86	£967	£328
IAM-based SCC	2%	50%	1.030	1.37	1.82	£84	£488	£328
IAM-based SCC	3.5%	50%	0.991	1.32	1.77	£86	£489	£330

Note: There are multiple ways to evaluate the benefits and costs of the heat pump subsidy. We report the marginal value of public funds (MVPF) as a welfare measure, alongside resource, government, and social cost per tonne as measures of cost-effectiveness. Results vary by the appraisal discount rate (the UK Treasury recommends 3.5% (HM Treasury, 2020)), and by the share of households that are subsidy-induced ('marginal' in the MVPF literature) versus non-additional ('inframarginal'). Carbon benefits are monetized either using UK marginal abatement cost-based carbon values (MAC), which assumes a social cost of carbon of approximately £280/tonne; or damage-based social cost of carbon estimates from integrated assessment models (IAM), which assumes a social cost of carbon of approximately £166/tonne ($\$_{2020}185$/tonne). In the IAM-based case, the social cost of carbon is taken from Rennert et al. (2022) and embeds a 2% near-term discount rate in its construction; in all cases, program costs and benefit streams are discounted at the appraisal rate shown in each row. Our preferred specification is the first row: a 3.5% appraisal discount rate and MAC-based social cost of carbon (as per UK Government guidance), and an assumption that 50% of households are marginal.

Based on these same assumptions, we also estimate an implied optimal subsidy — the point at which an additional £1 of subsidy generates no further societal benefit — of around £7,155, close to the current policy level, though this figure inherits the same sensitivities discussed above. If we include the learning-by-doing benefits in the calculation, the optimal subsidy rises to £12,045.

Figure 8: Marginal Value of Public Funds (MVPF) of the Boiler Upgrade Scheme



Note: We show the welfare benefits and costs of the subsidy for air-source heat pumps — specifically, for the first row of Table 3 ("MAC-based", 3.5% discount rate, 50% of households as marginal). We show these benefits and costs per £7,500, which from October 2023 is the level of the subsidy offered to British households for adopting an air-source heat pump. In blue, we show benefits: transfers to households receiving the subsidy, CO_2e abatement benefits from marginal households, and air quality benefits from marginal households. These total £9,397 per £7,500 subsidy (1.253, in navy). In light purple, we show the costs. First, the subsidy itself. Next, lost VAT from avoided boiler purchases from marginal households. Then, two increases in Government revenue that reduce the Government cost: extra VAT from increased energy expenditure and the "climate change fiscal externality" of tax revenue from avoided climate change. These total £7,615 per £7,500 (1.015, in dark purple). The MVPF is then 1.253/1.015 = 1.23.

It is worth emphasizing that our evaluation of heat pumps' impact is in the context of a subsidy that mandates full replacement of the previous heating system. In this context, the heat pumps lead to a nearly complete elimination of historical gas consumption. In other contexts, households might choose to keep their previous systems as back-up, which might dampen the fuel switching impacts, carbon abatement, and welfare benefits.

Households with poorly insulated homes, or those with a strong preference for rapid temperature recovery, may systematically prefer gas heating, while households with tighter building envelopes or stronger preferences for temperature stability may be more likely to adopt heat pumps. To the extent that adoption is selective on these dimensions, our estimates reflect the average treatment effect on the treated — that is, outcomes for the observed population of adopters — and may not generalize to non-adopters, for whom the welfare effects of heat pump adoption could differ.

3.2 Heat Pump Impacts on Private Operating Costs

Separate from the MVPF calculation, we estimate impacts on households' operating costs. Based on our estimates and retail prices as of 15 June 2024, an average heat pump household spends about £10 less per year on energy than a comparable gas-heated home, using the utility's standard tariff's electricity and gas prices per kWh at that date (or £79 more per year using the Government's estimated retail energy costs in 2024). For context, we estimate that households paid approximately £2,100 per year for energy prior to heat pump adoption on the utility's standard tariff at those same prices. Against that benchmark, the £10/year implied operating cost saving at those prices reflects almost no change. Note that this is before any private cost savings from time-of-use pricing, which, as discussed in Section 2.2.2, reduce heat pump operating costs by £321/year.

Although we find that they use less total energy than the gas boilers they replace, the much higher retail unit price of electricity relative to gas offsets this efficiency gain. This in part reflects a broader mispricing of energy across fuels. Following Borenstein and Bushnell (2022*a*,*b*), fixed cost recovery in regulated utility markets raises retail prices above the private marginal cost of producing energy, an effect that is more pronounced for electricity because its infrastructure is more capital intensive and regulatory rate-making bundles a greater share of fixed costs into volumetric charges. At the same time, unpriced externalities mean that the private marginal cost falls below the marginal social cost, which can partially offset some of the cost recovery overpricing. A third mechanism further widens the price distortion: public purpose programs. Certain policy programs can be funded through energy bills, as is the case in the UK for a number of policies. The resulting distortion weakens private incentives to electrify, even when electrification is socially beneficial. This pricing differential is a live policy issue in many countries. Recent UK policy changes, including the partial removal of electricity levies announced in November 2025 (HM Treasury, 2025), as well as the European Commission's Action Plan for Affordable Energy (European Commission, 2025), explicitly attempt to reduce the electricity–gas per-kWh price ratio, partly to support electrification and heat pump deployment.

Motivated by Borenstein and Bushnell (2022*a*,*b*), we can look at how households' operating costs would change under alternative pricing regimes that remove price distortions. We analyze a sequence of stylized pricing scenarios that progressively move retail energy prices toward marginal social cost. For each scenario, we explicitly reconstruct retail unit prices by identifying the relevant policy, network, and carbon cost components. We estimate the aggregate magnitude of these components using annual expenditures associated with major electricity subsidies, and convert these aggregates into per-kWh charges by allocating them over total national electricity or gas consumption from Department for Energy Security and Net Zero (2024).

Beyond the price baselines (1a)–(1d), our scenarios include: (2) removing part of legacy electricity policy costs from per-kWh charges in line with the UK Government's recent announcement (HM Treasury, 2025); (3) removing all explicit policy costs from electricity unit prices; (4) removing volumetric recovery of electricity network costs[4]; (5) applying carbon pricing to household gas consumption, which is currently exempt; and (6) pricing carbon in both electricity and gas at the UK Government's central social cost of carbon. These scenarios are not intended as literal policy proposals, but rather as transparent benchmarks designed to quantify the magnitude of existing pricing distortions. [5]

Table 4: Heat Pump Operating Cost Differences under Alternative Pricing Regimes

Scenario	Heat pump penalty (+) / saving (−), £ per year	Gas price (£/kWh)	Electricity price (£/kWh)
(1a) Govt estimated prices	£186	£0.0816	£0.3528
(1b) Govt estimated prices, no gas standing charge	£79	£0.0816	£0.3528
(1c) Utility prices	£97	£0.0604	£0.2450
(1d) Utility prices, no gas standing charge	–£10	£0.0604	£0.2450
(2) Partial electricity policy costs reduction	–£49	£0.0589	£0.2245
(3) Full removal of electricity policy costs	–£106	£0.0589	£0.2022
(4) Remove electricity policy costs + network charges	–£227	£0.0589	£0.1547
(5) Scenario 4 + gas priced under UK ETS	–£326	£0.0701	£0.1547
(6) MSC: Scenario 4 + both fuels priced at SCC	–£596	£0.1142	£0.1997

Note: Entries show the change in annual operating costs for a heat pump household relative to a gas boiler. Positive values indicate a higher cost; negative values indicate savings. Calculations assume fixed annual energy use of 2,551 kWh electricity and -8,744 kWh gas. Scenarios (1a)–(1d) vary retail price assumptions and treatment of the gas standing charge (£107 per year), with Scenario (1d) used as the main benchmark. Scenarios (2) and (3) progressively remove policy costs, which mostly fall on electricity. Scenario (4) removes *network* costs from unit rates, as well. Scenario (5) includes all of these changes, but introduces carbon pricing on gas (which is currently exempt, when used for home heating). Scenario (6) brings both fuels to their marginal social cost (MSC), where electricity unit rates have policy and network costs removed, and both fuels are priced at the UK Government's official social cost of carbon (SCC). All scenarios are stylized counterfactuals intended to illustrate the magnitude of pricing effects rather than specific policy proposals. For context, we estimate that households paid approximately £2,100 per year for energy prior to heat pump adoption on the utility's current standard tariff. Note that this is before any private cost savings from time-of-use pricing, which, as discussed in Section 2.2.2, reduce heat pump operating costs by £321/year. More detailed notes are available in Section A.6.6.

By rebalancing electricity and gas prices toward their marginal social costs — that is, removing upward distortions from fixed cost recovery and public purpose programs while internalizing externalities — these scenarios quantify the extent to which observed operating-cost penalties reflect pricing institutions rather than the underlying efficiency of heat pump technology. Table 4 reports the implied change in annual household heat pump operating costs under each scenario, relative to a gas boiler, holding usage fixed and abstracting from installation costs. As electricity "headwinds" are progressively removed and gas prices move closer to their marginal social cost, the operating cost savings from heat pumps increase.

[4] The question of how to recover electricity network costs is itself an important economic consideration. For example, McRae (2024) argues for greater reliance on fixed charges when recovering network costs.

[5] We note two simplifications. First, Scenario 6 prices only carbon (via the UK Government's social cost of carbon) and does not additionally price local air pollution externalities (e.g., from gas combustion or marginal electricity generation), so it understates a fully comprehensive marginal-social-cost benchmark. Second, we hold standing (fixed) charges constant across scenarios even as we vary volumetric unit prices; in practice, a regulator recovering fixed network costs would likely adjust standing charges to preserve revenue neutrality. This is particularly relevant for the gas standing-charge disconnection scenarios (1b, 1d), where at scale, other gas customers would face higher standing charges to recover the network costs no longer collected from disconnecting households. We view both simplifications as second-order relative to the main pricing distortions discussed.

In presenting these counterfactual operating cost impacts, we assume that changes in electricity and gas prices per kWh do not induce changes in household energy consumption. Estimated changes in electricity use (2,551 kWh) and gas use (-8,744 kWh) are therefore held fixed across all pricing scenarios. This is a strong assumption, since households may adjust usage in response to price changes. Our objective, however, is not to model behavioral demand responses under alternative policy regimes, but to provide transparent, stylized calculations that isolate the mechanical effect of different pricing structures on relative operating costs. The scenarios should therefore be interpreted as accounting exercises that quantify the magnitude of existing pricing wedges and illustrate how policy "headwinds" and "tailwinds" shape the private economics of heat pump adoption.

Finally, note that the analysis uses 2024 operating costs and does not model how these pricing regimes would evolve over a 20-year equipment lifetime. As the electricity grid continues to decarbonize, consistent carbon pricing would likely reduce the carbon cost component of electricity relative to gas, strengthening the operating cost advantage of heat pumps over time — especially in Scenarios 5 and 6. Even in the static comparisons presented here, however, the results highlight an important contrast: while the baseline operating cost difference is modest relative to overall household energy expenditure, the policy wedges embedded in retail prices are economically meaningful. Removing electricity policy and network costs and introducing carbon pricing on gas materially shift the relative cost comparison, making heat pumps more clearly cost saving under pricing regimes that better align retail prices with marginal social costs.

An implication of this analysis that we do not fully explore is its interaction with the welfare and subsidy calculations in Section 3. Heat pump adoption in Great Britain remains low relative to the stock of technically suitable homes, and our MVPF and optimal-subsidy estimates are calibrated to this setting, characterizing marginal adoption behavior under current retail prices, where the payback period on a typical £5,213 net installation cost is extremely long (Scenario 1d). A policy-relevant question raised by fuel mispricing is how large a subsidy — or how much price reform — would be needed to move most households with suitable homes to voluntarily choose a heat pump over a gas boiler. Table 4 suggests that even under our most aggressive re-pricing scenario (Scenario 6), where operating costs fall by close to £600 per year, the implied payback period is still around nine years — a substantial improvement on the status quo, but not obviously fast enough on its own to drive mass adoption absent a continuing subsidy or further price convergence. We therefore view current mispricing as one plausible contributor to slow diffusion, and correcting it as likely to reduce, but probably not eliminate, the subsidy required for widespread adoption among suitable households. Re-pricing would also affect government revenue directly and independent of any adoption response — for instance, applying carbon pricing to gas would raise revenue, while removing policy costs from electricity bills would lower it — and a full accounting would need to net these effects against any fiscal savings from a lower required subsidy. Quantifying these interactions properly would require adoption elasticities with respect to payback periods that are not currently available in the literature or estimable from our data, so we leave a fuller treatment of pricing and subsidy design for mass adoption to future work.

4 Conclusion

Our study shows that heat pump adoption induces substantial substitution away from fossil fuels: household gas consumption falls sharply, while electricity use rises by around one third as much in kWh terms. These relative effect sizes reflect the higher energy efficiency of heat pumps versus gas boilers. The primary policy relevance of this fuel switch lies not in aggregate energy savings per se, but in the resulting emissions reductions. Under the current UK electricity generation mix, household CO_2e emissions fall by approximately 39%. Under projected grid decarbonization pathways (UK Government, 2024), cumulative emissions reductions from heat pump adoption rise to around 72% over 20 years.

Economically, these effects operate in two related ways. First, heat pumps deliver energy efficiency gains in converting energy into useful heat. In contrast to much of the prior energy-efficiency literature, we find little evidence of rebound, which means the engineering energy efficiency gains translate closely into realized energy and carbon savings. Second, electrification shifts heating demand onto the electricity grid, where the marginal social cost of consumption varies over time. This creates a congestion and temporal mispricing problem that is largely absent under gas heating.

We show that time-of-use pricing can meaningfully mitigate this distortion. Households on the heat pump–specific tariff reallocate demand away from peak periods and toward off-peak hours, with little change in total daily consumption. The primary economic role of such tariffs is therefore not to reduce overall electricity use, but to improve the alignment between household demand and underlying system conditions. In this way, tariff design emerges as a natural complement to electrification.

While we find little effect on CO_2e at 2024 marginal carbon intensities from the time-of-use tariff, the greater impact may be on peak demand for future electricity grids: our findings show that, despite behavioral constraints associated with home heating, heat pump owners respond to price signals to shift demand away from peaks. This shift could reduce network reinforcement needs and lower system costs associated with electrification, as suggested in energy system modeling (Franken et al., 2025). We see this load shifting away from peak periods even on the coldest days of the year and from all building types in our sample, contrary to concerns that load shifting from heat pump owners will not be possible under the temperature and grid conditions when it is needed most. Indeed, we find evidence that load shifting *increases* on the coldest days of the year.

These findings come with a caveat about external validity. Heat pump adopters in our sample are likely those for whom heat pumps are most desirable or well suited, so the observed effects need not reflect population treatment effects; we expect them to generalize reasonably well nonetheless, since the response is largely mechanical and tied to outdoor temperature rather than to idiosyncratic traits of early adopters. The heat pump tariff results are more sensitive to selection into treatment by structural winners and low-shifting-cost households: our sample skews toward larger homes and, we suspect, more technologically engaged households, which likely contributes to the large observed load-shifting response. As adoption spreads to the smaller homes with occupants less familiar with automation, we would expect smaller absolute effects, though still meaningful ones relative to heat pump and home size.

Our analysis also clarifies the role of retail energy pricing in shaping private incentives. Under current retail prices, heat pumps do not meaningfully reduce household operating costs. Electricity prices embed significant policy and network costs through volumetric charges, while household gas prices largely exclude climate externalities. This pricing structure weakens private incentives to electrify, even when electrification is socially beneficial. When retail prices move closer to marginal social cost, through rebalancing electricity levies or pricing carbon consistently across fuels, the private operating cost savings from heat pumps increase substantially. In this sense, current pricing creates "headwinds" for electrification that are not rooted in the underlying energy efficiency of the technology. However, even under current retail prices, the addition of a time-of-use tariff can lower costs below average boiler operating costs.

From a welfare perspective, our calculations suggest the UK heat pump subsidy is welfare-enhancing under a range of plausible assumptions, largely driven by significant carbon savings. As discussed in Section 3, this conclusion rests on assumptions — including the additionality of subsidy recipients and the social cost of carbon used — that are each subject to meaningful uncertainty. The societal value of heat pump adoption would increase further if technology costs fall, including from learning by doing seen in the deployment of other technologies, and if the carbon intensity of electricity generation falls faster than expected.

Overall, heat pumps should be understood as a decarbonization technology that combines energy efficiency gains with fuel switching. Their social value would be enhanced by complementary policies: electricity and gas pricing regimes to align private incentives with marginal social costs, and time-of-use pricing to mitigate the impact of electrified heating on system costs.

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A Online Appendices

Contents

A.1 Heat Pump Appendix

A.1.1 Identification and Estimation Details

Callaway and Sant'Anna Difference-in-Differences Estimators: Our outcome Y_{it} is the energy consumption (gas, electricity or gas + electricity consumption, which we call "total energy") for household i in week t. We define G as the first week the heat pump was fully installed. We do not observe if households change heating systems later, but we consider it unlikely. $Y_{it}(0)$ is household i's potential energy use at time t if they remain untreated. $Y_{it}(g)$ is the potential energy use for household i at time t if they were first treated in week g. G_{ig} is a dummy variable equal to one if a household i had a heat pump installed in week g, and zero otherwise. For simplicity, we will consider that some households get a heat pump in week 2 (in reality, we observe more weeks before treatment). Thus, $g = 2, \ldots, \tau$.

The observed and potential outcomes for each household i can be written as:

$$Y_{it} = Y_{it}(0) + \sum_{g=2}^{\tau}(Y_{it}(g) - Y_{it}(0)) \cdot G_{ig} \tag{1}$$

We define the Average Treatment Effect on the Treated (ATT) for cohort (week of adoption) g at time t (referred to as the group-time average treatment effect in the Callaway and Sant'Anna (2021) framework) as:

$$ATT_{gt} = \mathbb{E}_{gt}\left[Y_t(g) - Y_t(0) \mid G_g = 1\right] \tag{2}$$

This group-time ATT measures the expected difference in energy consumption at time t for households who received the heat pump in week g, compared to what their consumption would have been without the treatment.

The dynamic effects (event-style analysis) for the time e since adoption, with $e = t - g$, can be written as:

$$\theta_{es}(e) = \sum_{g \in G} \mathbf{1}\left\{g + e \leq \tau\right\} P(G = g \mid G + e \leq \tau) \cdot ATT(g, g+e) \tag{3}$$

Here, $P(G = g \mid G + e \leq \tau)$ represents the probability that a household was first treated in week g, given that they are observed e periods after treatment. This probability acts as a weight, ensuring that the treatment effect $ATT(g, g+e)$ is appropriately scaled according to the size of the group treated in week g and their exposure duration. This aggregation averages the treatment effect for all households who have been treated for exactly e periods. However, it should be noted that this approach introduces some compositional effects because it mixes the treatment effects across different cohorts who might have different baseline energy consumption patterns due to seasonality or other factors. Therefore, it should only be interpreted as the treatment effect for exposure e if we assume that $ATT_{g,g+e}$ does not vary across cohorts. In the case of heat pump analysis, this effect varies across cohorts as households install their heat pumps at different times of the year.

Then, we calculate the calendar-time average treatment effect, which can be defined as:

$$\theta_c(\tilde{t}) = \sum_{g \in G} \mathbf{1}\left\{\tilde{t} \geq g\right\} P(G = g \mid G \leq \tilde{t}) \cdot ATT(g,t) \tag{4}$$

This expression captures the average treatment effect at a specific calendar time $\tilde{t}$, weighted by the probability that a household was treated by week $\tilde{t}$. This helps in understanding the impact of heat pump installations across different points in time, accounting for when the treatment was administered.

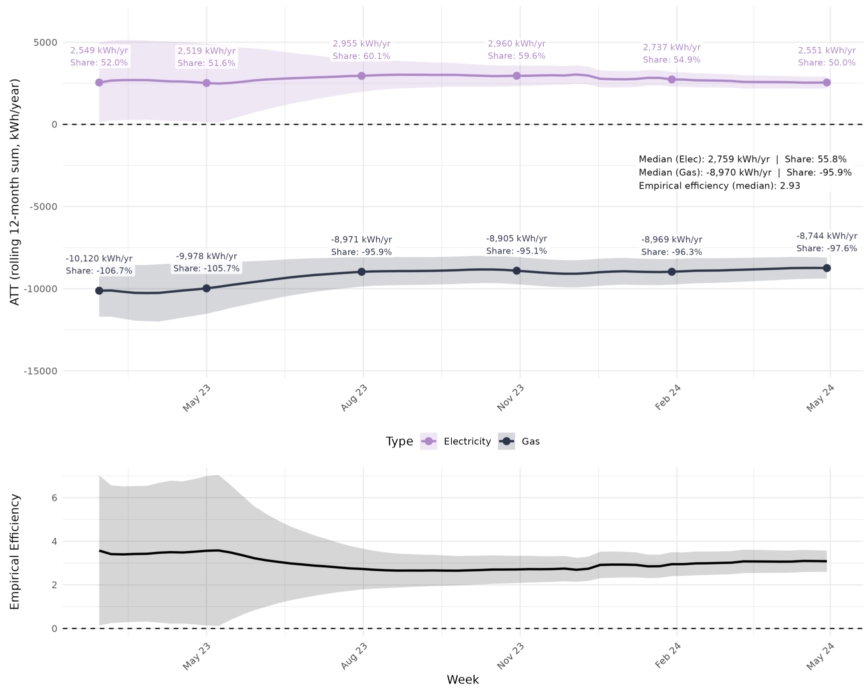
Finally, the simple overall treatment effect can be expressed as:

$$\theta_W^O = \frac{1}{\kappa} \sum_{g \in G} \sum_{t=2}^{\tau} \mathbf{1}\left\{t \geq g\right\} ATT_{gt} \cdot P(G = g \mid G \leq \tau) \tag{5}$$

where $\kappa = \sum_{g \in G} \sum_{t=2}^{\tau} \mathbf{1}\left\{t \geq g\right\} P(G = g \mid G \leq \tau)$. This normalization ensures that the weights sum to 1. The overall treatment effect θ_W^O is a weighted average of the group-time ATTs, putting more weight on larger groups and those who have remained in treatment for longer periods. This method avoids the issues associated with traditional TWFE models, such as negative weighting, which can lead to biased estimates.

Yearly Estimates Using 12-month Rolling Averages: We show how our main results differ by analysis date. Each point shows a different set of the 12-month rolling average, over time, for our electricity consumption impact, gas consumption impact, and ratio of gas consumption impact (times 0.9, to account for gas boiler inefficiency) to electricity consumption impact.

Figure A.1: Yearly Estimates Using 12-Month Rolling Average Calendar ATTs



Comparing Heat Pump TWFE and CS Main Results: This analysis compares our main results using the Callaway and Sant'Anna (2021) (CS) estimator to estimates from a TWFE model applied to the same data.

Table A.1: HP Installation on Energy Consumption in kWh

	TWFE		CS	
	Electricity	Gas	Electricity	Gas
Model:	(1)	(2)	(3)	(4)
Variables				
Is HP Installed = 1	3,177.7***	-10,276.3***	3,388.6***	-11,011.1***
	(126.7)	(246.5)	(168.4)	(312.9)
Pre-Treatment Average				
Pre-Treatment Consumption	5,086.4	9,980.4	5,027.3	9,938.8
Fixed-effects				
Household	Yes	Yes		
Week	Yes	Yes		
Fit statistics				
Observations	110,901	91,123		
Number of Households	1,308	1,110	1,308	1,110
Number of cohorts (CS)			100	99
Number of Time Periods	131	129	124	124
R^2	0.65444	0.72375		

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Main Results Using Both Not-Yet-Treated and Never-Treated as Control: We model the impact of heat pumps on electricity, gas, and overall energy consumption (all in kWh). In this analysis, we include households who had a deal but had not yet had an installation by 15 June 2024 (whereas our main analysis excludes these households).

Table A.2: HP Installation on Energy Consumption in kWh (Never-treated)

	TWFE		CS	
	Electricity	Gas	Electricity	Gas
Model:	(1)	(2)	(3)	(4)
Variables				
Is HP Installed = 1	2,944.6***	-9,750.6***	2,905.4***	-9,367.0***
	(119.2)	(227.8)	(162.4)	(267.4)
Pre-Treatment Average				
Pre-Treatment Consumption	5,133.0	9,803.1	5,049.5	10,097.9
Fixed-effects				
Household	Yes	Yes		
Week	Yes	Yes		
Fit statistics				
Observations	158,621	129,009		
Number of Households	1,942	1,581	1,942	1,581
Number of cohorts (CS)			101	100
Number of Time Periods	129	129	129	129
R^2	0.64110	0.72409		

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

CS Estimates among Sample with Gas as a Previous Heat Source Only: We model the impact of heat pump on electricity and gas among the subset of our adopters who are in our gas consumption analysis. In other words, the gas consumption results are the same as our main results, and are repeated here only for reference; the electricity consumption results are new, where households that did *not* have gas consumption are now excluded from the sample.

Table A.3: Heat Pump Installation Effects on Energy Consumption (Gas-Metered Households)

Model:	Electricity (1)	Gas (2)
Variable		
Is HP Installed = 1	3,616.1***	-11,011.1***
	(159.8)	(291.6)
Pre-treatment Average		
Pre-Treatment Consumption	4,902.9	10,097.9
Fit statistics		
Number of Households	1,111	1,110
Number of Cohorts	99	99
Number of Time Periods	124	124

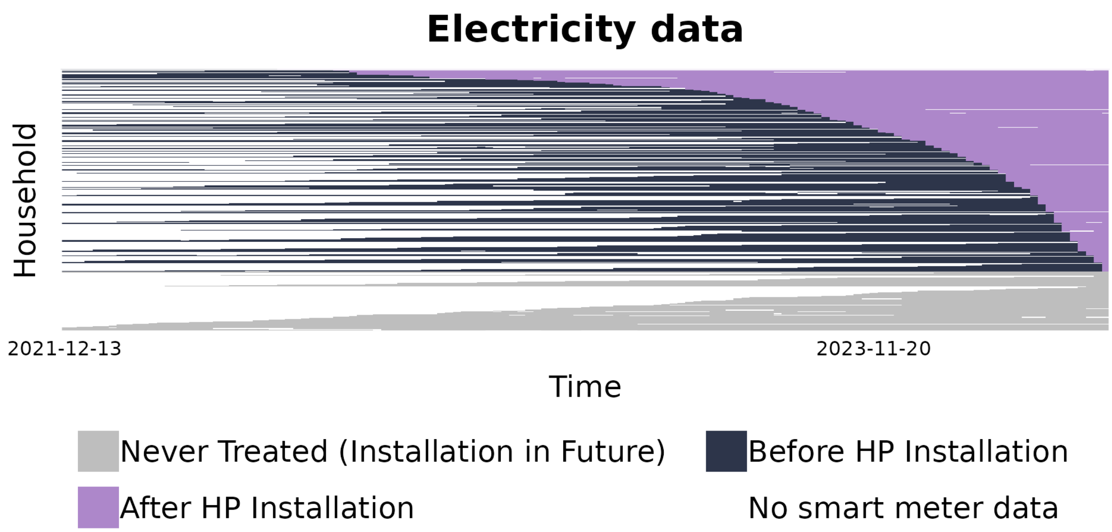
Clustered (Household) standard-errors in parentheses
Estimation Method: Doubly Robust
Control Group: Not Yet Treated
Anticipation Period: 4
Signif. Codes: *** 95% confidence band does not cover 0

Note: This table reports the simple CS estimates of the impact of heat pump installation on electricity (column 1) and gas consumption (column 2). Both models are estimated on the subsample of households with observed gas consumption prior to installation, and therefore use a smaller sample than the full electricity-only analysis.

A.1.2 Additional Heat Pump Results

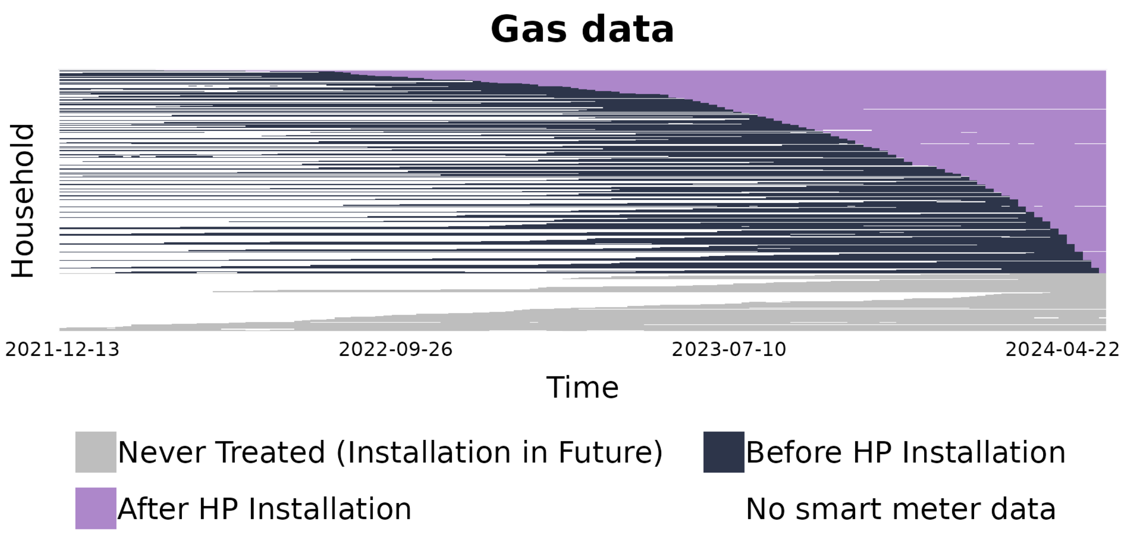
Data Availability: Here we visually show consumption data availability depending on household adoption status.

Figure A.2: Smart Meter Electricity Data Availability for Heat Pump Owners



Note: This figure displays the availability of smart meter *electricity* consumption data for a random sample of 500 heat pump adopters over time. Each row represents a household and each column a date. Purple segments indicate periods after heat pump installation, black segments indicate periods before installation, grey segments indicate households that install after the end of our data window (never-treated within the observed period), and white areas denote dates with no available smart meter data. Households are grouped by installation timing so that those with identical pre- and post-installation histories are displayed together. The figure is constructed using weekly consumption data.

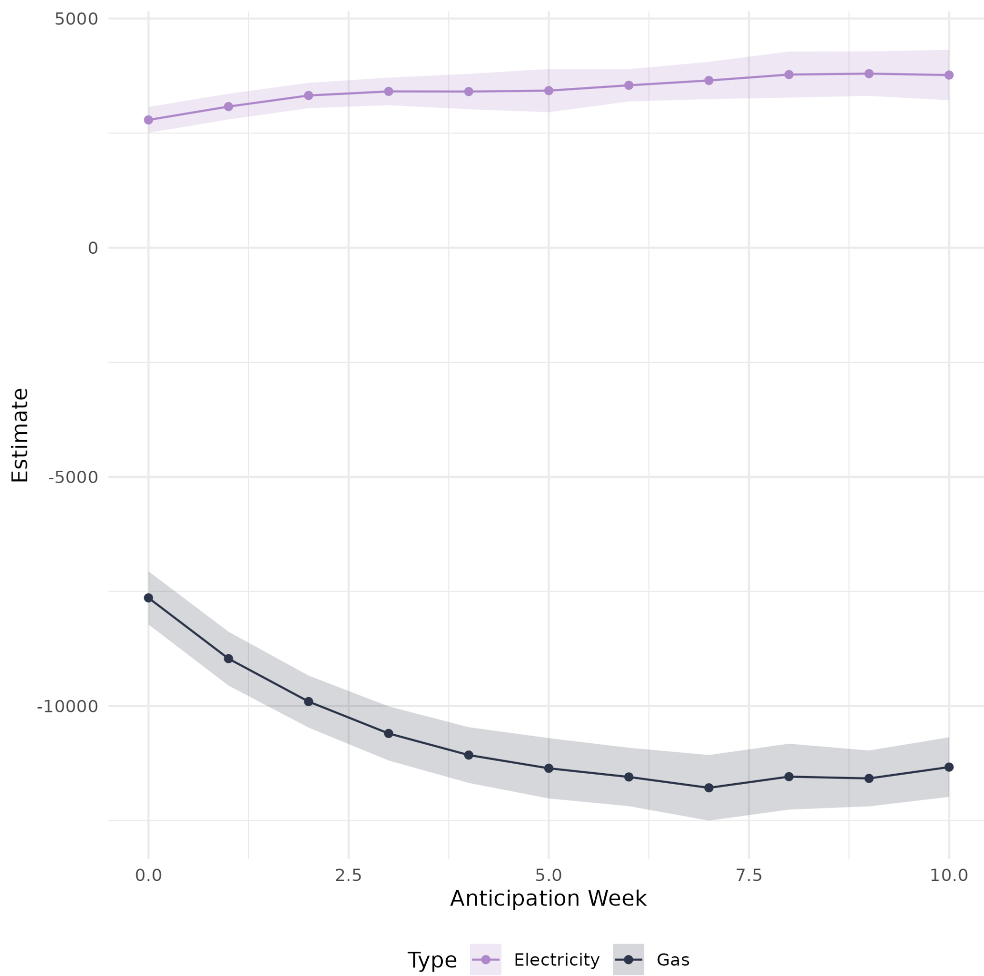
Figure A.3: Smart Meter Gas Data Availability for Heat Pump Owners



Note: This figure displays the availability of smart meter *gas* consumption data for a random sample of 500 heat pump adopters over time. Each row represents a household and each column a date. Purple segments indicate periods after heat pump installation, black segments indicate periods before installation, grey segments indicate households that install after the end of our data window (never-treated within the observed period), and white areas denote dates with no available gas smart meter data. Households are grouped by installation timing so that those with identical pre- and post-installation histories are displayed together. The figure is constructed using weekly consumption data.

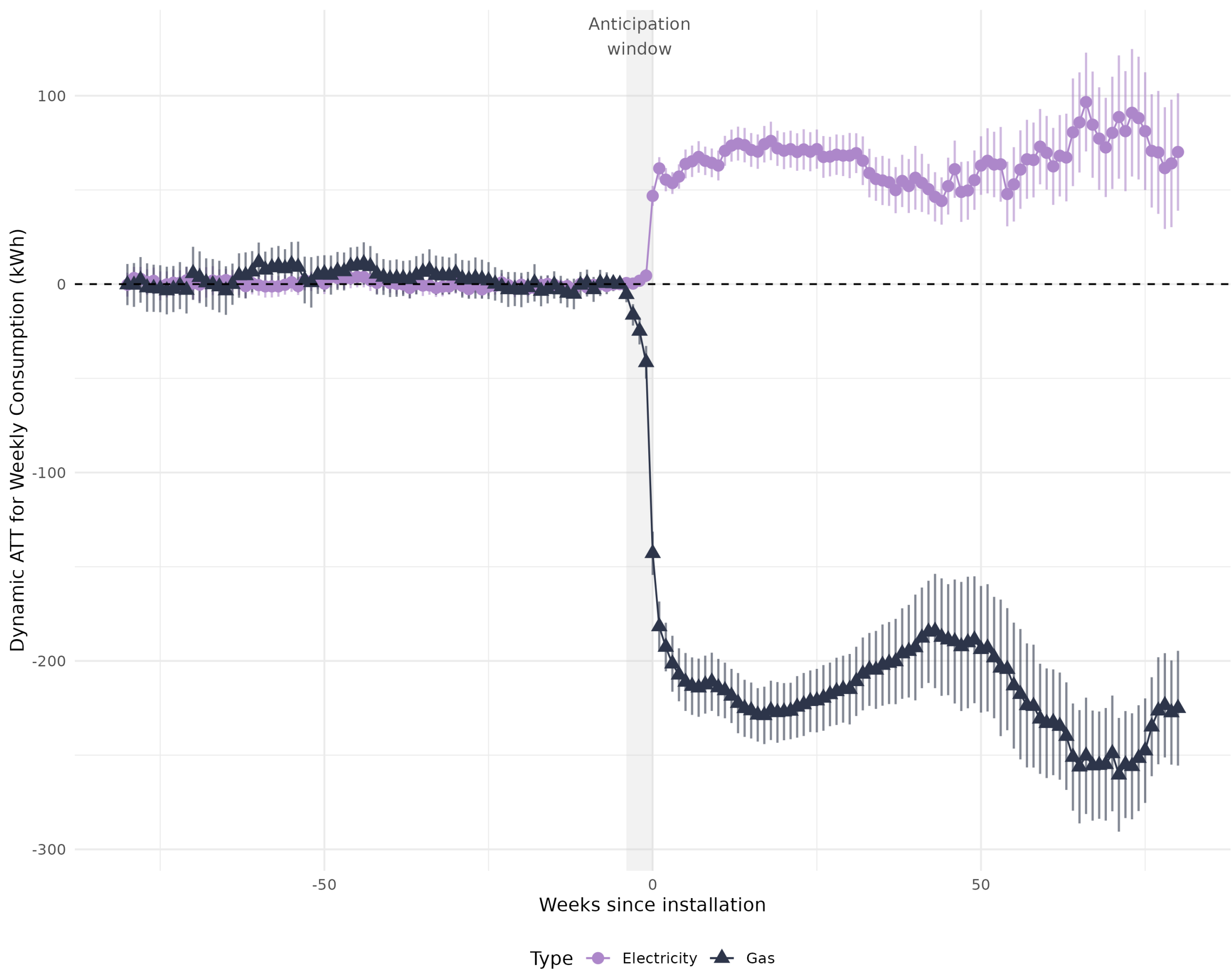
Anticipation Checks: We plot how our CS estimates change depending on the length of anticipation period pre-adoption. We observe modest anticipation effects beyond one week, especially for gas consumption. Estimated impacts grow slightly with longer anticipation periods, likely because some households remove gas boilers before heat pump installation, potentially up to one month before installation; they may then rely on portable electric heaters or other alternative heating sources in the interim.

Figure A.4: Heat Pump Impacts Depending on Assumed Anticipation Period (in Weeks)



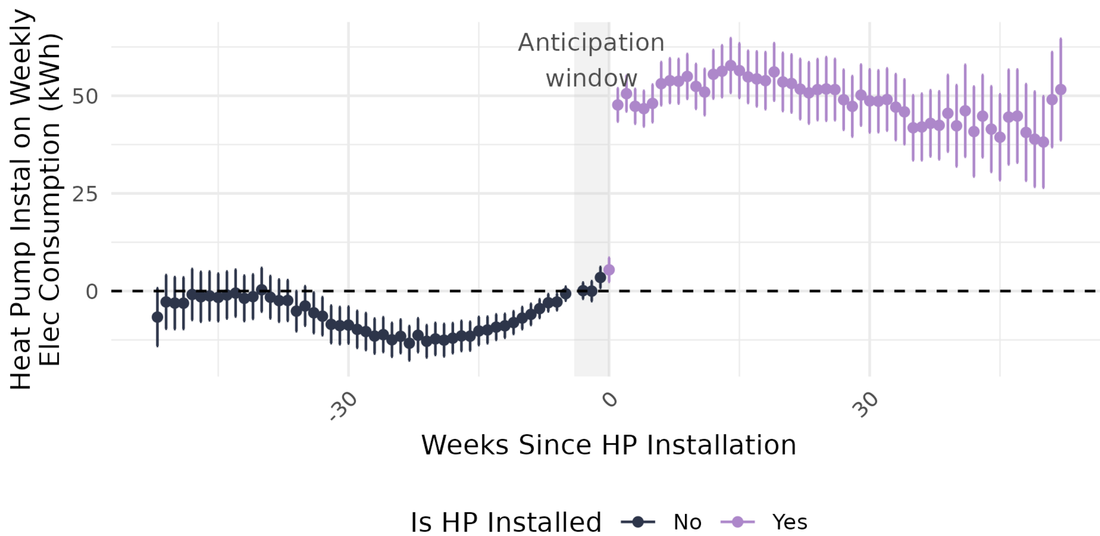
Dynamic ATT with Monthly Trends: In this section, we add household-by-calendar-month fixed effects to the main DiD estimation, acknowledging it may partially absorb treatment effects that operate through persistent, month-specific changes in energy consumption following heat pump installation. Consequently, this specification is conservative and may attenuate long-run level effects. Reassuringly, we find that estimated treatment effects remain similar in magnitude to the baseline results, indicating that our findings are not driven by household-specific seasonal usage patterns or seasonal selection into treatment.

Figure A.5: Dynamic ATT with Account-Month Trends



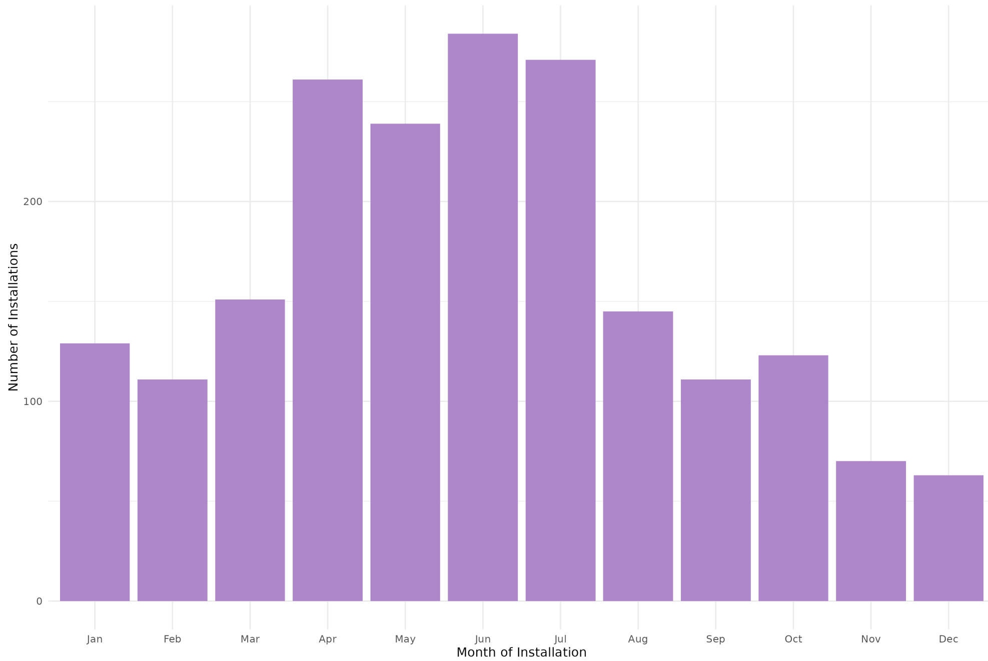
TWFE Event Study: We show an event study using our TWFE models of heat pump impacts on electricity consumption.

Figure A.6: Event Study — Heat Pump Installation on Weekly Electricity Consumption



Monthly Distribution of Heat Pump Installations: We show the monthly distribution of heat pump installations, as a visual demonstration of seasonality of adoption dynamics.

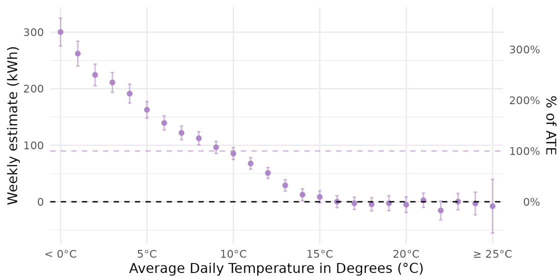
Figure A.7: Monthly Distribution of Heat Pump Installations



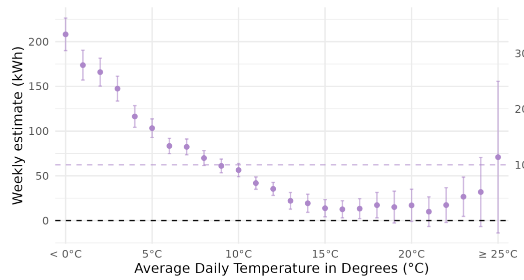
A.1.3 Heat Pump Impact by Outside Temperature

Heat Pump Consumption by Time of the Day and Outside Temperature: In this section, we explore how the relationship between temperature and electricity consumption varies across time of day. We use daily data grouped by the heat pump tariff periods — morning, afternoon, peak, and overnight — as a convenient framework for parsing intra-day variation, even though most heat pump adopters in our sample are not on the heat pump tariff. This analysis suggests that colder temperatures drive increased electricity demand, with broadly consistent patterns across all rate periods.

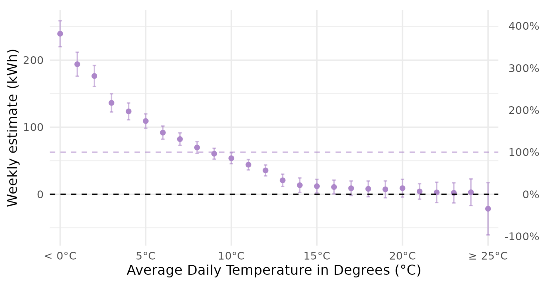
Figure A.8: Impact of Outdoor Temperature after Heat Pump Installation on Weekly Electricity Consumption



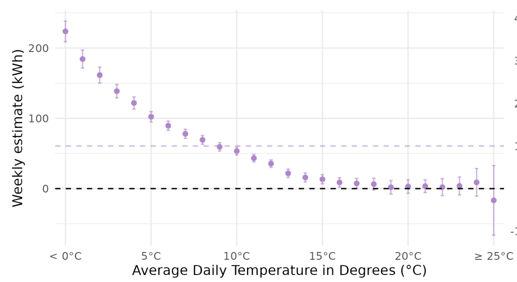
(**a**) Morning — 4am–7am



(**b**) Afternoon — 1pm–4pm



(**c**) Peak Time — 4pm–7pm



(**d**) Other Hours

A.2 Heterogeneity Analysis

This appendix presents additional analyses exploring how the impact of heat pump installation varies across household, property, and area characteristics. We first study heterogeneity by local income and property values, before investigating whether engineer-specific installation effects contribute meaningfully to variation in outcomes. Next, we study heterogeneity by the home's energy efficiency, measured using the UK's Energy Performance Certificate (EPC), a standardized rating that summarizes insulation quality, heating system performance, and expected heat loss (higher EPC ratings indicate more energy-efficient homes). We then consider building size and predicted heat loss, regional patterns, and households' previous heating systems (for example, gas versus electric heating). Finally, we examine interactions with other low-carbon technologies, specifically electric vehicles (EVs) and rooftop solar PV, and test whether they materially change the estimated effects of heat pump adoption.

A.2.1 Engineer-Specific Treatment Effects and Variance Decomposition

We estimate the contribution of engineer-specific treatment heterogeneity by interacting the heat pump installation indicator with installing-engineer indicators in a fixed-effects specification:

$$Y_{it} = \beta HPInstalled_{it} + \sum_{e} \gamma_e HPInstalled_{it} \times Engineer_e + \omega Temp_{it} + \alpha_i + \delta_t + \epsilon_{it} \tag{6}$$

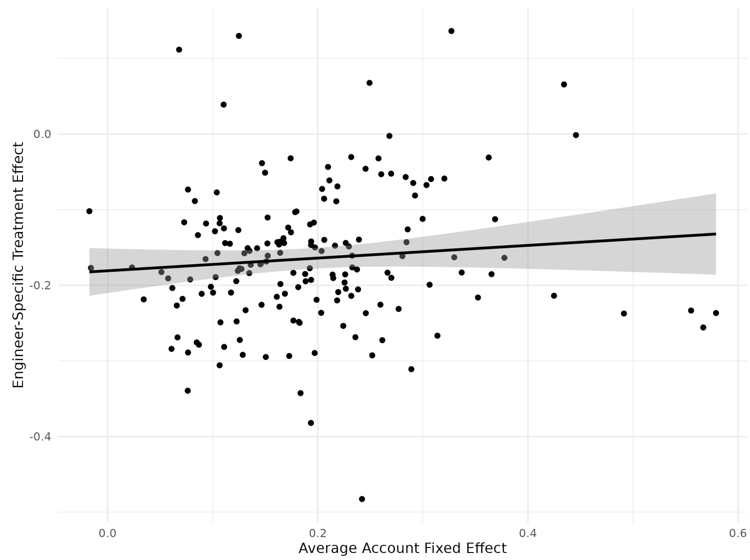
We restrict the sample to 1,145 households and 175 engineers with at least two installations. A variance decomposition partitions the total variance in electricity use into household fixed effects, date fixed effects, temperature effects, the average treatment effect, engineer-specific deviations, covariance terms, and residual variance.

Household fixed effects account for the vast majority of consumption variance, followed by time controls and the average heat pump effect. Engineer-specific heterogeneity explains only a small share. Figure A.9 shows no strong evidence of sorting between households and engineers.

Table A.4: Decomposition of Variance in Consumption Outcomes

	Component	Share
1	Account FE	0.368
2	Date FE	0.037
3	HDD FE	0.006
4	ATE	0.070
5	Engineer Interaction	0.011

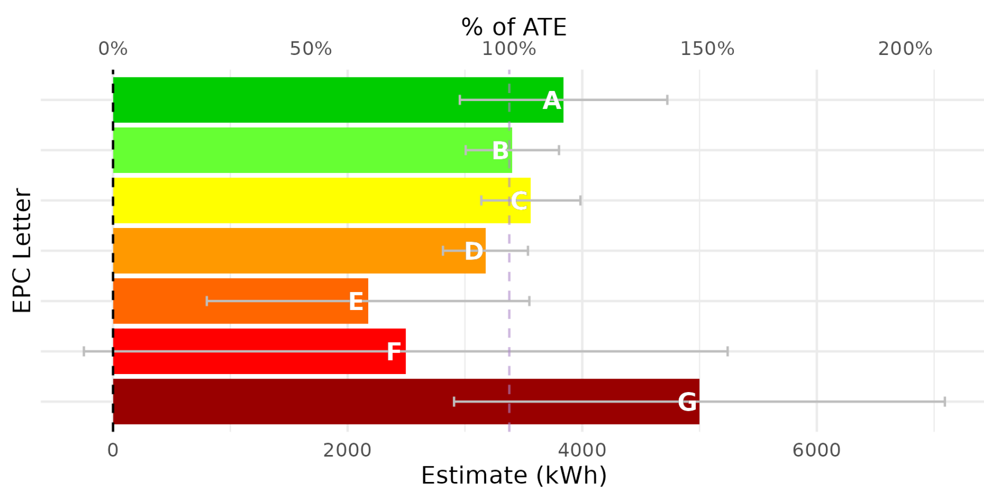
Figure A.9: Treatment × Engineer Effects versus Average Household Fixed Effects



A.2.2 Energy Efficiency of the Property

Figure A.10 shows no significant interaction between heat pump installation and the home's EPC rating. The EPC is a standardized UK measure of a property's energy efficiency, based on insulation quality, heating system performance, and overall heat loss; higher-rated homes are more energy efficient. This implies that the relative increase in electricity use following installation is broadly similar across energy efficiency levels.[6]

Figure A.10: Impact of Heat Pump Installation by EPC Rating

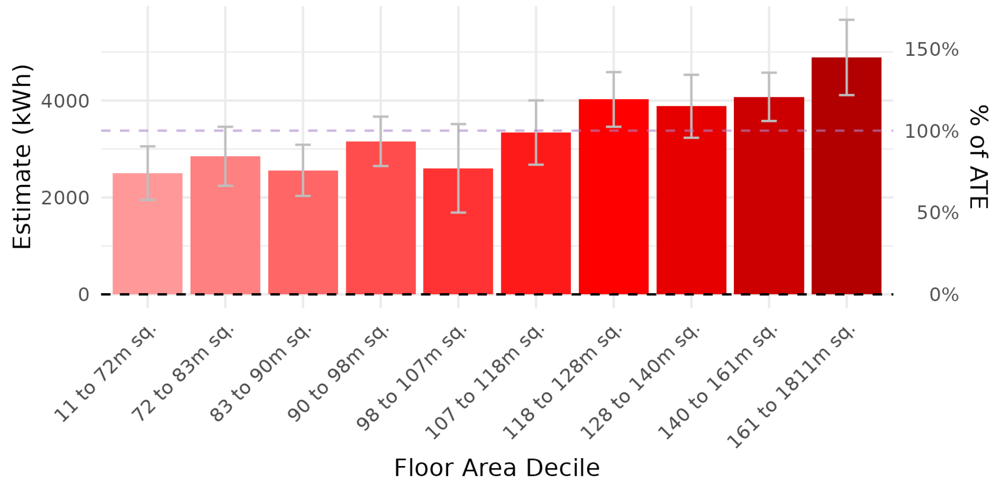


[6]This should not be confused with the direct relationship between EPC rating and consumption — less energy efficient homes consume more electricity overall.

A.2.3 Floor Area and Heat Loss

Larger homes exhibit greater increases in electricity consumption after heat pump installation (Figure A.11), likely because floor area proxies for heat loss: bigger homes typically require more energy to maintain indoor temperatures.

Figure A.11: Impact of Heat Pump Installation by Floor Area



A similar pattern appears when using predicted heat loss based on EPC-derived algorithms (Figure A.12). Some of the regional variation in Figure A.13 may also reflect differences in average floor area among adopters across regions.

Figure A.12: Impact of Heat Pump Installation by Heat Loss Decile

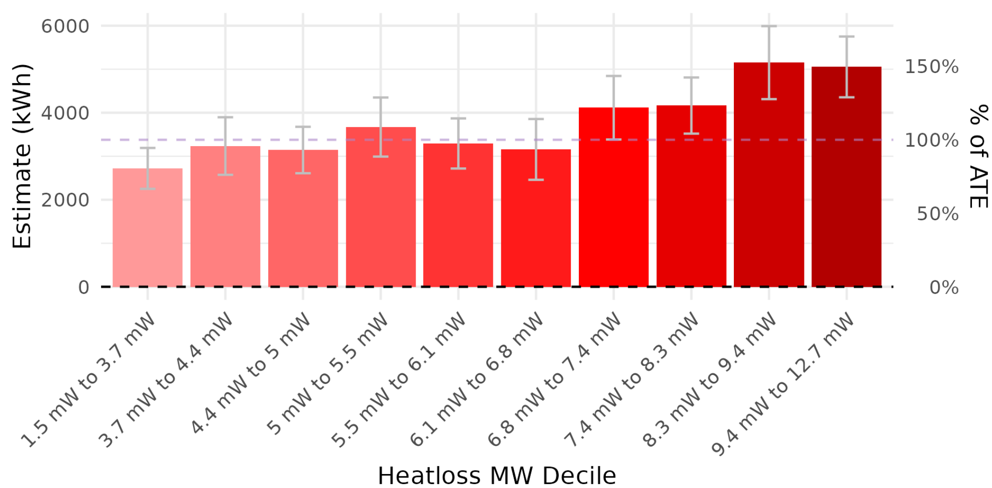
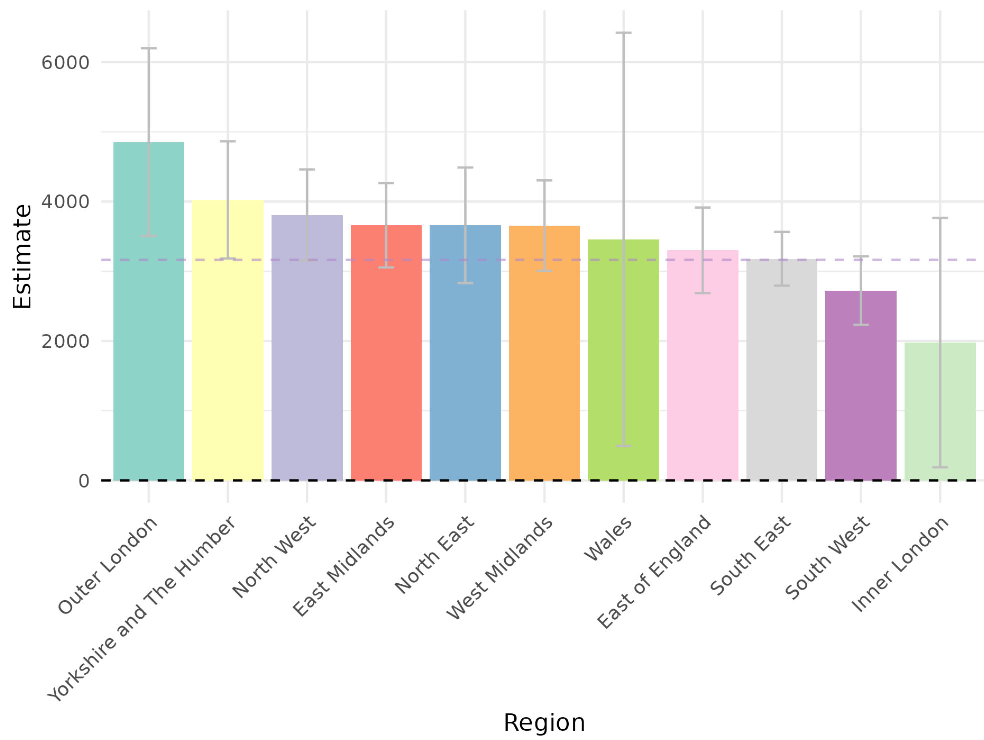


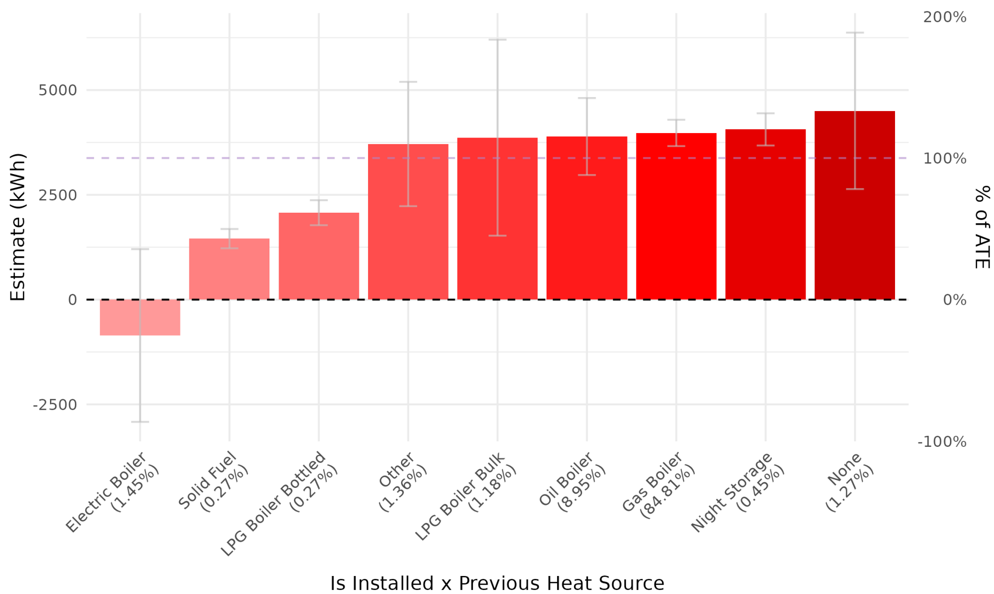
Figure A.13: Impact of Heat Pump Installation on Half-Hourly Electricity Consumption by Region



A.2.4 Previous Heat Source

Administrative data from the heat pump purchase process provide information on households' previous heating systems. As shown in Figure A.14, households previously using electric or mixed heating show smaller electricity increases (sometimes negative) after heat pump installation. Former gas users — who represent the majority of the sample — show large positive shifts.

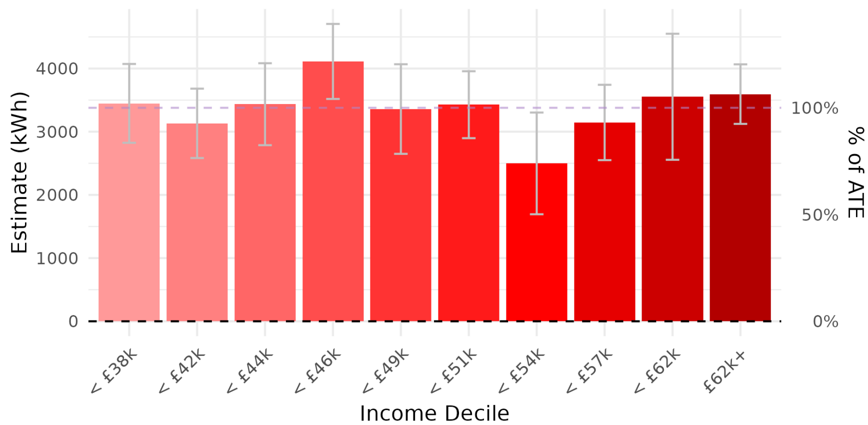
Figure A.14: Impact of Heat Pump Installation by Previous Heat Source



A.2.5 Area Income and Property Value

We examine whether the heat pump's impact varies with area income by splitting MSOA income into deciles (Figure A.15). We find little evidence of a systematic relationship between income and treatment effects.

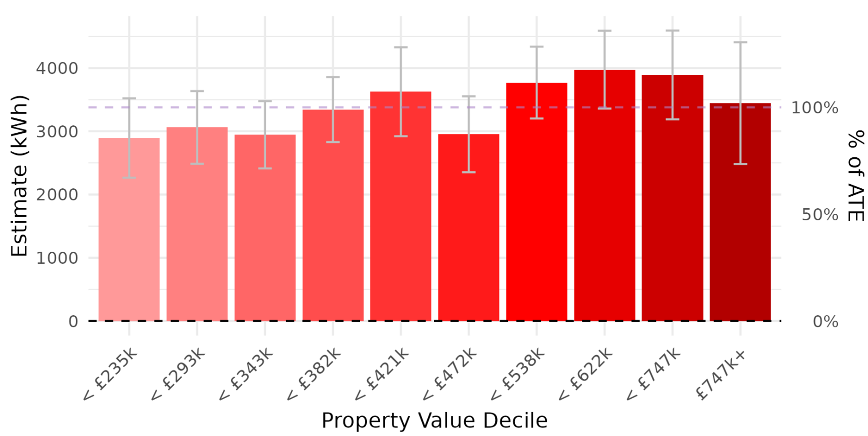
Figure A.15: Impact of Heat Pump Installation by MSOA Income



Note: We show the interaction between MSOA income and heat pumps' impact on daily electricity consumption in kWh (left axis) in a TWFE model. The dashed gray line shows the TWFE average treatment effect; the right axis shows the ratio of the MSOA-income-decile-specific effect to the average treatment effect.

A similarly noisy pattern appears when examining property value deciles (Figure A.16), though higher-value homes may experience somewhat larger increases.

Figure A.16: Impact of Heat Pump Installation by Property Value Decile



A.3 Mechanisms and Threats

In this section, we explore other threats to identification, such as the co-varying adoption of other technologies in the home.

EV Ownership: In this section, we examine whether EV ownership interacts with the impact of heat pump installation, and whether installing a heat pump changes EV charging behavior.

To do this, we create a binary variable for EV ownership.[7]

We interact EV ownership with heat pump installation in a TWFE difference-in-differences specification. As shown in Table A.5, EV ownership does not significantly alter the electricity consumption response to heat pump installation. EV-owning households have higher baseline electricity consumption, but the estimated heat pump effect is statistically similar between EV owners and non-owners.

We then examine charging behavior before and after heat pump adoption (Table A.6). For each charging event, we define the main period as the time during which most of the charging occurs, and compute the probability that charging takes place in each time-of-use period of the *Cosy* tariff described in Section 2.2. Our motivation is to test whether heat pump installation leads EV owners to shift charging behavior in ways that might interact with time-of-day electricity consumption patterns.

Using a linear probability model with household and day fixed effects, we find no evidence of systematic shifts in charging time. Prior to heat pump installation, around 95% of charging events occur during the "Other" period. Following installation, charging behavior remains unchanged. This contrasts with the clear charging shifts observed when households adopt the time-of-use tariff analyzed in Section 2.2.

Solar PV: Before installing a heat pump, households completed an administrative survey confirming their home's suitability and reporting the presence of other low-carbon technologies. From this survey we observe that 609 out of the 1,212 households in our sample that installed a heat pump also had rooftop solar PV.[8]

We interact the presence of solar PV with heat pump installation in a TWFE difference-in-differences estimation (Table A.7). Households with solar PV exhibit lower electricity consumption during daytime periods (afternoon and peak rate) prior to heat pump installation, consistent with self-generation offsetting grid demand.

Following heat pump installation, these households continue to consume less electricity during afternoon and peak periods, with slightly smaller increases in consumption in those periods relative to non-PV households. However, the overall electricity consumption effect of heat pump installation remains similar across groups. This suggests that solar PV primarily affects the timing of grid consumption rather than the total electricity demand associated with heat pump operation.

Insulation Improvements and Other Changes to the Home: A potential threat to identification is that insulation upgrades may coincide with heat pump installation. While we cannot empirically separate

[7] EV owners are defined as having at least one charging event per week for two consecutive weeks. EV charging is defined as consumption above 3.5 kWh per half-hour for 4 to 12 consecutive half-hours. The 3.5 kWh threshold reflects the assumption that most charging is done using chargers drawing 7 kW or more. Once an EV is detected, the household is defined as an EV owner for the remainder of the analysis period.

[8] The survey is missing for the earliest installations, which is why the sample size here is 1,212 rather than 1,308.

Table A.5: HP Installation on Electricity Consumption Controlling for EV Ownership

Dependent Variable:	Electricity Consumption in kWh	
Model:	(1)	(2)
Variables		
Is HP Installed = 1	3,378.1***	3,031.3***
	(133.2)	(115.1)
EV User		2,327.7***
		(193.7)
EV User × Is HP Installed = 1		749.5***
		(221.0)
Pre-Treatment Average		
Pre-Treatment Consumption	5,085.66	5,085.66
Fixed-effects		
HDD	Yes	Yes
Household	Yes	Yes
Day	Yes	Yes
Fit statistics		
Observations	752,943	752,943
Number of Households	1,308	1,308
Number of Time Periods	902	902
R^2	0.50013	0.50909

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Table A.6: HP Installation on Probability of Charging EV by Period

Dependent Variable:	Charging EV			
	Morning Off-peak	Afternoon Off-Peak	Peak Rate	Other
Model:	(1)	(2)	(3)	(4)
Variables				
Is HP Installed = 1	-0.0010	0.0048**	0.0014	-0.0052
	(0.0068)	(0.0024)	(0.0030)	(0.0083)
Baseline charging				
Baseline charging	0.02	0.01	0.02	0.95
Fixed-effects				
Household	Yes	Yes	Yes	Yes
Day	Yes	Yes	Yes	Yes
Fit statistics				
Observations	73,393	73,393	73,393	73,393
Number of Households	516	516	516	516
R^2	0.25780	0.16709	0.12171	0.26554

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

these effects, the **immediate** shifts in gas and electricity consumption shown in Figure 2 indicate that changes stem from the installation itself rather than contemporaneous insulation work. Access to the heat pump subsidy, which most of our sample used, required a valid Energy Performance Certificate (EPC) — the UK's standardized rating of a home's insulation quality and overall energy efficiency — with no outstanding insulation recommendations until 08 May 2024. This requirement makes major insulation upgrades at the time of installation unlikely.

Significant life events, such as having a baby, are also unlikely to align precisely with installation dates. If anything, random household changes among controls would attenuate treatment effects, implying our

Table A.7: HP Installation and Solar PV on Electricity Consumption

Dependent Variable:	Electricity Consumption in kWh				
Rate period	Morning Cosy	Afternoon Cosy	Peak Rate	Other	Overall
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Is HP Installed = 1	654.6***	379.0***	431.6***	1,944.6***	3,409.0***
	(42.84)	(31.74)	(41.12)	(123.3)	(183.6)
Has Solar PV × Is HP Installed = 1	-29.78	-33.78	-63.82	170.8	42.73
	(46.98)	(35.36)	(42.29)	(154.8)	(209.0)
Pre-Treatment Average					
Pre-Treatment Consumption - No Solar PV	457.20	509.49	693.70	3,310.74	4,968.68
Pre-Treatment Consumption - Has Solar PV	416.59	616.54	548.35	3,744.14	5,323.71
Fixed-effects					
HDD	Yes	Yes	Yes	Yes	Yes
Household	Yes	Yes	Yes	Yes	Yes
Day	Yes	Yes	Yes	Yes	Yes
Fit statistics					
Observations	697,040	697,240	697,209	697,997	697,998
Number of Households	1,212	1,212	1,212	1,212	1,212
Number of Time Periods	916	916	916	916	916
R^2	0.31733	0.26336	0.31308	0.48048	0.48647

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

estimates may be conservative.

A.4 Heat Pump Tariff Appendix

A.4.1 Wholesale Prices by Heat Pump Tariff Time-of-Use Period

Table A.8: Wholesale Price Averages for Heat Pump Tariff Periods in 2022, 2023, and 2024

Period	2022 (£/MWh)	2023 (£/MWh)	Jan-Jun 2024 (£/MWh)
Morning Off-Peak (4am–7am)	175	86	55
Afternoon Off-Peak (1pm–4pm)	193	91	57
Peak (4pm–7pm)	242	179	77
Other 15 Hours of the Day	198	97	64

Note: We show average wholesale prices during the four key periods where adopting households faced different prices per kWh across 2022, 2023, and 01 January through 15 June 2024, based on data from LCP Delta (2024).

A.4.2 Rates by GSP Group and Across Time

Figure A.17: Rates by Period and GSP Group as of 01 June 2024

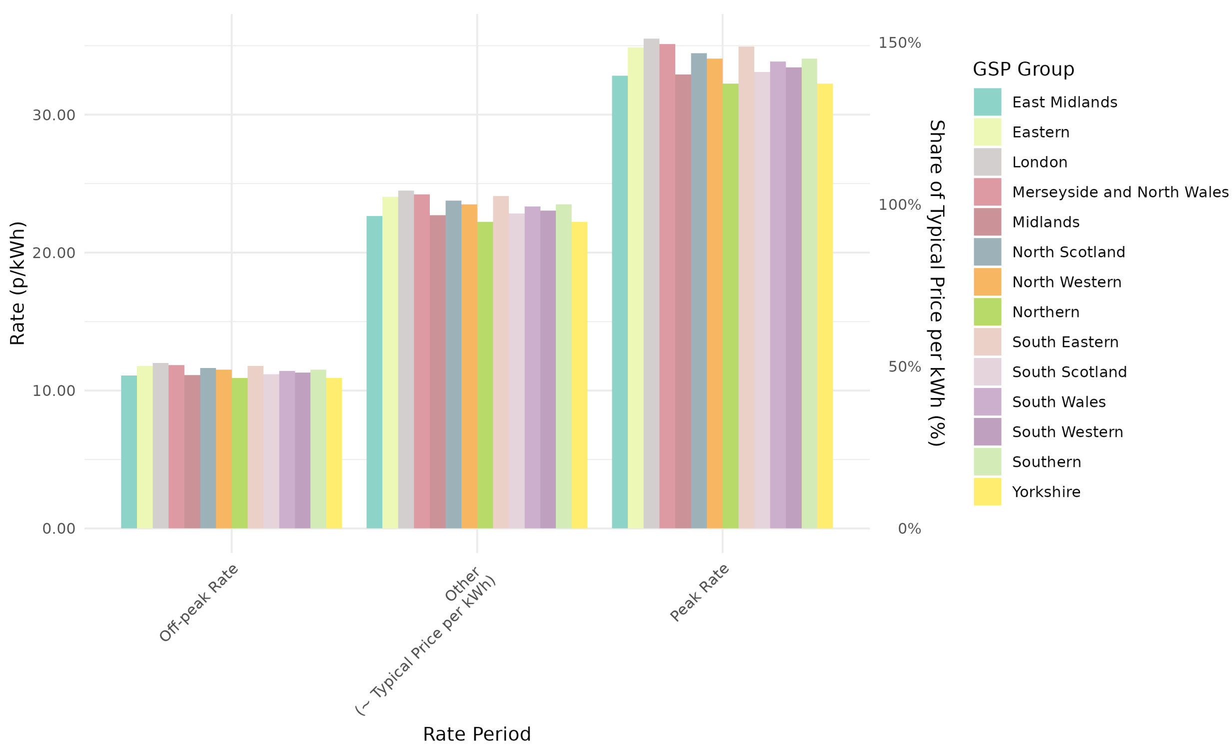
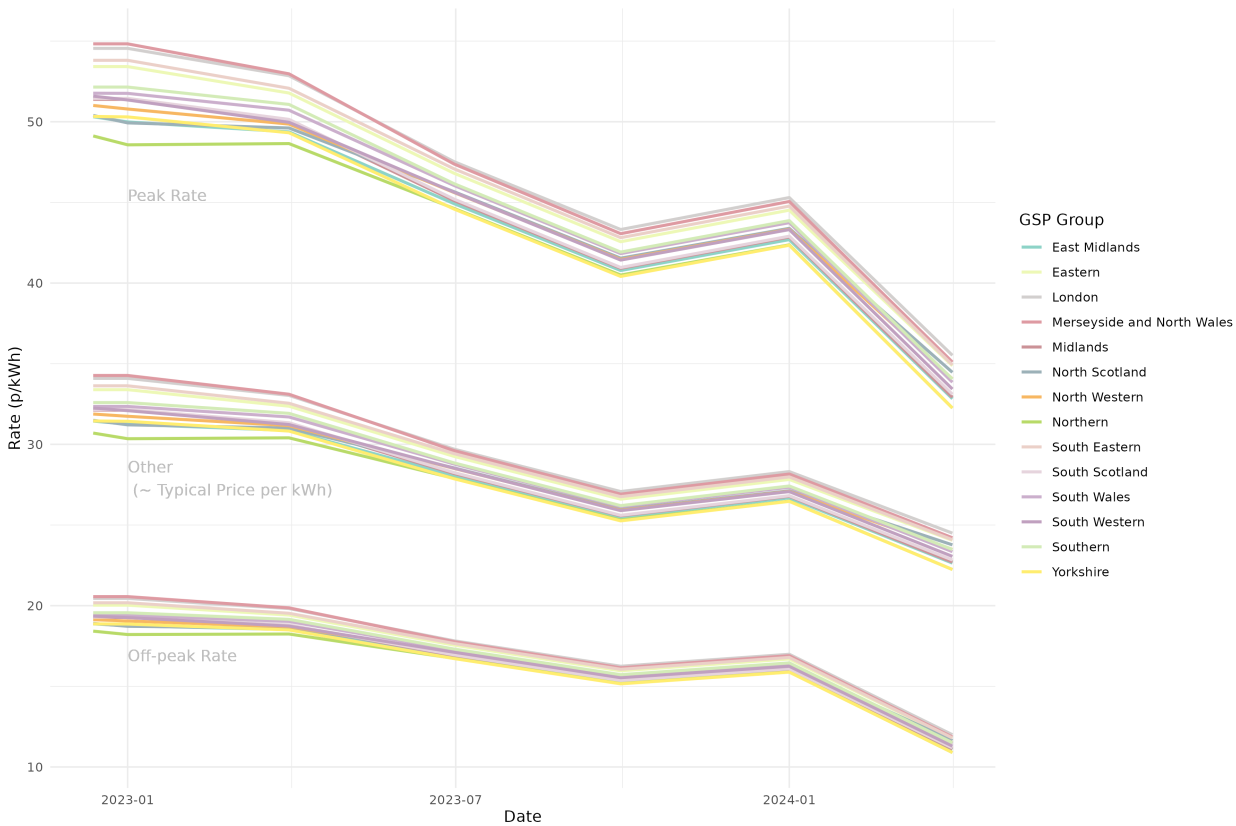
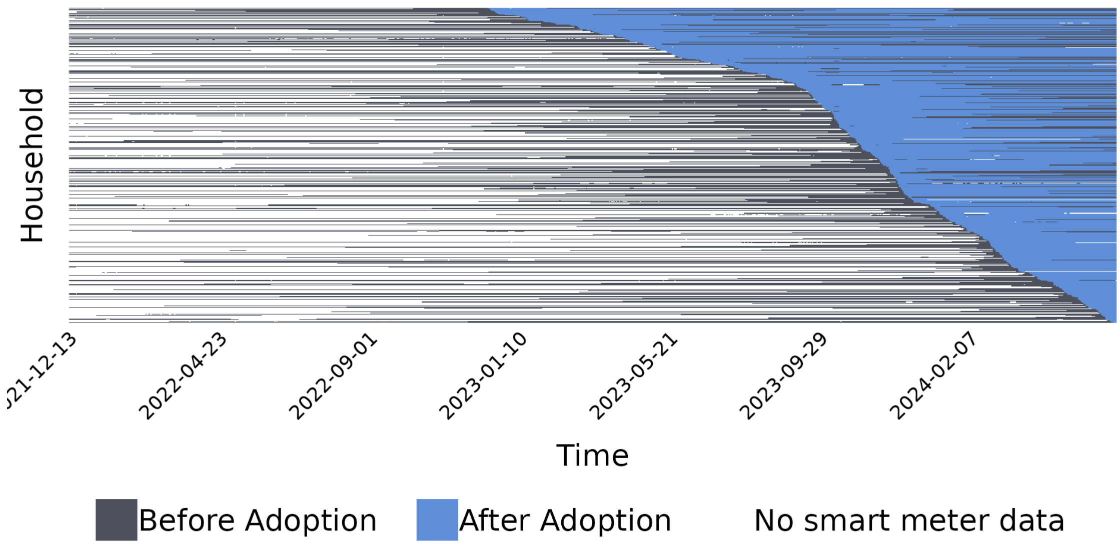


Figure A.18: Rates over Time



A.4.3 Smart Meter Data Availability for the Tariff Analysis

Figure A.19: Smart Meter Data Availability for Tariff Adopters



Note: This figure displays the availability of smart meter electricity consumption data for a random sample of 500 tariff adopters over time. Each row represents a household and each column a date. Blue segments indicate periods after tariff adoption, black segments indicate periods before adoption, and white areas denote dates with no available smart meter data. Households are grouped by adoption timing so that those with identical pre- and post-adoption histories are displayed together, improving readability. The figure is constructed using half-hourly consumption data aggregated to the overall rate period.

A.4.4 Main Results Comparing Tariff TWFE and CS Results

Table A.9: Heat Pump Tariff Adoption on Half Hourly Electricity Consumption

Dependent Variable:	Half Hourly Consumption in kWh									
	TWFE					CS				
	Morning Off-peak	Afternoon Off-peak	Peak Rate	Other	Overall	Morning Off-peak	Afternoon Off-peak	Peak Rate	Other	Overall
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Variables										
Contract Active = 1	0.5832***	0.3388***	-0.1600***	-0.1306***	0.0154***	0.5071***	0.2926***	-0.2242***	-0.1066***	0.0105
	(0.0121)	(0.0076)	(0.0045)	(0.0041)	(0.0029)	(0.0138)	(0.0095)	(0.0098)	(0.0074)	(0.0071)
Pre-Treatment Average										
Half Hourly Consumption	0.3952	0.3298	0.4261	0.3979	0.3922	0.4378	0.3822	0.3174	0.3625	0.3776
Fixed-effects										
HDD	Yes	Yes	Yes	Yes	Yes					
Household	Yes	Yes	Yes	Yes	Yes					
Day	Yes	Yes	Yes	Yes	Yes					
Fit statistics										
Observations	3,147,834	3,148,386	3,148,357	3,152,987	3,152,989					
Number of Households	6,629	6,629	6,629	6,629	6,629	6,631	6,631	6,631	6,631	6,631
Number of cohorts (CS)						78	78	78	78	78
Number of cohorts (CS)						78	78	78	78	78
Number of Time Periods	916	916	916	916	916	129	129	129	129	129
R^2	0.57303	0.48659	0.48922	0.61662	0.66845					

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

A.4.5 Survey Responses

We conducted a tariff survey to understand more about the mechanisms of energy demand shift inside the home, as well as heat pump and other low-carbon technology interactions. We sent our survey to 1,000 heat pump tariff households on 08 July 2024, in which 39% of recipients responded.[9] According to these households, three brands — Mitsubishi, Daikin, and Vaillant — constitute the majority of heat pumps. Of the 70% of respondents who know their heat pump's size, the majority have heat pumps between 7-16 kW. The implied median size is 9-12 kW.

We also ask about whether and how households respond to the heat pump tariff's different price per kWh. 85% of respondents say they change their energy use in response to the time-of-use pricing schedule.[10] Among this 85% of respondents, 64% of these respondents use some form of automation — which we define as responding yes to at least one of using a smart thermostat, a special mode on the heat pump, or lower flow temperatures. 59% do so using a smart thermostat. Respondents could "tick" multiple options to this question; other popular methods included manual adjustments (34%), using alternative heating sources (11%), using lower flow temperatures (12%), and activating a special mode on the heat pump (7%). Among this same 85% of respondents, other key changes to the home's electricity consumption included modulating how and when the home battery charges and discharges (38%) and doing likewise with an EV charger (17%). Many free-text responses noted manual and semi-automated strategies involving other appliances, such as avoiding using the dishwasher and other energy intensive appliances during the peak rate period and using special water heaters during specific periods. In summary, households seem to employ a mix of methods to respond to the time-of-use pricing schedule, but automated methods dominate, in particular using a smart thermostat to set thermostat temperatures in line with the pricing schedule.

Finally, we ask about home characteristics and occupancy details. Among respondents, 60% have solar PV panels, 38% have batteries, and 18% have electric vehicle(s). Only 32% have no low-carbon technology other than their heat pump. We also ask when the household's heat pump was installed. We find that 18% have heat pumps installed before 2020; there is a relatively uniform spread of installations between 2010 and 2019, with very few before 2010. We see very fast growth in installations in 2020 and beyond: 4% of the 382 households had installations in 2020, 10% in 2021, 21% in 2022, 27% in 2023, and 17% in (the first half of) 2024.

Table A.10: Balance Table for Heat Pump Tariff Survey Responders and Non-Responders

Variable	Survey (N = 293)	No Survey (N = 417)
Energy Efficiency	65.38	64.12
	(18.17)	(18.61)
EAC	7,593.86	7,858.04
	(5,504.88)	(5,961.49)
Floor Area	146.84	143.09
	(76.35)	(81.51)
Property Value	543,038.73	523,676.32
	(391,945.68)	(386,740.94)

[9] We see in Table A.10 that respondents and non-respondents are similar on key observable characteristics — property energy efficiency rating, floor area, and property value.

[10] Among households who did not respond affirmatively to this question, some added free-text responses that indicate they charge and discharge a home battery rather than changing other energy consumption behaviors. We see suggestive evidence in Table A.11 that battery charge and discharge is indeed an important part of the impact for households with home batteries.

A.4.6 Heterogeneity by Low-Carbon Technology Ownership among Survey Respondents

When a household adopts a smart tariff, the utility sends them an on-boarding survey that includes questions about which low-carbon technologies they own. A total of 2,439 tariff adopters in the sample responded to this survey, indicating which other low-carbon technologies they have in their homes. Note that this is different from the tariff survey we sent to 1,000 adopting households asking about their experience and behavior in responding to the tariff (Section A.4.5) and the administrative survey done prior to heat pump installation. We use these responses to interact technology (battery, solar, and EV) ownership and tariff adoption in Table A.11. A limitation of this analysis is that we do not know how respondents compare to non-respondents, and some respondents may have acquired more low-carbon technologies since completing the survey. In addition, the interpretation of the coefficients is nuanced — it is the impact of *owning* the low-carbon technology, not directly using it. In this way, the coefficients contain both the impact of the low-carbon technology itself, and the fact that people with more low-carbon technologies might be more affluent, having larger properties and thus higher electricity consumption.

We use the on boarding survey responses to examine how tariff adoption interacts with ownership of other low-carbon technologies. For respondents without any other low-carbon technologies, the impact of the heat pump tariff on energy use in the morning and afternoon is significantly smaller.

A key finding is that battery owners tend to increase consumption during cheaper periods and reduce it during normal and peak periods, suggesting they charge their batteries when prices are lower. Solar PV owners show less variation, likely using their solar electricity in the afternoon.

Table A.11: Impact by low-carbon technologies

Dependent Variable:	Half Hourly Consumption in kWh				
Rate period	Morning Off-peak	Afternoon Off-peak	Peak Rate	Other	Overall
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Contract Active = 1	0.2164***	0.1958***	-0.0891***	-0.0529***	0.0090
	(0.0208)	(0.0162)	(0.0112)	(0.0082)	(0.0064)
Homebattery × Contract Active = 1	0.7313***	0.3700***	-0.0988***	-0.1661***	0.0208*
	(0.0414)	(0.0276)	(0.0179)	(0.0141)	(0.0109)
HasSolarPV × Contract Active = 1	-0.0025	-0.0616**	-0.0174	0.0078	-0.0054
	(0.0347)	(0.0245)	(0.0190)	(0.0130)	(0.0104)
HasEV × Contract Active = 1	0.4163***	0.2028***	-0.0881***	-0.1164***	-0.0061
	(0.0542)	(0.0357)	(0.0201)	(0.0195)	(0.0132)
Pre-Treatment Average					
Half Hourly Consumption	0.3852	0.3162	0.3961	0.3873	0.3790
Fixed-effects					
Household	Yes	Yes	Yes	Yes	Yes
Day	Yes	Yes	Yes	Yes	Yes
HDD	Yes	Yes	Yes	Yes	Yes
Fit statistics					
Observations	1,221,827	1,222,010	1,222,011	1,223,652	1,223,652
Number of Households	2,439	2,439	2,439	2,439	2,439
Number of Time Periods	16	16	16	16	16
R^2	0.59222	0.49055	0.48056	0.61079	0.65592

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Finally, as discussed in Table A.12, EV owners seem to shift their charging from normal and peak periods to morning and afternoon off-peak periods.

Table A.12: Adoption on Probability of Charging EV by Period

Dependent Variable:	Charging EV			
	Morning Off-peak	Afternoon Off-peak	Peak Rate	Other
Model:	(1)	(2)	(3)	(4)
Variables				
Contract Active = 1	0.5562***	0.1040***	-0.0416***	-0.6185***
	(0.0146)	(0.0074)	(0.0049)	(0.0166)
Baseline				
Baseline charging	0.0534	0.0299	0.0472	0.8695
Fixed-effects				
Household	Yes	Yes	Yes	Yes
Day	Yes	Yes	Yes	Yes
Fit statistics				
Observations	127,789	127,789	127,789	127,789
Number of Households	1,743	1,743	1,743	1,743
R^2	0.53117	0.25667	0.19607	0.64428

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

A.4.7 Households That Switch Away from Heat Pump Tariff

In this section, we examine whether electricity consumption effects differ between households that remain on the tariff and those that subsequently leave. We find that the magnitude is somewhat larger for leavers, likely reflecting a greater ability to take advantage of off-peak periods. We also show that leavers are about twice as likely to own an EV, suggesting that their decision to switch may be driven by the search for a tariff better suited to EV charging.

Table A.13: Impact for Leavers

Dependent Variable:	Half Hourly Consumption in kWh				
Rate period	Morning Off-peak	Afternoon Off-peak	Peak Rate	Other	Overall
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Contract Active = 1	0.5832***	0.3387***	-0.1600***	-0.1306***	0.0154***
	(0.0121)	(0.0076)	(0.0045)	(0.0041)	(0.0029)
Pre-Treatment Average					
Half Hourly Consumption	0.3952	0.3298	0.4261	0.3979	0.3922
Fixed-effects					
HDD	Yes	Yes	Yes	Yes	Yes
Household	Yes	Yes	Yes	Yes	Yes
Day	Yes	Yes	Yes	Yes	Yes
Fit statistics					
Observations	3,148,056	3,148,619	3,148,592	3,153,227	3,153,229
Number of Households	6,656	6,656	6,656	6,656	6,656
Number of Time Periods	916	916	916	916	916
R^2	0.57303	0.48661	0.48922	0.61662	0.66845

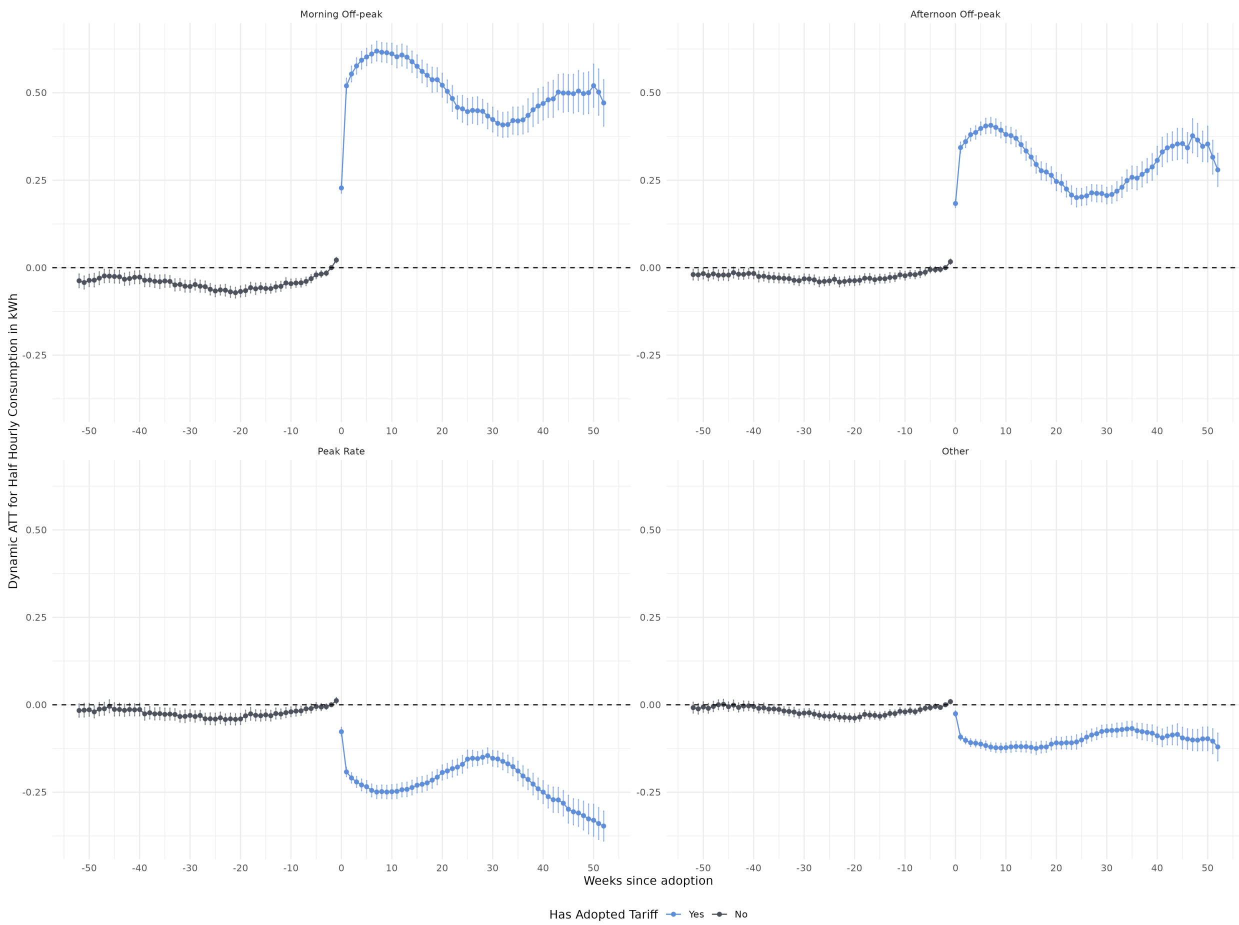
Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

A.4.8 Dynamic and Calendar ATTs

We next examine how the heat pump–specific tariff affects electricity consumption over time using both dynamic and calendar-time average treatment effects from the CS framework.

The dynamic ATTs trace the evolution of consumption before and after tariff adoption, allowing us to assess pre-trends and the persistence of load shifting.

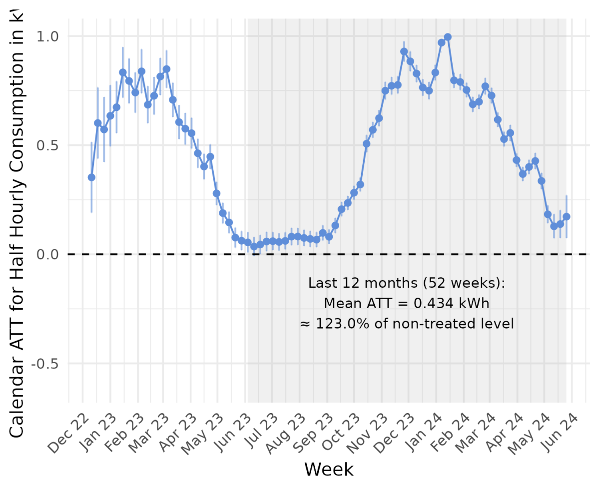
Figure A.20: Heat Pump Tariff Dynamic ATTs



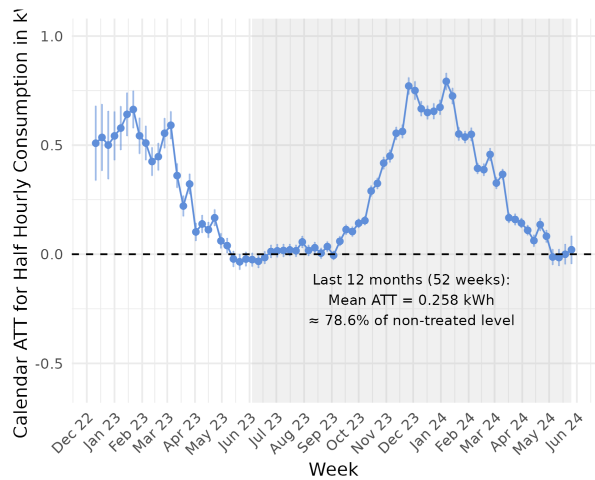
Note: We show dynamic ATTs from our CS models of the tariff impact on households' electricity consumption by rate period. Colors: black indicates before adoption, while blue indicates after adoption. Top left: morning off-peak. Top right: afternoon off-peak. Bottom left: evening peak. Bottom right: all other periods of the day.

The calendar ATTs aggregate effects over the sample window, providing a complementary view of how consumption changes over time. We further disaggregated this analysis by rate period: morning and afternoon off-peak periods, the evening peak, and the remaining hours of the day.

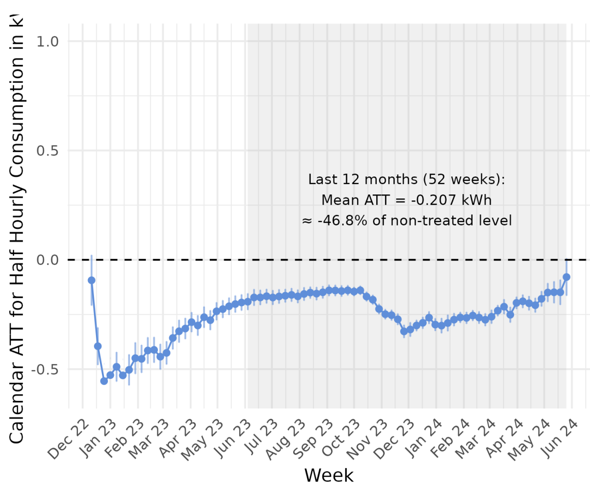
Figure A.21: Calendar-Time Treatment Effects of the Heat Pump Tariff by Rate Period



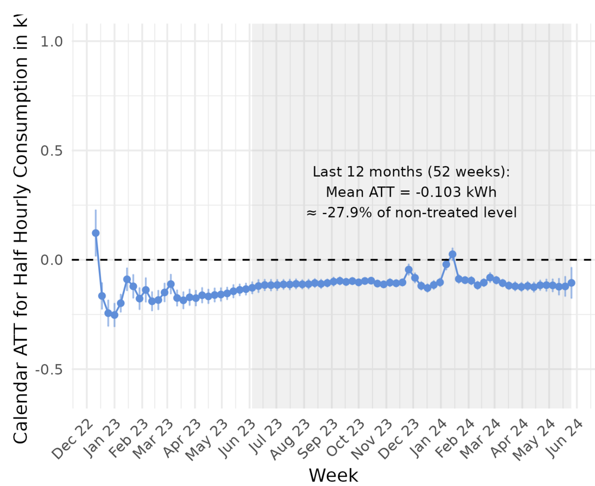
(**a**) Morning Off-Peak (4am–7am)



(**b**) Afternoon Off-Peak (1pm–4pm)



(**c**) Peak Period (4pm–7pm)



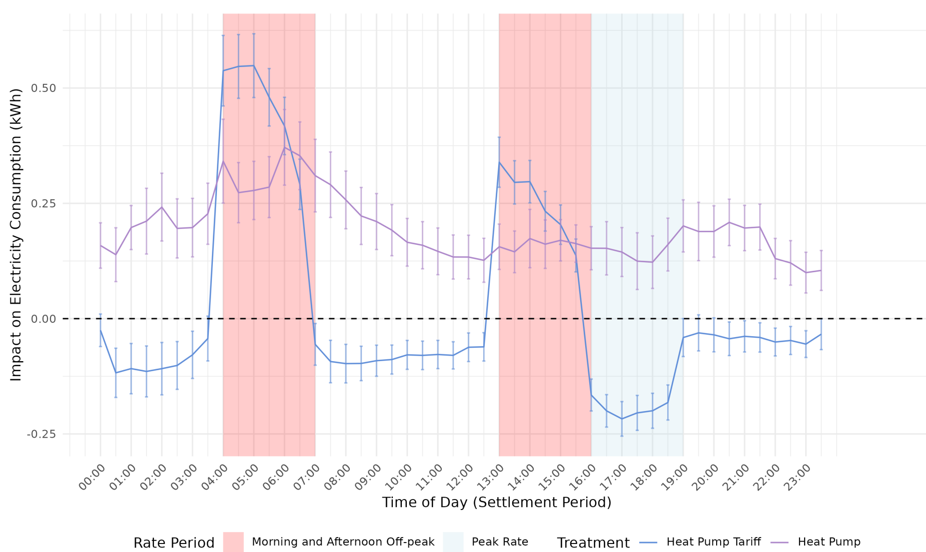
(**d**) Other Periods

Note: Each panel shows calendar-time average treatment effects on the treated (ATT) from Callaway–Sant'Anna difference-in-differences models, estimated separately by rate period. Points represent weekly calendar ATTs with 95% confidence intervals. Shaded regions highlight the final 12 months of available data (June 2023–June 2024); annotations report the mean calendar ATT over this period and its magnitude relative to the mean consumption level of not-yet-treated households.

A.4.9 Half-Hourly Impact

Figure A.22 plots estimated treatment effects of the heat pump installation and heat pump–specific time-of-use tariff on half-hourly electricity consumption over the day. We estimate a TWFE difference-in-differences specification in which an indicator for being either a heat pump adopter (heat pump adopter sample) or heat pump tariff adopter (tariff sample) is interacted with settlement-period indicators (half-hours of the day), using electricity consumption in kWh per half hour as the outcome. For the heat pump analysis, we exclude adopters on a time-of-use tariff before installation. We include fixed effects for calendar day, household, and outdoor temperature, specified as indicator variables for each integer degree between 0°C and 25°C, with temperatures below 0°C and above 25°C grouped into the boundary categories. We also control for EV charging. The plotted coefficients therefore represent the average change in electricity use in each half-hour attributable to the tariff, relative to the pre-adoption baseline. Error bars denote 95% confidence intervals based on robust standard errors clustered at the household level. Shaded regions indicate tariff rate periods (off-peak and peak), facilitating comparison between price incentives and observed load shifting.

Figure A.22: Reallocation of Heat Pump Electricity Demand after Time-of-Use Tariff Adoption



A.4.10 Heterogeneity Analysis

Estimated Annual Consumption Plots:

Figure A.23: Impact of the Heat Pump Tariff Adoption by EAC on Consumption

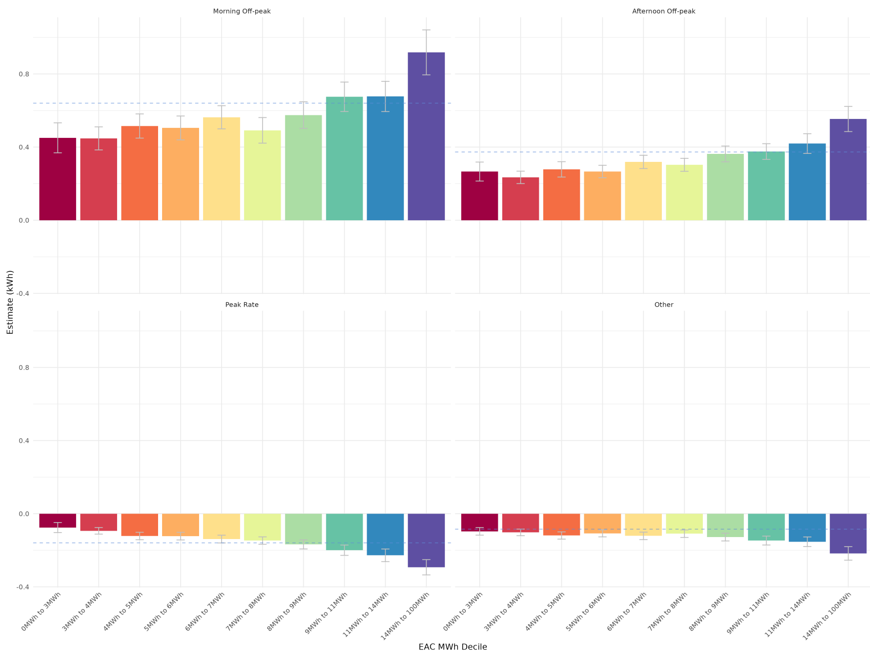
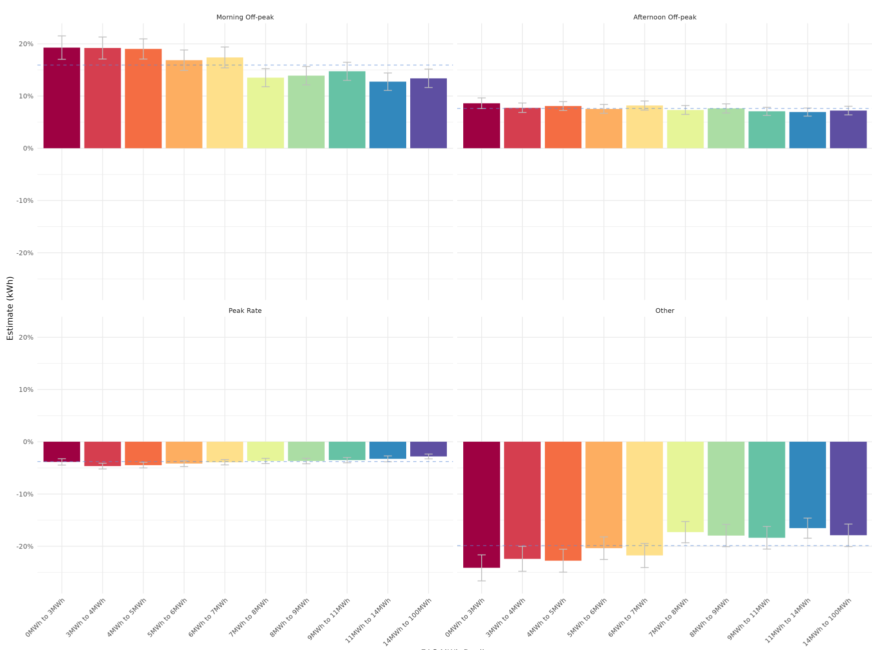
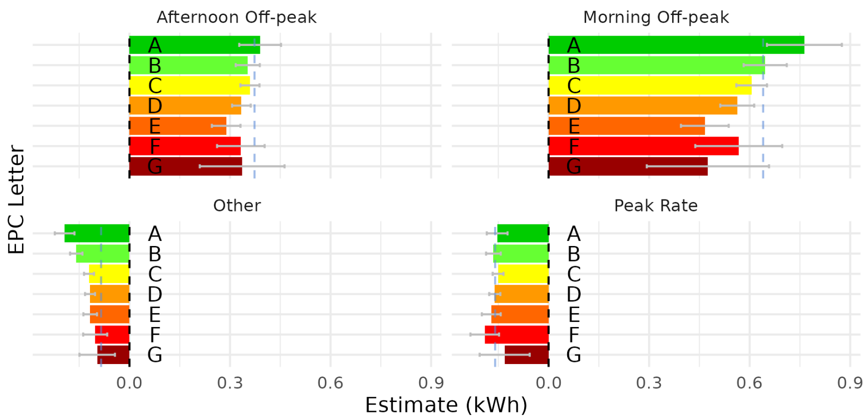


Figure A.24: Impact of the Heat Pump Tariff Adoption by EAC on Share of Consumption



Energy Efficiency Plots:

Figure A.25: Impact of the Heat Pump Tariff Adoption by EPC Score on Consumption



Floor Area Plots:

Figure A.26: Impact of the Heat Pump Tariff Adoption by Floor Area on Consumption

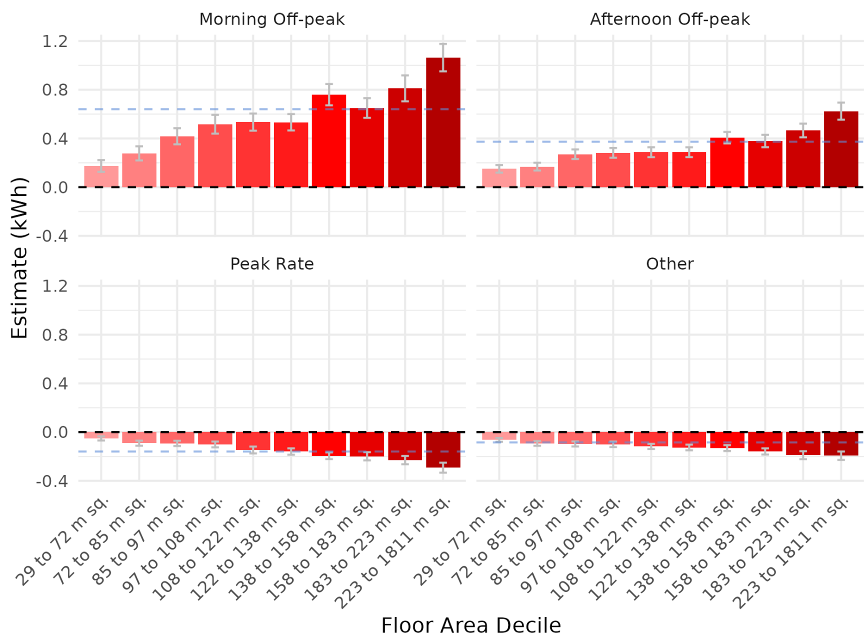
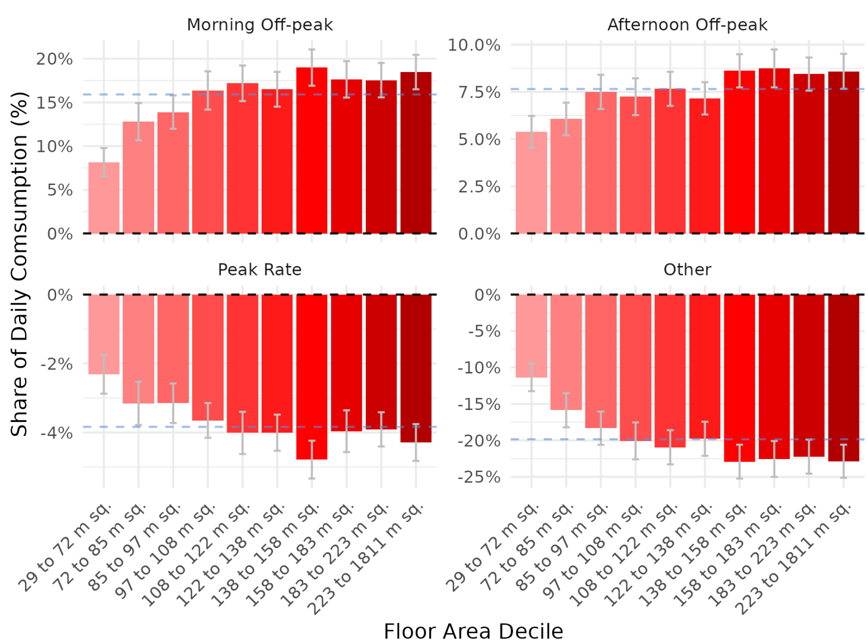


Figure A.27: Impact of the Heat Pump Tariff Adoption by Floor Area on Share of Consumption



Heat Loss Plots:

Figure A.28: Impact of the Heat Pump Tariff Adoption by Heat Loss on Consumption

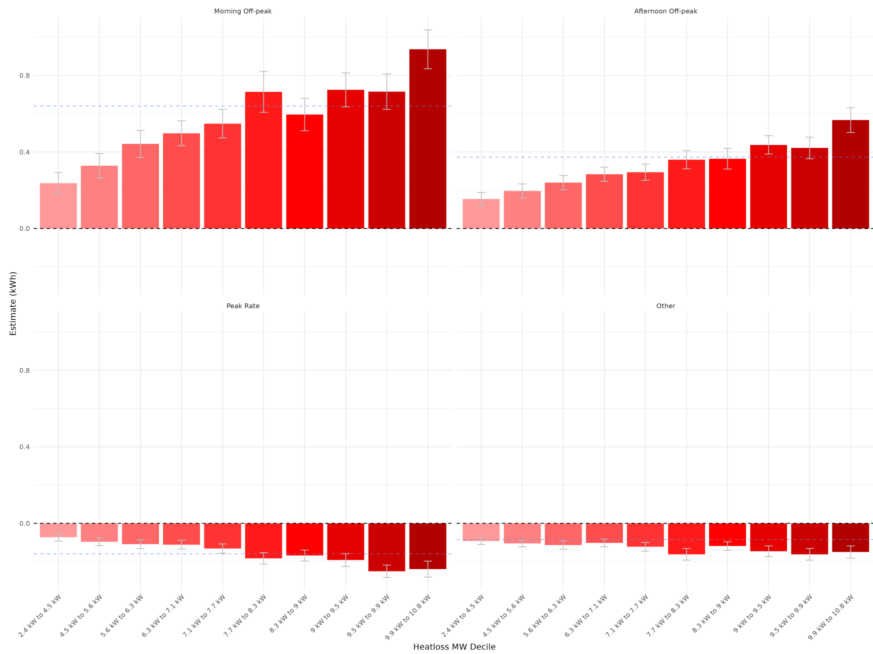
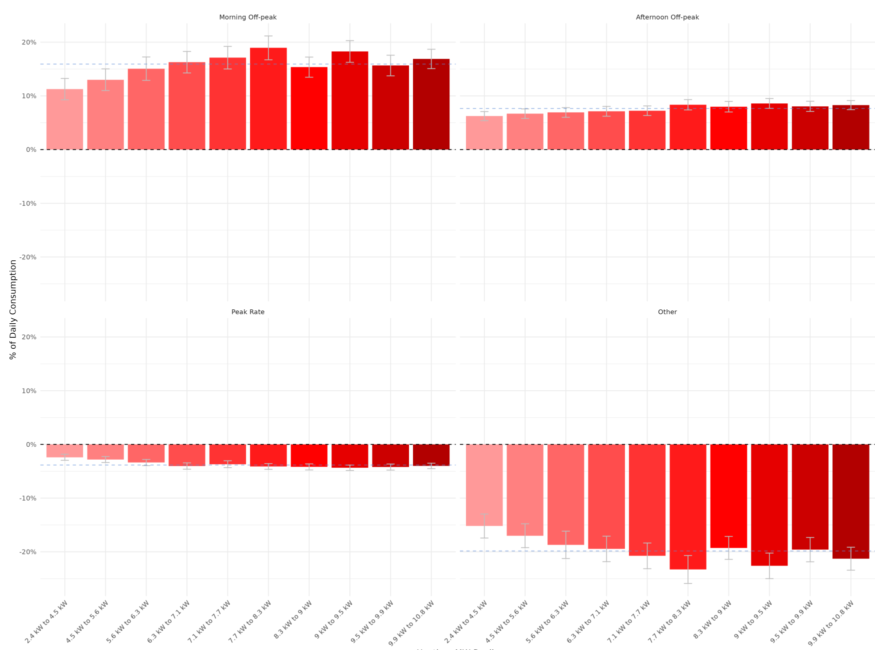
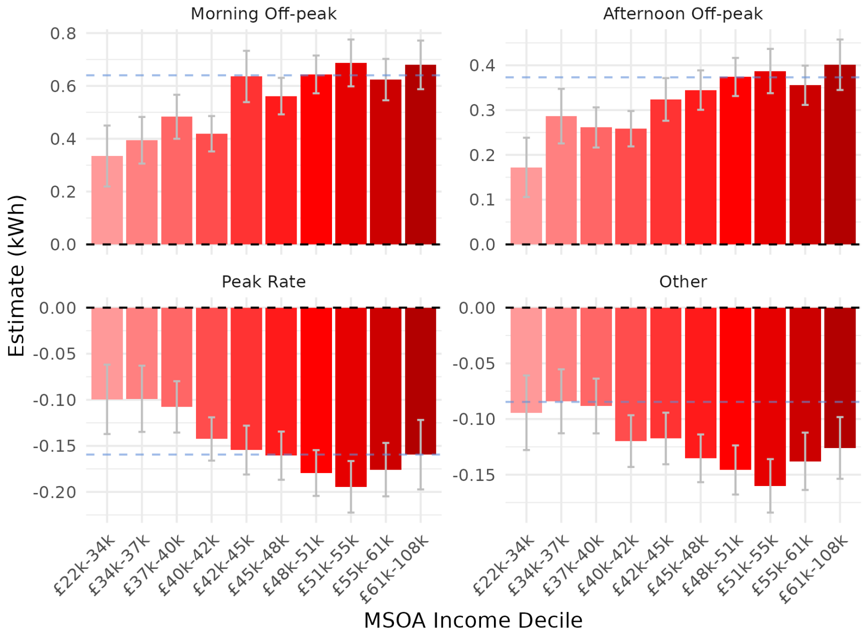


Figure A.29: Impact of the Heat Pump Tariff Adoption by Heat Loss on Share of Consumption



MSOA Income:

Figure A.30: Impact of the Heat Pump Tariff Adoption by MSOA Income on Consumption



Households Previously on Time-of-Use Tariffs:

Table A.14: Heat Pump Tariff ("*Cosy*") Adoption by Previous Tariff Type

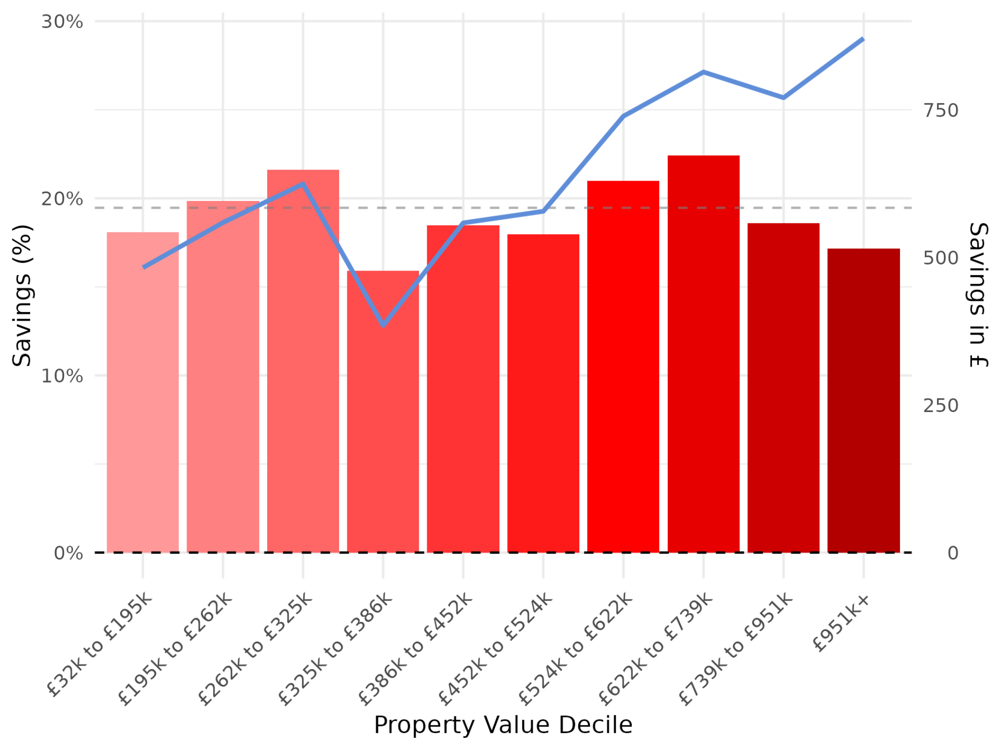
Dependent Variable:	Consumption in kWh				
Rate Period	Morning Cosy	Afternoon Cosy	Peak Rate	Other	Overall
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Cosy Contract Active = 1	0.4623***	0.2910***	-0.1472***	-0.0997***	0.0154***
	(0.0118)	(0.0077)	(0.0049)	(0.0042)	(0.0032)
Prev is ToU × Cosy Contract Active = 1	0.6604***	0.2614***	-0.0688***	-0.1684***	0.0003
	(0.0403)	(0.0228)	(0.0109)	(0.0105)	(0.0072)
Pre-Treatment Average					
Half Hourly Consumption Non-ToU	0.39	0.34	0.45	0.39	0.39
Half Hourly Consumption ToU	0.42	0.27	0.32	0.43	0.39
Fixed-effects					
HDD	Yes	Yes	Yes	Yes	Yes
Household	Yes	Yes	Yes	Yes	Yes
date	Yes	Yes	Yes	Yes	Yes
Fit statistics					
Observations	3,145,210	3,145,773	3,145,746	3,150,375	3,150,377
Size of the 'effective' sample	6,644	6,644	6,644	6,644	6,644
Number of Time Periods	916	916	916	916	916
R^2	0.58489	0.48951	0.48936	0.62039	0.66817

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

A.4.11 Average Savings by Property Value

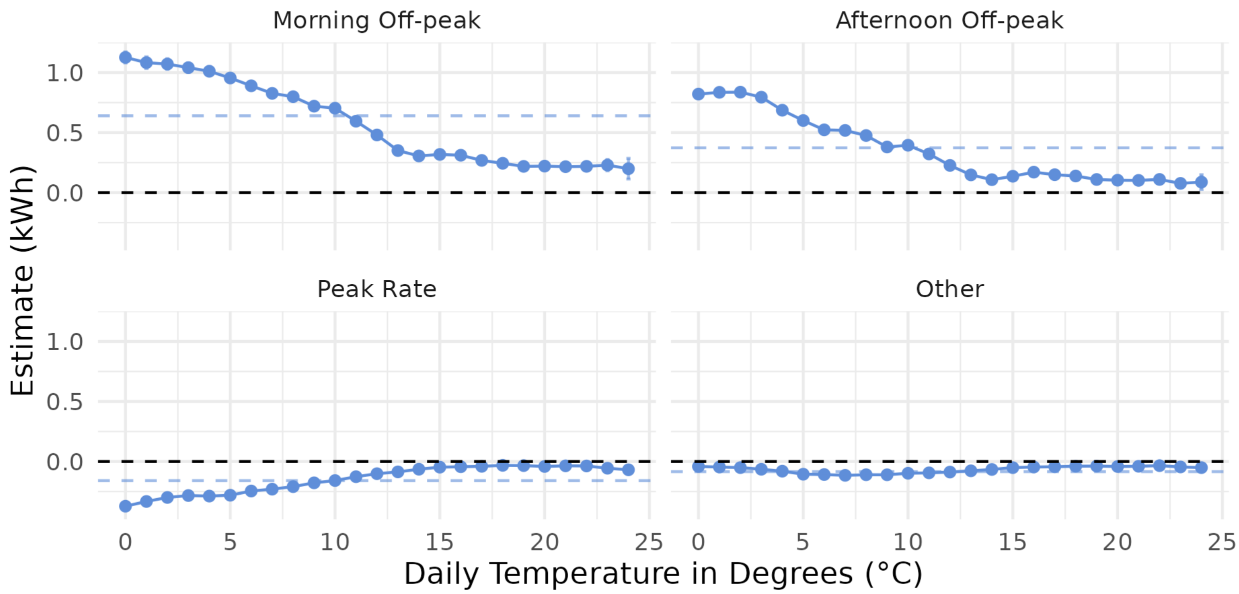
In this section, we calculate the average savings by comparing the cost difference between the average price per kWh and the heat pump tariff price per kWh for each rate period ("structural savings", assuming their consumption per rate period does not change), as well as the savings from load shifting, using the coefficients from the difference-in-differences analysis by property value decile. The results show that average savings hover around 18% across all property value deciles (based on estimated property prices), as depicted by the red bars and the blue dashed average line in Figure A.31. The bold blue line represents the average savings in pounds per year, shown on the secondary axis. We observe that higher property value deciles tend to have larger savings, but these households also have higher overall adoption energy bills.

Figure A.31: Average Tariff Savings by Property Value



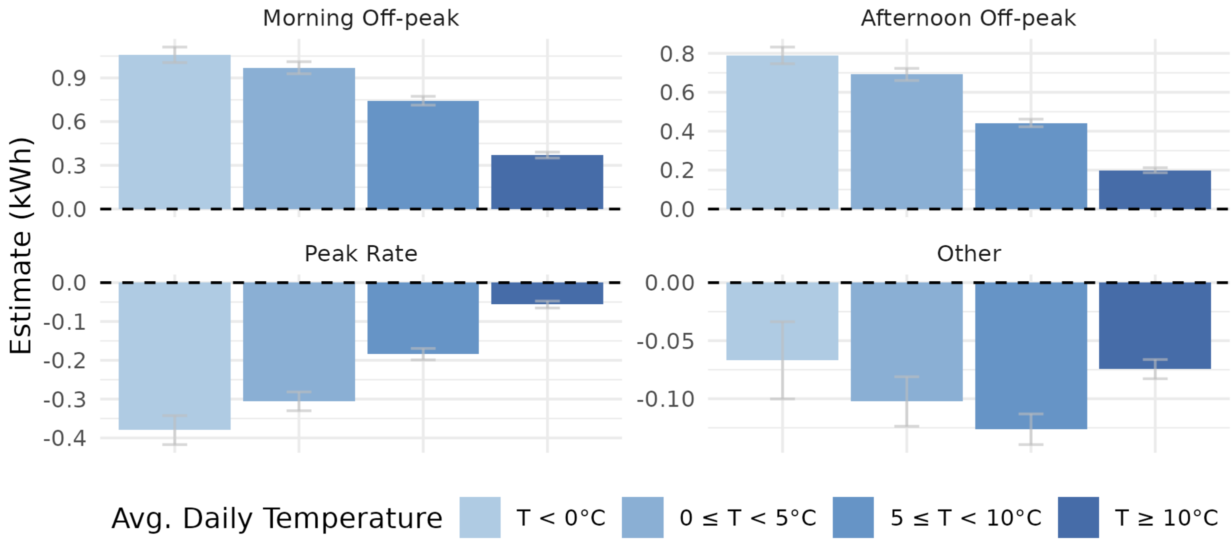
A.4.12 Impact of Heat Pump Tariff by Outside Temperature

Figure A.32: Impact of the Heat Pump Tariff by Outside Temperature



Note: We show the interaction between temperature (the average temperature on a day) and heat pump tariff's impact on daily electricity consumption in kWh (left vertical axis) in a TWFE model. We also show the TWFE ATE main effect in dashed blue, and thus on the right vertical axis we show the ratio of the TWFE interaction over the main effect; we interpret this ratio as showing when the temperature-conditional heat pump impact is higher or lower than the tariff "main effect".

Figure A.33: Impact of the Heat Pump Tariff Adoption by Outside Temperature on Consumption



A.5 External Validity

A.5.1 External Validity Tables

We compare heat pump adopters to a random sample of the utility's smart meter households and to other geographic areas in England and Wales.

We first compare the geographic areas in which heat pump adopting households are located with other geographic areas in England and Wales in Table A.15. We perform the same comparison for tariff adopters in Table A.16. We rely on these ecological comparisons because we lack individual-level data on certain key household characteristics, such as income.

In Great Britain, the Office for National Statistics (ONS) compiles data on income and related statistics at several geographic levels. We use the middle layer super output area (MSOA). There are 7,201 MSOAs in England and Wales, each containing on average approximately 8,000 residents.[11] Our dataset covers approximately 6,000 MSOAs with complete information on income, demographics, and socio-economic characteristics.

Areas with heat pump adopters have slightly higher incomes (£49.3k vs. £46.1k) and lower deprivation levels. This pattern is consistent with prior evidence that low-carbon technology subsidies often reach higher-income households (Borenstein, 2017, Borenstein and Davis, 2016, De Groote and Verboven, 2019, Feger et al., 2022, Metcalf, 2019), and contrasts with the pattern of heat pump adoption documented in the United States by Davis (2024). Using the Index of Multiple Deprivation (IMD), we also find that adopters live in less deprived areas.[12]

The population in areas with heat pump households is also slightly older and somewhat more likely to have achieved a Level 4 qualification (a measure of educational attainment roughly equivalent to a post-high-school vocational degree / first year of a bachelor's). Property prices in treated areas are broadly similar to those in other areas, suggesting that early adopters do not differ systematically across all economic dimensions.

While adopters may differ from other households in unobservable ways, our estimates mainly reflect early adopters living in relatively well-insulated homes. This is consistent with eligibility conditions for the Boiler Upgrade Scheme prior to May 2024.

Table A.15: External Validity by Area for Heat Pump Installations

	Weighted Mean	
Variable	MSOAs with HP Installations (N = 1,104)	Other MSOAs (N = 5,976)
Total annual income (£)	49,323.84 (9,700.39)	46,079.25 (11,290.53)
Property price (£)	384,517.82 (159,046.28)	367,330.35 (264,659.20)
Average HH Size	2.36 (0.17)	2.39 (0.28)
HH Not Deprived in Any Dim. (%)	52.08 (7.43)	47.33 (8.90)
Average Age	42.26 (4.08)	40.46 (4.74)
Share Level 4 Qualifications (%)	28.33 (7.70)	27.27 (9.98)

[11] Scotland uses a different system of geographic aggregation; we focus this descriptive analysis on England and Wales.

[12] The IMD datasets measure relative deprivation across small areas of the United Kingdom, incorporating income, employment, education, health, crime, housing access, and environmental conditions.

Table A.16: External Validity by Area for Tariff Adopters

	Weighted Mean	
Variable	MSOAs with Tariff Adopters (N = 2,860)	Other MSOAs (N = 4,220)
Total annual income (£)	48,596.70 (10,660.63)	45,235.41 (11,208.87)
Property price (£)	403,053.22 (211,456.98)	347,407.98 (272,038.97)
Average HH Size	2.34 (0.18)	2.41 (0.31)
HH Not Deprived in Any Dim. (%)	51.64 (7.65)	45.67 (8.81)
Average Age	42.57 (4.41)	39.49 (4.45)
Share Level 4 Qualifications (%)	29.49 (8.91)	26.03 (9.89)

We further investigate the external validity of our samples by examining how their composition evolves over time. We define *Early* and *Late* adopters based on the median installation or adoption date, splitting the sample into two groups for the balance tables Table A.17 and Table A.18. In both cases, early adopters tend to have slightly larger and more expensive properties, which is associated with higher Estimated Annual Consumption (EAC).

Table A.17: Balance Table for Heat Pump Early and Late Adopters

Variable	Early (N = 633)	Late (N = 665)
Energy Efficiency	72.31	72.35
	(12.93)	(13.84)
EAC	6,074.35	4,504.87
	(3,896.65)	(3,240.99)
Floor Area	117.74	111.72
	(37.20)	(75.51)
Property Value	487,716.75	437,472.03
	(223,143.35)	(207,921.34)

Table A.18: Balance Table for Heat Pump Tariff Early and Late Adopters

Variable	Early (N = 3023)	Late (N = 3039)
Energy Efficiency	67.20	63.80
	(17.41)	(18.40)
EAC	8,179.71	7,183.82
	(5,660.98)	(5,007.10)
Floor Area	151.57	139.48
	(72.84)	(82.37)
Property Value	562,231.96	512,052.21
	(396,946.68)	(403,517.94)

A.5.2 External Validity: Reweighting to General Smart Meter Population

To further assess the external validity of our results, we complement the difference-in-differences analysis with a matching exercise designed to reweight our sample so that it more closely resembles the general smart meter population.

In this exercise, we compare heat pump adopters to a randomly selected group of households with smart meters. We observe pre-trial (December 2021) Estimated Annual Consumption (EAC) and property characteristics for a subset of households: 658 heat pump adopters and 1,948 households drawn from the 5,000 randomly selected smart meter households. We do not observe these variables for the full samples because EAC data are unavailable for households that joined the partner utility after 2021.

Consistent with the patterns described in Section A.5.1, Table A.19 shows that heat pump adopters tend to live in larger and more valuable properties and have higher electricity consumption than the random smart meter sample. Even prior to installation, adopters have higher electricity demand than typical smart meter households. Tariff adopters have similar EPC ratings to the random sample, while heat pump adopters have somewhat better energy efficiency ratings, reflecting eligibility requirements under the Boiler Upgrade Scheme.

Table A.19: External Validity for Heat Pump Tariff and Heat Pump Adopters

Variable	Heat Pump Tariff (N = 5993)	Heat Pump Adopters (N = 1298)	Random Sample (N = 3378)
Energy Efficiency	65.54	72.33	64.93
	(17.94)	(13.40)	(12.74)
EAC	7,675.11	5,270.26	3,917.97
	(5,367.39)	(3,659.54)	(3,240.51)
Floor Area	145.49	114.66	98.94
	(77.80)	(60.02)	(67.92)
Property Value	540,570.60	461,975.04	378,621.37
	(401,413.57)	(216,856.05)	(289,121.41)

We match households on pre-adoption characteristics including property value, energy efficiency, floor area, and Estimated Annual Consumption. The matching procedure uses full matching with an Average Treatment effect on the Controls (ATC) estimand so that the heat pump adopter sample resembles the random smart meter population along observable characteristics. We also impose calipers to ensure that matched households are sufficiently similar along these dimensions.

After matching, the covariate distributions become substantially more balanced, as shown in Table A.20. The matching procedure excludes 47 heat pump households and 47 households from the random sample due to caliper restrictions.

Once balance is achieved, we re-estimate the treatment effects using a TWFE model with weights derived from the matching procedure (Table A.21). The resulting estimates are very similar to those obtained from the baseline TWFE regressions (Table A.1). Electricity consumption increases by 3,207.2 kWh while gas consumption decreases by 10,322.8 kWh, compared with baseline estimates of 3,177.7 kWh and –10,276.3 kWh respectively. This similarity indicates that the main results are not driven by observable differences between heat pump adopters and the broader smart meter population.

Table A.20: Covariate Balance Before and After Matching (Heat Pump)

Variable	Mean (Treated)	Mean (Control)	Std. Mean Diff.
Pre-matching			
Distance	0.32	0.23	0.81
Property Value	473, 410.90	389, 879.90	0.27
Estimated Annual Consumption	4, 158.31	3, 946.74	0.07
Energy Efficiency	72.50	65.04	0.59
Floor Area	117.50	99.20	0.33
Post-matching			
Distance	0.23	0.23	0.01
Property Value	357, 478.50	342, 181.00	0.05
Estimated Annual Consumption	3, 484.10	3, 463.07	0.01
Energy Efficiency	66.17	66.47	-0.02
Floor Area	95.37	92.16	0.06

Table A.21: TWFE using Matching Weights (Heatpump)

Model:	Electricity (1)	Gas (2)
Variables		
Is HP Installed = 1	3,207.2***	-10,322.8***
	(142.8)	(318.0)
Fixed-effects		
HDD	Yes	Yes
Household	Yes	Yes
Week	Yes	Yes
Pre-Treatment Average		
Yearly Consumption	4,608.40	10,014.74
Fit statistics		
Observations	62,608	53,362
Number of Households	606	542
Number of Time Periods	129	129
R^2	0.66214	0.73193

Clustered (Household) standard-errors in parentheses
*Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

A.6 Welfare Analysis: Methodological Details

A.6.1 Calculation Framework

We evaluate the welfare effects of the UK's heat pump subsidy using the marginal value of public funds (MVPF) framework developed by Hendren and Sprung-Keyser (2020) and applied to environmental policy by Hahn et al. (2024). The MVPF is defined as the ratio of total social willingness to pay to net government expenditure:

$$\text{MVPF} = \frac{\Delta W + \Delta E}{\Delta G - \Delta T},$$

where ΔW denotes private willingness to pay, ΔE environmental externalities, ΔG direct government spending, and ΔT fiscal externalities.

The subsidy is £7,500. Average total installation cost is £12,713 (Microgeneration Certification Scheme (MCS), 2024), implying private expenditure of £5,213 after the subsidy. We assume the relevant counterfactual is a gas boiler costing £2,250 (Myers et al., 2018). The incremental capital cost of adopting a heat pump relative to a boiler is therefore £2,963.

We incorporate operating cost differences using estimated annual energy changes of 8,744 kWh reduction in gas consumption and 2,551 kWh increase in electricity consumption. Retail energy prices are taken from contemporaneous UK averages. Using a 20-year equipment lifetime and a 3.5% social discount rate following HM Treasury (2020), we calculate the net present value of operating cost differences. Combining incremental capital costs and discounted operating cost changes yields the net private resource cost of heat pump adoption absent environmental benefits.

A.6.2 Environmental Externalities

Environmental benefits are calculated using marginal emissions factors consistent with UK Government guidance. We use 0.2 $kgCO_2e$ per kWh for gas (Department for Energy Security and Net Zero, 2023*b*) and 0.23 $kgCO_2e$ per kWh for electricity in 2024 (UK Government, 2024). The electricity emissions factor is projected to decline over time in line with published decarbonization pathways, reaching near-zero intensity by the early 2040s. This approach reflects long-run marginal emissions rather than short-run average grid intensity, which is appropriate for evaluating durable capital investments.

Combining the observed energy changes with these emissions factors, we estimate an annual reduction of approximately 1.16 tonnes of CO_2e emissions in 2024. Over a 20-year heat pump lifetime, this corresponds to a cumulative reduction of roughly 31.26 tonnes of CO_2e. Carbon is valued at approximately £280 per tonne of CO_2e following the UK Government's carbon valuation guidance (Department for Energy Security and Net Zero, 2023*a*). Environmental benefits are computed as the discounted value of avoided emissions over the equipment lifetime.

For air pollution benefits, we use UK Government (2024) (Table 15: Air quality activity costs from primary fuel use, 2022 p/kWh), which reports air quality costs for various primary fuel uses, including electricity and gas. Heat pumps reduce air pollution associated with gas consumption in the UK, while their increased electricity use generates some additional air quality harms. The net effect is a benefit to air quality, beginning at £11 per year in 2024. As with CO_2e abatement, these benefits increase over time, reaching £16 per year by 2043, reflecting the projected decarbonization of the UK electricity grid and the corresponding reduction in electricity-related air pollution. The net present value of these benefits is £206. Total air pollution benefits remain small relative to CO_2e abatement benefits, primarily because natural gas combustion contributes relatively little to local air pollution.

A.6.3 Subsidy Incidence and Marginal Adoption Assumptions

We make explicit assumptions about how the heat pump subsidy affects heat pump demand. The subsidy increased to £7,500 in October 2023. We assume that 50% of subsidy recipients are marginal adopters induced by the policy, while 50% are inframarginal and would have adopted absent the subsidy. This assumption is consistent with evidence on large energy-related investment subsidies for homeowners (Hahn et al., 2024) and parallels the approach in Davis (2024).

Inframarginal adopters are assumed to value the subsidy pound-for-pound. For marginal adopters, we assume that average valuation equals 50% of the subsidy. This follows the standard triangle approximation to deadweight loss introduced by Harberger (1964) and adopted in the MVPF literature (Hahn et al., 2024, Hendren and Sprung-Keyser, 2020). Under a linear demand curve, the average valuation among marginal consumers equals one-half of the subsidy. Under the 50% marginal assumption, households therefore capture 75% of the subsidy value in expectation. As a robustness check, we also consider an alternative calibration in which only 25% of adopters are marginal, implying that households capture 87.5% of the subsidy value.

A.6.4 Fiscal Externalities

Fiscal externalities arise from changes in tax revenues associated with energy use and equipment purchases. Reduced gas consumption lowers VAT revenues on gas sales, while increased electricity consumption raises VAT revenues on electricity. Differences in VAT treatment between boilers and heat pumps also affect tax receipts. We calculate the net present value of these revenue changes over the equipment lifetime using the same 3.5% discount rate.

In addition, we incorporate the climate fiscal externality, defined as the present value of future carbon tax revenues or abatement cost savings associated with reduced emissions. This term reflects the interaction between the policy and the government's broader climate commitments. The net fiscal externality modestly offsets the upfront subsidy cost and enters the denominator of the MVPF calculation as ΔT.

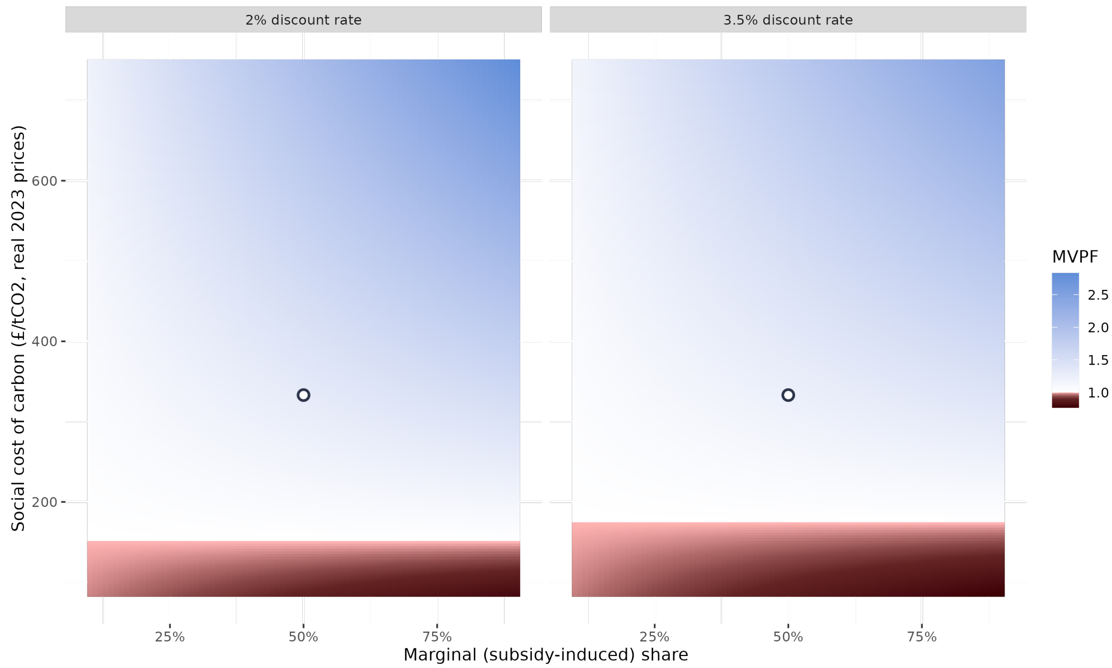
A.6.5 Joint Sensitivity to Additionality and the Social Cost of Carbon

The Average MVPF rests on two judgment calls in particular: the marginal (subsidy-induced) share of adopters, m, discussed above, and the social cost of carbon (SCC) used to value avoided CO_2e emissions. Reasonable analysts differ on both: additionality rates vary substantially across subsidy programs and settings, and the SCC is itself contested, with UK Government MAC-based and IAM-based (Rennert et al., 2022) estimates alone differing by nearly a factor of two (Table 3). Figure A.34 recomputes the Average MVPF over a wide grid of both parameters jointly, holding all other inputs at their baseline values, at a 2% discount rate and HM Treasury (2020)'s recommended 3.5% appraisal discount rate.[13]

Blue shading marks combinations for which the subsidy remains welfare-enhancing on average (MVPF ≥ 1); red marks combinations for which it does not. The white circle marks our preferred specification ($m = 50\%$, SCC at the UK Government MAC-based central path). Two patterns stand out. First, the effect of m on the MVPF depends on the assumed SCC: at low carbon prices, a larger induced share *lowers* the MVPF, because more of the subsidy goes to households who value it at only half its face value without enough environmental benefit to compensate; at higher carbon prices this reverses, and a larger induced share raises the MVPF. Second, the carbon price at which the subsidy breaks even (MVPF $= 1$) does not depend on m at all. Households who would have adopted anyway receive a pure transfer, worth exactly what it costs, so they never move the break-even; it is set entirely by the subsidy-induced adopters, who break even precisely when the avoided-carbon benefit offsets the half of the subsidy they do not value privately. At that carbon price every adopter breaks even individually, so the mix between the two groups is irrelevant. In other words, the additionality share affects how far above or below 1 the MVPF is, but not which side of 1 the program falls on.

[13] The appraisal discount rate governs the discounting of the monetized benefit and cost streams over the 2024–2043 horizon; it is distinct from any discount rate embedded in the derivation of the carbon value itself. Our baseline carbon values follow the UK Government's target-consistent (marginal-abatement-cost) path, which is anchored to the cost of meeting legislated emissions targets rather than to a discounted damage stream, and so is not a function of the appraisal rate. We therefore treat the vertical axis as an assumed carbon price and vary it freely. Damage-based (IAM) values instead rise with a lower discount rate; for those, the panels should be read as fixing the carbon price and varying only the rate applied to the streams, not as re-deriving the price at each rate.

Figure A.34: Sensitivity of the Average MVPF to Additionality and the Social Cost of Carbon



Note: Each panel shows the Average MVPF (Table 3) over a grid of the marginal (subsidy-induced) share of adopters, m, and the social cost of carbon, holding all other inputs at their baseline values, at a 2% (left) and 3.5% (right) appraisal discount rate. Blue indicates MVPF ≥ 1 (welfare-enhancing on average); red indicates MVPF < 1. The white circle marks our preferred specification ($m = 50\%$, SCC at the UK Government MAC-based central path). The social cost of carbon axis is expressed in £/tCO_2e (2023 prices), averaged over the 2024–2043 horizon.

A.6.6 Heat Pump Operating Cost Scenarios

Entries in Table 4 report the implied change in annual operating costs for a heat pump household relative to a gas boiler. Positive values indicate that heat pumps are more expensive to operate; negative values indicate savings. Calculations hold fixed the estimated annual consumption changes associated with heat pump adoption (2,551 kWh electricity; -8,744 kWh gas), i.e., we assume no behavioral response to the price changes. All scenarios are stylized counterfactuals intended to illustrate the magnitude of pricing wedges rather than represent specific policy proposals.

Scenarios (1a)–(1d) present alternative retail price baselines differing in unit prices and the treatment of the "gas standing charge", a daily fee for remaining connected to the gas grid. Scenario (1a) assumes continued gas connection; Scenario (1b) assumes disconnection, saving the household £107 per year. Scenarios (1a) and (1b) use UK Government retail price estimates (UK Government, 2024), with (1b) also assuming gas disconnection. Scenarios (1c) and (1d) use the utility's actual pricing (again with the latter scenario, (1d), assuming gas disconnection).

Scenarios (2)–(6) build on the partner utility's retail pricing baseline from Scenario (1d), progressively removing legacy electricity policy costs, including the Renewables Obligation (RO), Feed-in Tariffs (FiT), Contracts for Difference (CfDs), and the Energy Company Obligation (ECO). Scenario (2) removes 75% of RO costs and all ECO costs. Scenario (3) removes all explicit electricity decarbonization levies, and Scenario (4) additionally removes the volumetric recovery of electricity network charges, moving toward marginal-cost pricing. CfDs are sensitive to wholesale prices, as they are defined as the difference between generators' strike prices and the day-ahead wholesale price, which serves as the reference price for the subsidy, for each half-hour settlement period. This creates an inverse relationship: higher wholesale prices reduce subsidy payments, while lower wholesale prices increase them. In this analysis, we use CfD costs from 2024 only. These costs are projected to increase from 2027 onward, particularly as payments begin for new subsidized generation, including new nuclear capacity. Finally, we do not include Capacity Market costs that are currently borne by bill-payers. Although these costs could reasonably be classified as policy costs, the classification is debatable, as the Capacity Market is a capacity adequacy mechanism that interacts closely with wholesale energy prices, for example by increasing available supply and thereby placing downward pressure on prices.

Scenarios (5) and (6) introduce carbon pricing on household gas consumption, currently exempt from the UK Emissions Trading Scheme (ETS). Scenario (5) applies the 2024 UK ETS allowance price (£56/tCO_2). Scenario (6) prices emissions from both electricity and gas at the central social cost of carbon (£273/tCO_2 in 2024 prices). Electricity already embeds some carbon costs via the UK ETS applied to power-sector generators, so extending carbon pricing to gas has a larger effect on relative costs.

Emission intensities are from Department for Energy Security and Net Zero (2025). Note that this particular source assumes somewhat higher carbon intensity of electricity (207g/kWh) than using a grid average carbon intensity; for example, Table 1 in UK Government (2024) reports average carbon intensities of 140-150g/kWh. We use the higher figure as it is the official Government guidance for carbon accounting exercises. Were we to use the lower figure, the heat pump operating cost savings would be even more pronounced in Scenario 6. Note also that we have used slightly different carbon intensities here (2025 vintage) than in our welfare analysis (2024 vintage), given the forward-looking nature of this analysis.

In creating these scenarios, we assumed no changes in unit rates above and beyond the direct impacts of rebalancing. Specifically, we assume no further changes by the utility, i.e., changes in mark-up / gross margin.