The Proof of the Pudding is in the Heating: A Field Experiment on Household Engagement with Heat Pump Flexibility

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Overview

Electricity demand flexibility is crucial for the energy transition, especially with the growing variability of renewable sources like wind and solar. Achieving the European Union's target of 32% renewable energy in gross final consumption by 2030 [1] requires not only significant changes in electricity supply but also in demand, with households aligning their usage to periods of high renewable generation. As space and water heating account for 78% of energy consumption in EU households [2], heat pumps (HPs), which electrify these needs, hold significant potential for flexibility. By enabling short-term shifts in heating demand, flexible HP usage can reduce reliance on carbon-intensive peak power plants and enhance grid stability. Economic incentives, such as time-varying prices, have been promoted to encourage this flexibility. However, the behavioral economics literature on flexibility highlights that barriers like status quo bias, bounded rationality, and response fatigue often prevent households from fully exploiting their flexibility potential.

This study explores a setup that mimics what is sometimes referred to as 'direct load control', where aggregators remotely manage HPs to lower system demand during periods when electricity prices are high (and renewable generation is low) and raise it when they are low (and renewable generation is abundant). By investigating household responses to the remote management of their heating and the impacts on comfort, we provide quantitative estimates of the flexibility potential of HPs and advance recommendations for designing future flexibility schemes.

Methods

We conducted a field experiment during the winter seasons of 2022–2023 and 2023–2024 to evaluate the flexibility potential of residential HPs in nine well-insulated households near Ghent, Belgium. Across 287 interventions, HPs were temporarily switched off until one of three predefined criteria was met: the indoor temperature dropped below a threshold, the domestic hot water (DHW) tank temperature fell below 40°C, or the household manually overrode the intervention via an online platform. Some interventions were pre-notified a day in advance, allowing households to override preemptively. As the experiment lacked a separate control group, we used the average HP operation during non-intervention periods as counterfactual. This approach allowed us to estimate the impact of interventions on HP power consumption during and after the interventions, accounting for potential long-lasting changes in HP consumption patterns.

We measured five key variables shaping HP flexibility potential: intervention duration before the HP is automatically or manually restarted (hours), power reduction (kW), energy reduction (kWh), energy consumption increase in the post-intervention period, and financial savings (€). We conducted this analysis at two levels: the individual HP level, focusing on periods when HPs were blocked (referred to as 'interventions'), and the fleet level, capturing the aggregated response of a fleet of HPs during 'flexibility events', where an intervention is initiated simultaneously across all units in the fleet, resulting in events during which some HPs remain blocked by the intervention while others have already resumed normal operation. Additionally, we used linear regressions to examine how factors such as indoor and outdoor temperatures and time of day influenced intervention duration and rebound energy consumption.

Results

The interventions lasted an average of 12.8 hours before meeting one of the predefined stopping criteria. The strongest predictor of intervention duration is the indoor temperature at the start of the intervention, with a one-degree (Celsius) increase extending duration by 1.9 hours on average. Similarly, outdoor and DHW tank temperatures at the start of the intervention have a positive and significant effect on duration, while the time of day at which the intervention is initiated has no effect. Interestingly, a dummy variable for whether the intervention was pre-notified is insignificant, suggesting that households did not strategically adjust thermostat settings or behavior in response to notifications.

Firstly, during flexibility interventions, HP power consumption dropped by 84% on average, saving 3.5 kWh of electricity per intervention. However, significant rebound effects eroded these savings, as HPs require an additional 2.5 kWh above the counterfactual over 16 hours post-intervention to restore indoor and DHW temperatures to user-defined setpoints. We show that the rebound magnitude is strongly influenced by the difference between indoor temperature and the thermostat setpoint at the end of the intervention, with a one-degree increase in this difference resulting in 0.9 kWh of additional rebound consumption within 16 hours. As a result, interventions lead to a net decrease of 1 kWh of electricity on average.

Secondly, the quantitative analysis of flexibility events at the fleet-level is particularly valuable to flexibility program operators, as these actors are interested in estimates of aggregate power reductions over a pool of flexible units, where some units return to normal operation earlier than others, thereby reducing the maximum achievable power reduction. At the fleet-level, net power consumption per unit in the fleet is reduced by 250 W on average at the start of the event, gradually returning to 0 W after 18 hours as some units in the fleet reactivate. Analyzing heterogeneity in fleet-level power reductions with outdoor temperature reveals that initial power reductions are larger in colder weather, reaching 600 W per HP when temperatures are below 3 °C. Further, using the power reduction profiles over time and by outdoor temperature, we simulated the financial savings achieved per event if they were initiated at each hour of the winters 2022-2023 and 2023-2024. We limited our financial analysis to calculating savings under day-ahead price volatility, which captures only one value stream for flexibility programs. While average savings per event per HP amounted to just €0.13, targeting periods of high price volatility, such as during the 2022 energy crisis, can increase savings to as much as €1.1 per event and HP.

Finally, we investigated the discomfort households experienced in the experiment. In a post-experiment survey, households reported low to moderate discomfort during interventions. On average, indoor temperatures dropped by 0.69 °C between the start and the end of an interventuion. However, interventions that were manually overridden showed considerably larger temperature drops, averaging 1.06°C by the time of override. This suggests that households reacted rationally to greater discomfort, although we show that this behavior was not consistent. This aligns with a thematic analysis of the comments households left on the experiment's online platform during overrides, which indicated that participants primarily overruled for three reasons: feeling too cold, having someone sick at home, or needing comfort for someone working or studying at home.

Conclusions

In this field experiment, we demonstrated the feasibility of residential HP flexibility while largely maintaining comfort in well-insulated households. The mixed approach employed in our setup, where interventions could be manually or automatically stopped, provided users with some degree of control over their HPs—a feature we envision becoming standard in future flexibility programs. Indeed, as evidenced by the manual overrides, the acceptability of flexibility interventions is time- and context-dependent, driven by multiple factors, meaning households are not homogeneous actors who either accept or reject flexibility. Besides, while the key incentive for household participation in flexibility programs is expected to lie in reductions in heating bills, the financial savings we calculated under day-ahead price volatility were relatively modest. However, the minimal impact on comfort makes daily implementation of interventions throughout the heating season feasible, allowing small savings to aggregate into significant annual reductions. Therefore, as a relatively low-cost way to enhance energy system efficiency, we recommend that policymakers support and invest in commercial and academic efforts to advance the understanding, development, and large-scale adoption of heat pump flexibility. Our experiment shows that HP flexibility can address periods of low wind and/or solar production lasting a few hours. Although HPs are not a solution for extended Dunkelflaute events, we demonstrate potential for unannounced, shorter-term flexibility, as we show that households do not adapt their behavior based on intervention notifications. Finally, this topic offers significant potential for further research. Future studies should explore strategies where flexibility interventions involve preheating homes during cheaper hours before interrupting heating during more expensive periods, which could further increase the acceptability of flexibility. Additionally, since our sample was limited to well-insulated homes, it will be important to assess how these findings generalize to other dwelling types or households as HP adoption increases. Less-insulated homes could also provide flexibility, particularly if high-temperature heat pumps replace fossil-fueled systems, offering greater power reductions but shorter intervention times, while still maintaining comfort.

References

[1] Council of the European Union. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council: of 11 December 2018 on the promotion of the use of energy from renewable sources. http://data.europa.eu/eli/dir/2018/2001/oj

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This extended abstract is an adaptation (including verbatim excerpts) of a working paper that will be made available following the submission of the abstract.