Evaluating domestic demand side response trials in UK dwellings with smart heat pumps and batteries

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Keywords

demand response, existing social housing, monitoring, survey

Abstract

Smart heating and battery technologies are beginning to be deployed in UK homes to alter the timing of domestic energy demand to enable residential demand side response (DSR). This paper empirically evaluates the impact of DSR trials on grid electricity import and household experience regarding disruption to routines, thermal comfort and noise disturbance in 17 thermally efficient social housing dwellings (Barnsley, England) with air source heat pumps, 5 kWh smart batteries and solar photovoltaic panels (1.3–3.0 kWp). Four DSR trials were run during the latter part of the heating season of 2021 to shift electricity demand away from peak times using automated control of battery and heat pumps to impose two-hour 'turn-down' interventions during peak times and two-hour 'turn-up' interventions at expected times of local surplus renewable generation. The turn-down trials were driven by price signals (time of use tariffs) and grid carbon intensity. While during turn-down interventions grid electricity import was minimised, it was increased through battery charging and heat pump use during turn-up trials. Internet of Things based sensors recorded time-series data on grid electricity use, battery charging-discharging and heat pump electricity use. Telephone surveys were conducted with residents following the trials.

All turn-down interventions reduced grid import electricity. or time of use trials, grid import was reduced up to 1.7 kWh per household (85 %) between 5–7 pm and controllable load was reduced up to 4.3 kWh per household. For the turn-up trials, grid electricity import was increased up to 3.6 kWh per household and controllable load was increased up to 2.6 kWh per household between 1–3 pm. Household surveys revealed general concerns about the project related to fuel costs, indoor temperature and hot water temperature. Although a few households noticed battery noise during the trials, no one reported it as a concern. For 77 % of responses, trial changes were acceptable even amongst households who noticed changes in indoor temperature and battery noise. The general acceptability of automated DSR, under thermal comfort limits and manual override, are promising for the wider application of domestic DSR driven by price signals, although a continued focus on individual user support regarding the deployment of new technologies is needed. Additionally, individual dwellings may show different levels of demand response depending on the levels and patterns of electricity consumption.

Introduction

The UK government is committed to reaching net zero greenhouse gas emissions by 2050 along with the decarbonisation of the UK energy system such that it is run primarily from low carbon energy sources (HM Government, 2021). This will require a smarter, more flexible system which will be able to integrate increased amounts of intermittent wind and solar energy and match supply with demand at a national and local level, as well as working to minimise the overall generation, network capacity and network reinforcement required to satisfy demand, peak demand in particular. For consumers, a smart, flexible energy system can offer reduced energy costs by means of smart technologies and services (BEIS, 2021). Flexibility can be provided by interconnection and from flexible heating, electricity storage, smart battery charging and demand side response (DSR). However, the flexibility market for domestic customers in particular is underdeveloped. Domestic electrical loads which may be shifted in time consist of the use of household appliances e.g. washing machines and driers, electric space and hot water heating, and the charging of EVs. Additionally, home batteries can be charged using grid electricity at off-peak times or by self-generation of electricity, e.g. by solar panels, in order to release stored energy for use at peak times.

DSR uses the flexibility of consumers to better balance electricity demand with supply (BEIS, 2017a). It alters the timing of demand and can enable demand to be shifted from peak to off-peak times, or demand to be increased during times of high generation from renewables. Benefits to the domestic consumer include a reduction in energy bills achieved by the matching of their energy consumption to times when electricity is cheaper, as well as rewards for offering flexibility. This can be enabled by smart technologies, appliances, tariffs and services (BEIS, 2021). It has been questioned whether the current domestic loads offered by typical households in Britain would be sufficient to elicit a financially viable DSR option from small scale customer sites, however, future increases in domestic electrical loads could affect this (BEIS, 2017a). Achieving decarbonisation of heat by electrification of heating could create a greater opportunity for DSR; the deployment of 5.5 million heat pumps in UK homes by 2030 has been proposed in The Sixth Carbon Budget (Committee on Climate Change, 2020), as would the expected increase in EVs along with decreasing costs of home batteries in the near future. Automation and consumer trust, along with policy and market conditions are also factors for future DSR success (BEIS, 2017a).

The feasibility of DSR for domestic households has been demonstrated in small scale projects both within and outside the UK (BEIS, 2017b). For enrolment on DSR schemes, financial and environmental factors have been found to be particularly important (BEIS, 2017b; Parrish et al., 2020). Additional factors influencing enrolment include the complexity and effort of involvement, perception of risk and control, and interaction with household routines. Trust can be maintained with communication and timely resolution of issues (Parrish et al., 2020).

The UK Government plans to 'unlock' this market by supporting the deployment of smart energy technology, including the continued roll-out of smart meters, supporting the growth of electric vehicles (EVs), enabling smart tariffs, and providing regulatory support for flexibility providers and frameworks for consumer protection (BEIS, 2021). DSR can be achieved against a price signal or incentive based mechanism and by consumer control of electricity demand, or by automated control of demand by a third party (direct load control) (BEIS, 2017a). Householder control of the timing of energy demand can be manual or facilitated by means of smart timers, smart technology or smart appliances. It is envisaged that third party flexibility services will have an increasing role in the remote control of home energy management systems and the co-ordination of home storage, generation and appliances (BEIS, 2021). Automation or direct load control has been shown to increase response, particularly for electric heating (BEIS, 2017b). Without automation or direct load control, it may be problematic for householders to change electricity demand against a dynamic time of use tariff, and automation or direct load are seen as key for the provision of response and reserve services for the electricity system (BEIS, 2017a). Time of use tariffs use price signals to encourage the shifting of electricity consumption away from peak times towards times of low demand, or towards times of high renewables generation.

However, the literature dependence on data from DSR trials which are neither automated nor concern energy storage has been highlighted (Carmichael et al., 2021). DSR trials have not tended to involve homes with the combination of home batteries, electric heating, solar PV and automated DSR control, all technologies with an envisaged role in the decarbonisation of domestic energy consumption, nor have they considered both turn-down and turn-up DSR with these same assets. This paper provides empirical results for turn-down and turn-up DSR interventions achieved with automated control in combination with battery storage and heat pump operation, along with an evaluation of the household experience. Identification of any householder concerns with such technologies is important since a negative householder experience and technical issues are potential barriers to DSR (BEIS, 2017b). The aggregate impact of DSR interventions using price signals based on a flat (single) rate tariff and dynamic time of use tariffs applied to a group of 17 dwellings with electric heat pumps, home battery storage and solar photovoltaic (PV) panels with smart control is presented, and flexibility determined by measuring changes in grid electricity import and controllable load. A household survey was conducted to determine the householder experience of the trials in terms of thermal comfort, hot water availability and noise.

Evidence to date

Domestic DSR can be achieved by the shifting of electrical load by householders themselves through changing the timing of appliance and heating operation, either manually, or assisted by automation technology. It can also be achieved using third party control of energy systems. A trial of 48 dwellings located in Oxfordshire, England demonstrated that against a time of use tariff signal, eight homes, each with a 2 kWh battery under automated control, demonstrated a 20 % reduction in electricity consumption during evening peak times, a stronger response compared with homes under automated control of heating and hot water, or with appliances under manual or semi-automated control (Boait et al., 2019). Crawley et al. compared the results of two DSR trials in the UK (Crawley et al, 2021). One trial (Energywise) used smart meters and occupant control of household consumption to reduce peak load for social housing households in London, England, the other trial (NEDO) achieved DSR by installing heat pumps with automated control in homes in Manchester, England. Peak load reduction per household was around 25 times higher for the second trial. This difference in outcome was explained by the potential of heat pump technology to provide a larger peak reduction compared with the smaller loads for household appliances, along with thermal storage allowing heat pumps to be turned off during DSR events. Gupta & Morey (2021) found that compared with a baseline phase, under automated control by a third party, heat pump electricity consumption during the heating season across 10 dwellings in Barnsley, England, decreased by 10 %. The daily mean heat pump electricity consumption at peak times (4–7 pm) was 1.4 kWh, representing a potentially shiftable load. DSR has also been achieved by smart charging of EV batteries at non-peak times (FRED, 2021; Project Shift, 2021). The FRED project involved 250 UK homes, the majority with solar panels, and smart control of EV battery charging. Charging occurred mainly in the middle of the day and overnight, with those homes on a tariff containing off-peak rates usually charging during off-peak periods. Turn-up flexibility addresses network constraints when integrating renewable generation. For 46 trial homes in Cornwall, England, a dual-rate 'Sunshine tariff' was applied which rewarded electricity consumption between 10 am and 4 pm. Households with a hot water timer or other automated technology shifted 13 % of their consumption into the reward window compared with a 5 % shift for those households who shifted consumption manually (Western Power Distribution & Regen SW, 2017).

Battery storage can enable DSR by releasing energy at peak times, or absorbing energy when electricity generation from renewables is high. A case study in Denmark found that solar PV generation in combination with battery storage reduced peak loads for five households by 35–70 % (Christensen & Friis, 2017). The Sola Bristol project (England) determined that home batteries charged with solar PV generated electricity could export 20–40 % of their capacity to support evening peak demand (Zhao et al., 2015).

Time of use tariffs offer an enduring change to household demand profiles. The CrowdFlex project analysed data for UK domestic customers who switched to a time of use tariff, either Octopus Agile or Octopus Go[1] (CrowdFlex, 2021). Over a six month period following the change to a dynamic time of use tariff (Octopus Agile), there was an ongoing average reduction in demand over a three hour peak period (4–7 pm) of 0.1 kW (7 %) for non-EV households with no low carbon technology (n=544) and 0.2 kW (18 %) for EV households with no other low carbon technology (n=250).

As concerns the householder perspective of DSR, Bradley et al. (Bradley et al., 2016) considered the barriers to participation in tariff-based load shifting when householders themselves changed their timing of energy consumption. Barriers included the perceived disruption to patterns of living and lack of access to, or understanding of, the associated technology. Their pilot study of 10 UK households, which incentivised householders to move energy consumption to off-peak times (11 pm –7 am and 1–5 pm), facilitated by plug-based timers, resulted in off-peak consumption being increased from a benchmark of 23 % of total energy consumption to 41–44 % for two trial periods in summer of six weeks duration. Whether such a shift could be maintained long-term was a question for further research. Parrish et al. (Parrish et al., 2020) reviewed the motivations, barriers and enablers for DSR across 55 international studies consisting of trials, programmes and surveys. It was identified that automation or direct load control may support participant engagement and reduce the complexity and effort of the response, albeit with the condition that participant trust was to be maintained. Trust can be weakened by technical issues and lack of transparency for dynamic pricing and automation schedules. It was also suggested that the provision of support to use technologies enabling DSR, in terms of informed understanding and availability, could increase demand flexibility. Christensen et al. (2020) presented a study of three smart energy pilot trials (in Denmark, Norway and Austria) which between them included the elements of solar PV systems, energy monitoring and in-home display units for feedback, and semi-automated control. DSR was householder-driven against various financial incentives, but it was concluded that additionally, engagement, devices and competences (the skills and knowledge needed to incorporate DSR into daily routines) were required for the success of DSR initiatives. Although increased automated control should alleviate some of the effort involved in maintaining a DSR response, it is reasonable to believe that engagement, devices and competences will still be relevant where smart technology is deployed in conjunction with DSR, including where direct load control is employed. Following a trial in Wales in which homes used a combined air source heat pump (ASHP) and gas hybrid system under smart control, it was concluded that in order to avoid participant concerns and the reduction of participation numbers, prior explanations to participants about how the operation of a new system could differ from their expectations are required along with an understanding of the overall and individual benefits to participation (Sweetnam et al., 2019).

Recent pilot studies have involved various elements to attain domestic DSR, i.e. battery charging, electric heating, electrical appliances, and differing levels of control, from manual to automated, with automated control of battery storage or heating offering a stronger response. The current study brings the elements of battery storage, electric heating and automated control together and provides a measure of the demand response as well insight into the household experience of DSR where these three elements are combined. The study considers both turn-down and turn-up interventions, whereas the focus of other trials has been predominantly on turn-down trials alone.

Methodology and case study dwellings

DWELLING CHARACTERISTICS

The 17 dwellings consisted of 16 new-build (2014), well-insulated, two-storey social housing properties (Code 4 Sustainable Homes) and one post-war home within the UK Government funded BREATHE (Bringing Renewable Energy Automation To Homes Everywhere) project on domestic DSR. The dwellings were located in Barnsley, England. 13 homes were semi-detached, one was detached and two were flats. Each dwelling contained a 5 kWh Sonnen battery, a 5 kW Mitsubishi Eco Dan dual purpose ASHP which provided space heating and hot water, and a Passiv UK PassivLiving Hub smart control system. The control system allows optimisation of heating, hot water and battery operation to achieve a least cost outcome whilst avoiding thermal discomfort. This is achieved by the smart control of indoor temperature set points and operation of the ASHP and battery, in combination with machine learning and a dynamic building physics model of the dwelling, which take into account householders' schedules and preferences. Householders are able to temporarily override settings if desired. The 16 new build dwellings had a solar PV array (in the range 1.3–3.0 kWp), with underfloor heating downstairs and radiators upstairs. The post-war home had no solar PV installed and heating was provided via radiators. The default electricity tariff

1. Octopus Agile: A dynamic tariff using half-hourly energy pricing based on wholesale pricing. Octopus Go: A static tariff offering cheap rate electricity between 00:30-04:30. https://octopus.energy

for 14 dwellings was a flat (single) rate tariff with two homes on an Octopus Agile dynamic time of use tariff.

OVERVIEW OF DSR TRIALS

Four types of DSR trials were conducted from 12th March to 5th May 2021 as outlined in Table 1. The homes were divided into three trial groups (A, B and C). Groups A and B each consisted of six dwellings. For Trial 1, all 17 homes underwent two-hour turn-down interventions at peak times (6–8 am, 5–7 pm) against the price signal from their default tariff. Additionally, Groups A and B underwent Trials 2 and 3 whereby two-hour turn-down interventions at peak times were overlaid on a dynamic Octopus Agile and a carbon optimisation price signal, respectively, the former using forecast electricity prices and the latter based upon forecast carbon grid intensity for the Yorkshire region[2].

Time of use tariffs offer charging of the battery at times when electricity is lower cost. For Trial 4, homes in Groups A and B underwent two-hour turn-up interventions at times when local surplus renewable generation (e.g. solar, wind) was likely to be available (1–3 pm). Interventions were conducted on Mondays, Wednesdays and Fridays during trial weeks with one intervention per day.

Dwellings were allocated to Group A and Group B so that the groups had a similar total daily whole home energy consumption. It was originally planned that Group A and Group B would be compared with each other as alternate intervention and control groups to eliminate weather variables. However, due to the differences in grid electricity import at peaks times between the groups when comparing their baseline weeks, a quantitative comparison between the groups was impractical.

To assess the flexibility of the system, turn-down interventions involved minimising grid electricity import by using battery discharge to meet household electricity demand and reducing heat pump use, subject to temperature comfort limits, as well as maximising grid export. During turn-up interventions, household electricity consumption was increased by using grid electricity import to charge the battery and increase heat pump use, subject to temperature comfort limits during interventions (up to ±2 ºC from each household's usual set-point schedule). Additionally, a temporary override was in place whereby households could alter the upstairs (non-flats) or downstairs temperatures, or boost the hot water system. Interventions were allocated as secure or dynamic. For **secure interventions**, advance notice allowed the control system to anticipate the intervention, e.g. the battery could be charged or discharged, or the heat pump used for pre-heating if required. **Dynamic**[3] **interventions** were applied with no prior notice given to the control system.

The external daily temperatures for each baseline/trial period is provided in Table 2.

A five days baseline approach was used. Baseline energy consumption was calculated as the average of the energy consumption for the appropriate two-hour time interval over the five baseline days (weekdays). Baseline weeks were adjacent to trial weeks, with the exception of Trial 1 which used the closest preceding week for comparison that avoided pre-trial test interventions. The method assumes that the average energy consumption and weather conditions, e.g. external temperature and solar generation, are similar between baseline and intervention weeks. For baseline weeks, home assets were controlled as per the usual operation on their default tariff, which was a flat (single) rate tariff for the majority of dwellings (15 out of 17).

DATA COLLECTION

This social-technical study combines quantitative time-series data streams and qualitative data from household telephone surveys.

Quantitative data

Data streams for the analysis were provided at five minute intervals by Passiv UK, sourced from the battery and ASHP. Internal temperatures were provided at five minute intervals by Secure HRT4-B thermostats. Outdoor temperatures were obtained from Emley Moor weather station at hourly intervals. There was one failed intervention signal for all of the six Group B dwellings during Trial 2B and the intervention was rescheduled as Intervention 22 on 5th May. Since the mean daily external temperature on 5th May was 4.7 °C, 2.8 °C lower than that for the Trial 2B 22–26th March baseline, the 22–26th March baseline was kept for this intervention. There was one failed control signal to one of the households which occurred for Intervention 2, and for another dwelling, all power data for Intervention 1 was missing. Both of these occurrences were taken into account for calculations of energy reduction per household.

Qualitative data

The external control of heat pump and battery operation during interventions had the potential to disrupt household routines and householders' comfort. A series of telephone surveys containing 12 questions (8 closed and 4 open), was conducted between 24th March and 12th May to determine how the various trials affected householders in terms of hot water availability, perception of indoor temperature, noise from the battery and heat pump, and the effect of the trials on household activities. Householders were also given the opportunity to voice any concerns about the trials. Surveys were conducted following Trial 2 (this covered both the Trial 1 and Trial 2 periods), Trial 3 and Trial 4. 14 out of 17 households (82 %) provided telephone survey responses on at least one occasion. There were 31 survey responses in total. For Group A and Group B, the same survey was conducted three times where possible, resulting in 17 repeated surveys across these dwellings.

QUANTITATIVE DATA ANALYSIS APPROACH

Aggregate data analysis was performed over the relevant groups of dwellings to determine the overall effect of the interventions on grid electricity import and controllable load, as well as on daily power profiles. Where per household energy values are quoted, these are calculated simply as a sum over all dwellings divided by the relevant number of dwellings. Some analysis at an individual dwelling level is provided for a deep dive illustration. Two methods are used for the quantification of the impact of DSR interventions, the change in grid electricity import and

2. https://data.nationalgrideso.com/carbon-intensity1/regional-carbon-intensity-forecast

3. Differs in meaning from a 'dynamic' time of use tariff which describes the variation in electricity price with the time of day and day to day. https://data.nationalgrideso.com/carbon-intensity1/regional-carbon-intensity-forecast

Table 1. Summary of DSR trials schedule.

Trial (Price signal + turn-up/down)	Group	Baseline period	Trial period	Intervention time
1 Default tariff + turn-down	A+B+C	22-26 February	12-19 March	6-8 am or 5-7 pm
2A Octopus Agile + turn-down	A	29 March-2 April	22-26 March	6-8 am or 5-7 pm
2B Octopus Agile + turn-down	B	22-26 March	29 March-2 April	6-8 am or 5-7 pm
3A Carbon optimisation + turn-down	A	12-16 April	5-9 April	5-7 pm
3B Carbon optimisation + turn-down	B	5-9 April	12-16 April	5-7 pm
4A Default tariff + turn-up	A	26-30 April	19-23 April	1-3 pm
4B Default tariff + turn-up	B	19-23 April	26-30 April	1-3 pm

the change in controllable load compared with the appropriate baseline. For turn-down interventions, grid electricity import reduction provides a measure of grid avoidance, but does not account for electricity exported from the battery to the grid when grid export is targeted. Controllable load is the combined effect of heat pump electricity consumption and battery energy. It captures the contribution of grid export when grid export is provided by battery discharging. The change in controllable load over a period of time, e.g. over a two-hour intervention period, is defined as the change in heat pump electricity consumption plus the net change in battery.

Table 2. External daily temperatures for each baseline/trial period.

	Daily external temperature °C		
Date range	Mean	Min	Max
22-26 February	7.3	4.3	11.4
12-19 March†	6.4	3.9	8.8
22-26 March	6.8	5.6	7.9
29 March-2 April	9.6	4.4	14.7
5-9 April	2.8	0.3	5.5
12-16 April	4.2	2.3	5.3
19-23 April	8.3	6.7	10.0
26-30 April	5.6	4.0	7.7

† *Weekdays only.*

Results

QUANTITATIVE DATA ANALYSIS

Cross dwelling analysis

Data analysis was performed on aggregate across each group of dwellings, and the mean change per household calculated for grid electricity import, heat pump electricity consumption and controllable load during each two-hour intervention compared with the appropriate baseline period (Table 3).

Across the turn-down trials, grid electricity import reduction for secure interventions ranged from 0.8–1.3 kWh between 6–8 am and 0.3–1.7 kWh between 5–7 pm, with the secure 5–7 pm interventions for Trial 3B (carbon optimisation) providing the greatest absolute reductions. However, the secure 5–7 pm intervention for Trial 3A (carbon optimisation) provided the smallest reduction in grid electricity import. No particular reason for this result was apparent, but it was not due to increased heat pump use since heat pump electricity consumption was reduced compared with the baseline. It was noted that the bulk of grid electricity import for the intervention occurred within the first 20 minutes. For turn-down dynamic interventions, the reduction in grid electricity import ranged from 0.1–0.9 kWh between 5–7 pm. For 6–8 am, a single dynamic intervention was conducted (Trial 1) for which the grid electricity import was reduced by 0.3 kWh.

The reduction in controllable load for secure interventions ranged from 3.7–4.3 kWh between 6–8 am and 2.9–4.3 kWh between 5-7 pm, with the secure 5–7 pm interventions for Trial 3B (carbon optimisation price signal, Group B) again providing the greatest absolute reduction. For turn-down dynamic interventions, the reduction in controllable load ranged from 0.3–3.5 kWh between 5-7 pm. For the single 6–8 am dynamic intervention, controllable load was reduced by 0.4 kWh.

On aggregate, heat pump electricity consumption was apparent during all interventions, supplied at least in part, by the battery. Across the three turn-down trials, heat pump electricity consumption was reduced during all secure interventions by 0.1–0.7 kWh compared with the baseline. For dynamic interventions, the change in heat pump electricity consumption ranged from increasing by 0.1 kWh to decreasing by 0.7 kWh.

Figure 1(a) provides the aggregate daily power profile for the Trial 1 baseline, averaged over the five baseline days, as an example of usual demand. There was a broad afternoon/evening peak for grid electricity import between 3–10 pm, and battery discharge made a small contribution to home consumption during the evening peak. Figure 1(b) illustrates a high impact secure intervention during Trial 1 (Intervention 1) whereby the battery was charged ahead of the 5–7 pm intervention with solar generated electricity as well as grid electricity. During the intervention, battery discharge enabled grid electricity import to be reduced, as well as enabling electricity export.

Secure interventions were generally more effective than dynamic interventions due to the higher level of available battery charge at the start of interventions. Figure 1(c) illustrates a dynamic intervention of moderate impact during Trial 2 (Intervention 7). Although the battery was charged against the Octopus Agile time of use price signal in the morning, it had discharged before midday. Due to a combination of solar generation and grid electricity import, the battery was partially

Table 3. Mean change in energy consumption per household (grid electricity import, heat pump electricity consumption and controllable load) compared with baseline for each intervention (from aggregate data).

Intervention	Trial/Price signal	Secure or Dynamic	Time	Number of households	Grid electricity import kWh	Heat pump electricity consumption kWh	Controllable load kWh
1	Trial 1, Turn-down/Default	S	5-7 pm	17	-1.3 *(-65%)*	-0.1	-2.9
2		D	5-7 pm	16	-0.1 *(-3%)*	0.0	-0.3
3		S	6-8 am	17	-1.0 *(-73%)*	-0.3	-3.7
4		D	6-8 am	17	-0.3 *(-21%)*	-0.1	-0.4
5	Trial 2A, Turn-down/ Octopus Agile	S	5-7 pm	6	-0.8 *(-80%)*	-0.1	-3.5
6		S	6-8 am	5	-1.3 *(-84%)*	-0.1	-3.8
7		D	5-7 pm	6	-0.9 *(-86%)*	0.1	-2.7
22†	Trial 2B, Turn-down/ Octopus Agile	S	5-7 pm	6	-0.8 *(-81%)*	-0.3	-3.7
8		S	6-8 am	6	-0.8 *(-73%)*	-0.4	-4.3
9		D	5-7 pm	6	-0.9 *(-55%)*	0.0	-1.7
10	Trial 3A, Turn-down, Carbon optimisation	D	5-7 pm	6	-0.8 *(-80%)*	-0.4	-3.5
11		S	5-7 pm	6	-0.3 *(-36%)*	-0.5	-3.9
12		D	5-7 pm	6	-0.6 *(-63%)*	-0.3	-2.2
13	Trial 3B, Turn-down, Carbon optimisation	S	5-7 pm	6	-1.7 *(-85%)*	-0.7	-4.3
14		D	5-7 pm	6	-0.9 *(-44%)*	-0.7	-2.3
15		S	5-7 pm	6	-1.6 *(-76%)*	-0.6	-4.3
16	Trial 4A, Turn-up/Default	D	1-3 pm	6	-0.2 *(-13%)*	-0.3	1.7
17		S	1-3 pm	6	2.2 *(126%)*	-0.3	1.6
18		D	1-3 pm	6	-0.3 *(-15%)*	-0.2	1.4
19	Trial 4B, Turn-up/Default	S	1-3 pm	6	1.6 *(329%)*	0.1	2.5
20		D	1-3 pm	6	3.6 *(718%)*	0.3	2.6
21		S	1-3 pm	6	3.0 *(603%)*	0.3	2.2

†*Rescheduled intervention due to failed control signal to all dwellings.*

charged at the start of the 5–7 pm intervention which allowed subsequent battery discharge to contribute to home consumption as well as enabling grid export.

Figure 1(d) illustrates a turn-up intervention during Trial 4 (Intervention 19) where the battery was charged with solar generated electricity as well as grid electricity import. The amount of solar generation prior to, and throughout a turn-up intervention affected the amount of grid electricity import that could be used to charge the battery during the intervention.

Individual dwelling analysis

Figure 2(a) provides the daily power profile for the Trial 1 secure intervention between 5–7 pm (Intervention 1) for an individual dwelling, on a flat (single) rate tariff and with high daily household consumption (daily mean consumption was 36 kWh for November 2020–January 2021). The dwelling was a semi-detached house with five occupants. The battery was partially charged at the start of the intervention (battery energy level 52 %), probably due to high household consumption immediately prior to the intervention, and the battery had discharged by 5:45 pm since household consumption was too high for the battery to fully satisfy demand throughout the intervention. There was no grid export, and the heat pump was used throughout the intervention. Compared with the baseline, the reduction in grid electricity import was 0.8 kWh and the reduction in controllable load was 1.3 kWh.

Figure 2(b) provides the daily power profile for the Trial 2 secure intervention between 5–7 pm (Intervention 5) for an individual dwelling with low daily household consumption (daily mean consumption was 14 kWh for November 2020–January 2021). The dwelling was a ground floor flat with a single occupant. The battery was fully charged prior to the start of the

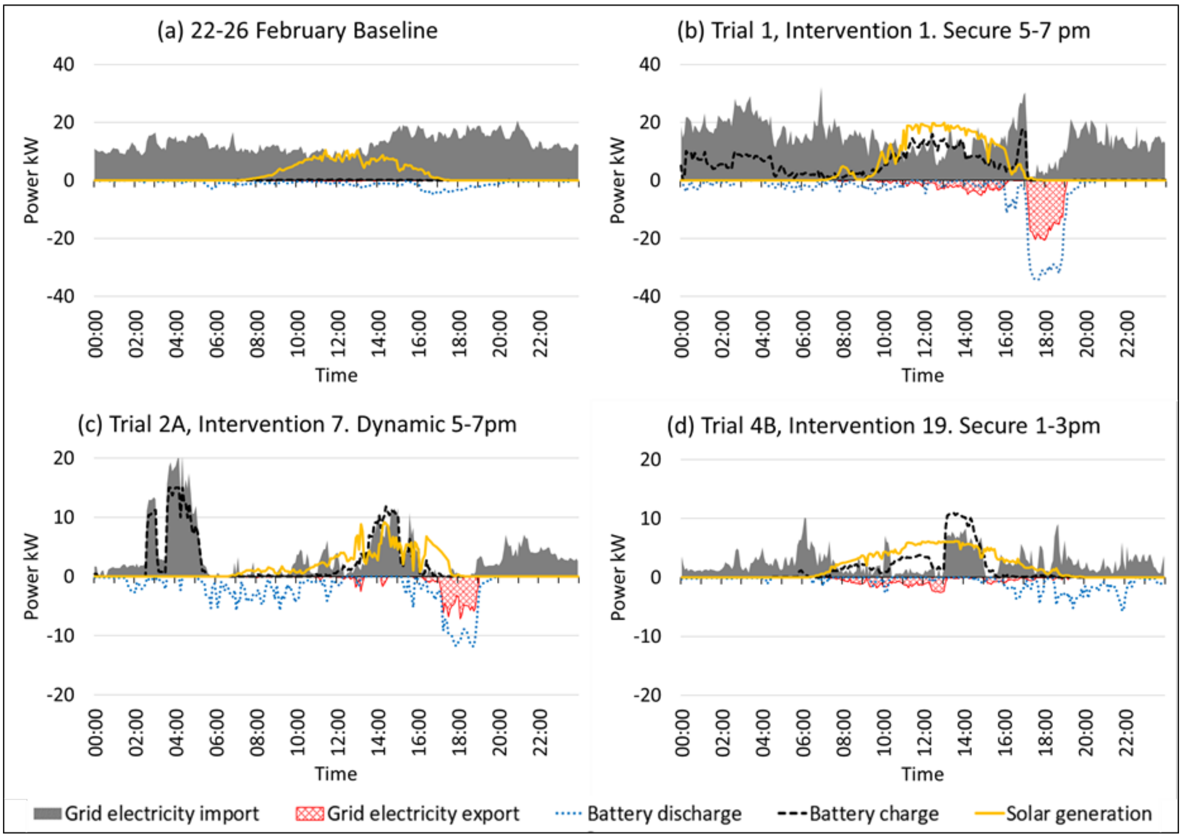

Figure 1. Aggregate daily power profiles for example interventions (a) February 22–26 baseline, (b) Intervention 1 – Turn-down and default price signal, (c) Intervention 7 – Turn-down and Octopus Agile price signal (d) Intervention 19 – Turn-up and default price signal.

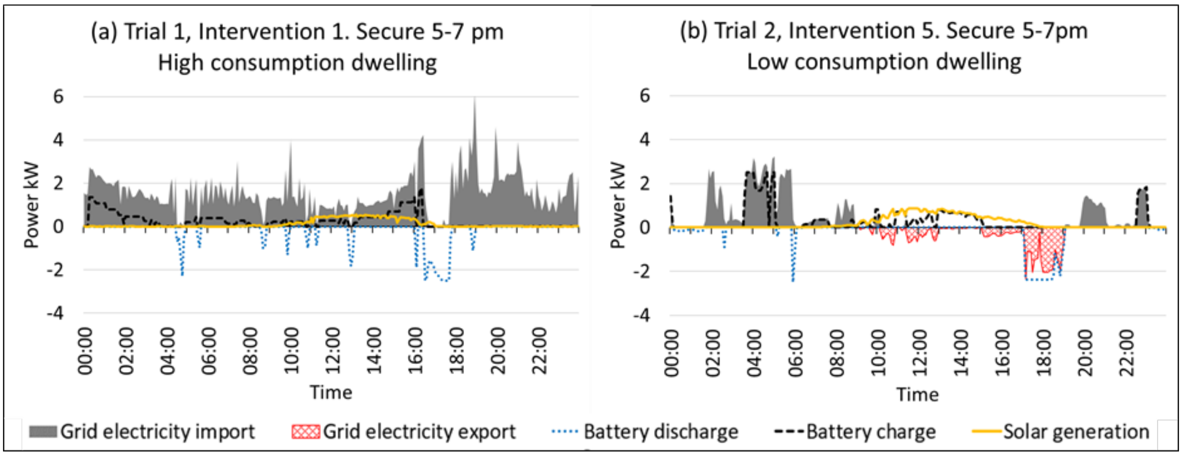

Figure 2. Individual dwelling daily power profiles for example interventions (a) Intervention 1 – Turn-down and default price signal for a high consumption dwelling (b) Intervention 5 – Turn-down and Octopus Agile price signal for a low consumption dwelling.

intervention by a combination of solar generated electricity and overnight grid electricity import against the time of use tariff. There was no grid electricity import or heat pump electricity consumption during the intervention and there was export to the grid as the battery discharged. Although the reduction in controllable load compared with the baseline was 4.0 kWh, the reduction in grid electricity import was only 0.1 kWh. Baseline grid electricity import between 5–7 pm for this dwelling was low, at 0.1 kWh and hence the potential for reduction of grid electricity import was limited.

RESIDENT EXPERIENCE

The telephone survey gained household insight concerning specific trial aspects, namely hot water availability, perception of internal temperature, noise disturbance and whether daily activities were affected by the trial, as well as the overall acceptability of the trials and general feedback. Across the trials, hot water was always or often available in 11 out of the 14 responding households, and sometimes available in two households, one of which commented that 'this was unusual' For the remaining household, hot water was rarely used as the householder preferred to use a kettle for washing up to obtain a higher water temperature. Hot water for showering was not affected since homes were equipped with electric showers.

About 58 % respondents (of 31 responses) indicated that the indoor temperature felt the same as usual across the trials. Table 4 provides a breakdown of the perception of indoor temperature across the trials. There was no particular pattern between households as to when the indoor temperature felt different from usual. The six responses across the trials where householders felt the indoor temperature was much colder than usual came from four households, three of which reported general issues with temperatures being too cold. For the remaining household, measured temperatures were not colder than usual at intervention times. For the three households which felt much warmer than usual, only for one dwelling could an increase in measured household temperature be linked with an intervention - there was a sharp rise in the downstairs temperature ahead of Intervention 1, suggesting pre-heating. For the turn-up trial, Trial 4, there were no reports of the indoor temperature feeling warmer than usual.

In response to 'Did you take any actions to change the household temperature?', 58 % (of 31 responses) stated that no action was taken and 39 % stated that the heating control app was used to change the temperature. However, for many households, changing the app was normal with changes in weather conditions and not necessarily due to the interventions.

Across all trials, four households were sometimes disturbed by noise from the battery and three households were sometimes disturbed by the heat pump. However, no household reported this as being a particular concern. In response to the question 'How were your daily household activities affected by the trial?', no households reported daily activities being affected by the trial itself.

For 77 % (of 31 responses) the trials were deemed acceptable, slightly acceptable, or 'neutral', for which a breakdown is provided in Table 5. Acceptability of the intervention-related changes was high, even amongst households who reported some lack of hot water availability, changes in temperature or noise disturbance. For 23 % (of 31 responses) the trial changes were deemed unacceptable, however, it is important to note that these responses were from the three households affected by ongoing issues concerning low indoor temperatures and it was this that was the overriding factor for the 'unacceptable' survey response.

In response to 'Do you have any concerns about the (DSR) trial?', only one household had a trial specific concern, that hot water was not always available. Nine householders reported general, ongoing concerns, not necessarily related to the trial weeks. Six comments related to electricity costs and one comment related to the hot water not being hot enough. A further six comments related to the indoor temperature; four households had concerns of this being too cold, with two of these having problems regulating the temperature using the heating control app, one household was too warm, and another was too cold in winter and too hot in summer. For the homes with temperature concerns, the control system was found to be delivering the requested temperatures and it was suspected that more guidance for users with respect to using their app to explicitly state their comfort requirements was needed. Of the households with no general concerns, one household commented that the system was 'spot on'

Table 4. Householder's perception of temperature during the trials.

Perception of internal temperature	Trials 1 & 2 responses	Trial 3 responses	Trial 4 responses	Total responses (out of 31)
Much warmer than usual	3	0	0	3 (10%)
Slightly warmer than usual	0	3	0	3 (10%)
The same as usual	6	6	6	18 (58%)
Slightly colder than usual	1	0	0	1 (3%)
Much colder than usual	3	1	2	6 (19%)
Total respondents per trial	13	10	8	31

Table 5. Householder's acceptability of trial changes during trials.

Acceptability of trial changes	Trials 1 & 2 responses	Trial 3 responses	Trial 4 responses	Total responses (out of 31)
Unacceptable	2	1	2	5 (16%)
Slightly unacceptable	1	1	0	2 (6%)
Neutral	2	0	1	3 (10%)
Slightly acceptable	2	2	0	4 (13%)
Acceptable	6	6	5	17 (55%)
Total respondents per trial	13	10	8	31

Discussion

All turn-down interventions demonstrated a reduction in grid import electricity, however this reduction could be small for dynamic interventions. An adequately charged battery ahead of an dynamic intervention is not guaranteed, being dependent on solar generation and the timing of low price grid electricity with a time of use tariff. For turn-down interventions, grid electricity import was minimised and grid export was maximised where possible, which provided an indication of the flexible load attainable with full utilisation of the battery. However, for implementation of such interventions it is assumed that financial incentives for the reduction of grid import and for export to the grid would be in place. Without targeted grid export, the battery could help to satisfy home demand post-peak. Turn-up interventions depended upon solar generation since this affected the amount of energy stored in the battery at the start of an intervention and thus the amount the battery could be charged from the grid. For Group A, with low solar generation for the baseline compared with the intervention week, it could be difficult to show an comparative increase in grid electricity import during interventions on sunny days. Additionally, for Group A, the daily mean temperature for the turn-up trial week was 2.7 °C warmer than for the baseline and there was a reduction in heat pump consumption for each intervention rather than increased use. For individual dwellings under conditions of high solar generation and low home energy consumption, it was possible for zero grid electricity to be imported during a turn-up intervention.

Battery discharge was the main contributor to changes in controllable load for both turn-down and turn-up interventions, with heat pump electricity consumption playing a much lesser role, reflecting the relative capability of the two assets. For secure turn-down interventions, the average heat pump reduction was 0.3 kWh out of an average reduction in controllable load of 3.8 kWh. For the secure turn-up interventions of Trial 4B, the average heat pump increase was 0.2 kWh out of an average increase in controllable load of 2.1 kWh. A deep dive into the behaviour of individual dwellings highlighted how DSR interventions can be affected by particular home consumption under certain conditions, with variability in the reduction of both grid electricity import and controllable load. High consumption can affect the amount of battery charge available immediately prior to an intervention and the battery may fully discharge before the end of the intervention. For a dwelling with normally low daily consumption, an intervention may be high impact in terms of controllable load due to discharging of a fully charged battery supplying home demand and export to the grid, but low impact in terms of grid electricity import reduction since grid import at this time is usually low. This illustrates that employment of both types of DSR measurement is useful. It also highlights that the same DSR approach can result in variability of results for different households and this needs to be considered with the implementation of a DSR scheme.

DSR changes were broadly acceptable to householders. Even during the Trial 4 turn-up, householders did not feel that indoor temperatures were any warmer than usual, as might have been expected. The three households which considered the trials as unacceptable or slightly unacceptable had general issues with indoor temperatures, not deemed as specifically related to the trial changes. The conditions under which this general acceptance was reported were well insulated homes, and operation of the heating system being subject to thermal comfort limits as well as a temporary override by householders. Heat pump operation could also be enabled by battery discharge where the battery energy level was sufficient. The household survey was useful in identifying any general issues with the systems, e.g. issues with using the heating control app. The majority of householders' concerns were general to the project and not specific to the trials. Although electricity costs were a concern across six dwellings with similar characteristics and a range of occupancy, for two householders, this was due to bills not going down as expected following the installation of heat pump and battery assets, rather than an increase in costs. For some householders, the expectation of the heating system performance itself played a part in their experience, since with heat pumps there was a slower warm-up time than with householders' previous gas systems. Additionally, some householders reported that the hot water temperature was cooler than for previous systems; the need for householder information on how the operation of a new system could differ from that expected has been highlighted by Sweetnam et al. (Sweetnam et al., 2019). For future projects with homes that are less well thermally insulated, this effect could be more pronounced if it were not considered along with householder understanding. Additionally, it is recommended that DSR interventions are conducted after a period of routine operation of new household assets to allow any system issues to be addressed which could otherwise negatively affect the perception of DSR. Training on the operation and control of new heating systems along with app operation is essential with ongoing support.

A limitation of the trial was the lack of repeated interventions with the same variables, e.g. time, type (secure/dynamic), trial, and group. Additionally, although the baseline periods were close to their respective trial periods so that home consumption patterns would be similar, the baseline method did not directly take account of the variation of weather, e.g. external and solar radiation.

Conclusions

Domestic electricity, which accounted for 38 % of UK electricity consumption in 2020 (Dukes, 2021), is a largely untapped source of DSR. DSR is an important instrument for the planned decarbonisation of the UK grid and the integration of renewables. The successful uptake of domestic DSR requires enabling technology, the removal of barriers to participation and householder acceptance. Automation of DSR can offer a relatively large energy response compared with manual involvement, and a longer term household engagement. DSR for both turn-down and turn-up interventions was demonstrated during the heating season for 17 dwellings equipped with a combination of assets regarded as key technologies for domestic DSR and the decarbonisation of domestic electricity, namely electric heat pumps, home batteries and solar PV panels along with third party automated control. There was little resistance to the DSR trials themselves, and acceptability of changes relating to interventions was high even among households who perceived temperature changes or who were disturbed by noise. This is promising for the acceptability of DSR interventions, however, with a larger sample size, a longer trial period at a different time of year, changes may be more noticeable. For this study, the automation of asset control was integral to the turn-down and turn-up responses attained. Given the general acceptability of the trials by householders, importantly under the conditions of thermal comfort limits and manual override, automation appears a promising way forward where these conditions are implemented.

A positive experience of new technologies, such as batteries and heat pumps along with their control, be it driven by household or third party, will be vital to a favourable reception for domestic DSR. A continued focus on the householder experience with individual support and training is necessary along with allowing for the 'settling in' of new equipment and the resolution of any initial issues. Homes with differing levels or patterns of consumption can show different levels of demand response, and DSR schemes should consider the response capabilities and requirements for individual households. Widespread uptake of domestic DSR will also rely upon the planned government support structures for both flexibility providers and consumers being in place.

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Acknowledgements

This work was carried out as part of the research project *Bringing Renewable Energy Automation to Homes Everywhere* entitled BREATHE, which was funded by the Department for Business & Industry *BEIS Innovative Domestic Demand-Side Response Competition*. We are grateful to other members of the BREATHE project, especially Energise Barnsley, Passiv UK and Barnsley Metropolitan Borough Council. Thanks are also due to the householders of the study for all their time and cooperation.