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Evaluation of residential demand response trials with smart heat pumps and batteries and their effect at the substation feeder

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ABSTRACT

Residential demand response using low carbon technologies can potentially offer energy flexibility to the electricity network along with integration of renewable generation. This paper seeks to empirically evaluate the effectiveness of residential demand response trials on a low voltage feeder of a secondary substation in Barnsley (UK). The study used a sample of 14 well-insulated dwellings equipped with home batteries, heat pumps and solar photovoltaic systems coordinated using automated control. Statistical analysis was undertaken using time-series monitoring data obtained at the individual dwelling level, dwelling sample and at the feeder level of the local low voltage network. Resident experience of the trials was assessed through qualitative data obtained from household telephone surveys. Over three weeks of trials, daily demand response interventions of 2 h duration were applied to the sample of 14 dwellings. For evening peak times, the mean reduction in grid electricity import was found to be 1.3 kWh (67%) per dwelling for turn-down interventions which aimed to minimise import. For turn-up interventions between 1 and 3 pm, the mean increase in grid electricity import was found to be 5.8 kWh (645%) per dwelling. The effect of interventions was measured at the low voltage network level for two single-phase feeders, where penetration of trial homes was approximately one-third. A reduction in mean real power up to 21% was observed for turn-down interventions as well as an increase in real mean power up to 307% for turn-up interventions. In general, the trials had little effect on residents in terms of thermal comfort, hot water availability, noise disturbance or disruption to routines, and where such effects were noticed, they were broadly acceptable. The widespread implementation of residential demand response schemes will require increased roll-out of time-of-use tariffs, enhanced resident support and extensive monitoring of low voltage feeders in electricity substations.

1. Introduction

Driven by net zero commitments, the route to decarbonise the UK's energy supply requires rapid growth in electrification across the heat, transport and power sectors in conjunction with increasing renewable electricity generation (Committee on Climate Change, 2020), (BEIS, 2020). A smart and flexible electricity system is required to incorporate low carbon energy with high levels of variable renewables generation, and this will utilise the flexibility of consumer demand and smart technologies, such as energy storage and flexible heating systems, smart appliances, and smart tariffs based on real time electricity pricing (BEIS, 2021a). The UK government aims to support the developing flexibility market by the continued rollout of domestic smart meters, which are required to enable participation in smart tariffs, and by reforms to consumer protection and regulatory frameworks (BEIS, 2021a). A key aspect of flexibility is demand response (DR), whereby the energy demand of end users can be shifted in time away from peak busy times and towards periods of high renewables availability, thus allowing the integration of variable renewables generation and smoothing of peaks and troughs in demand.

Domestic energy consumption currently accounts for 32% of the UK's energy consumption, with 66% of consumption from natural gas compared with 24% from electricity (Digest of UK Energy Statistics (DUKES 1.1.5), 2021), and the route to net zero carbon emissions by 2050 will require decarbonisation of the residential sector. The deployment of domestic low carbon technologies (LCTs), i.e. solar photovoltaics (PV), heat pumps, electric vehicles (EVs) and home battery storage, features in all four future energy scenarios outlined by National Grid ESO (Future Energy Scenarios National Grid, 2021). The 'Consumer Transformation' scenario in particular requires higher levels

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of consumer engagement, including smart control of electricity demand. Plans for the electrification of heat in the UK are targeting 600,000 heat pump installations by 2028 (HM Government, 2020). The combination of electrification, LCTs and smart control presents opportunities for residential DR. Residential DR is realised by the time-shifting of household electricity consumption, either by reducing grid demand (turn-down) or by absorbing energy from the grid at times when renewable generation is high (turn-up). This may be achieved through shifting appliance consumption, shifting space and hot water heating, or by charging and discharging home batteries for the storing and subsequent release of energy. DR can be manually controlled by residents, or automatically controlled, including third party or direct load control, with automation offering a real-time response to dynamic pricing and network requirements. Residential DR may be driven by a static time of use (TOU) tariff with fixed prices for peak and off-peak periods, or by a dynamic TOU tariff which changes in real-time. Other financial rewards may be given for offering flexibility, e.g. for turn-up flexibility or for individual interventions, such as critical peak events. The rollout of low carbon solutions will require a positive consumer acceptance along with market demand (HM Government, 2021).

The electricity grid will need to accommodate increasing numbers of residential LCTs as well as larger scale renewables generation, and this presents technical challenges, such as voltage and reactive power control, network resilience and protection, and active power balancing (Levi et al., 2020a). Smart network solutions, including DR and active network management, will allow reinforcements of networks to be deferred, particularly where the rate of deployment of LCTs on the network is unknown (Levi et al., 2020b). At the low voltage (LV) end of the network, where homes are connected to the grid, consideration has been given to modelling of the integration of LCTs (Reinders et al., 2017), and to energy management and forecasting in microgrids (Zahraoui et al., 2021; Aybar-Mejía et al., 2021). However, there is a lack of physical monitoring at the LV network level (Rafi et al., 2019), and monitoring in combination with DR intervention lacks a clear observed response, a gap which the current study addresses by providing experimental measurement of turn-down and turn-up responses at the dwelling and LV network levels. This work presents a series of three residential DR trials where homes were equipped with LCTs under smart control - a home battery, air source heat pump (ASHP) and solar PV.

1) An asset-based trial turn-down where it was planned that the battery would effectively cover heat pump demand.
2) A turn-up trial where battery and heat pump absorbed energy from the grid.
3) A turn-down trial which aimed to minimise grid electricity import.

This study aims to.

- Evaluate the effectiveness of residential DR turn-up and turn-down interventions in terms of grid electricity import and controllable load
- Determine the impact of the DR trials at the low voltage feeder of the secondary substation
- Explore the resident experience of the trials

2. Literature review

The scope of residential DR encompasses the variability of household demand, the control of heating, devices and LCT assets, along with weather forecasting and pricing schemes, including dynamic pricing. Predicting a demand response is therefore complex, and there is a wealth of scientific literature relating to the forecasting, simulation and modelling of DR scenarios. A review of optimisation techniques, which focus on optimising cost and energy benefits for the consumer and supplier, is provided in Panda et al. (2022), and a review of artificial intelligence (AI) techniques within the scientific literature, and as applied by commercial organisations and by DR projects, is provided in Antonopoulos et al. (2020). Smart meter data has been used to categorise and model customer types and behaviour (Wen et al., 2018; Haben et al., 2016; Le Ray et al., 2018). Cluster analysis was performed using smart meter data and attributes for 3622 households in Ireland as a categorisation method which could inform models of household demand (Haben et al., 2016), as well as for over 1900 households in Denmark equipped with heat pumps with automated control as part of the EcoGrid project, where two-tier pricing schemes were trialled to distinguish between price responsive and non-price responsive households (Le Ray et al., 2018). Smart meter consumption data for 1500 households on a dynamic TOU tariff in Austria was used to predict a 4–7% reduction in the country's energy system costs with the use of DR (McKenna et al., 2021). DR driven by price signals can lead to additional peaks in consumption, and the dual optimisation of customer energy costs and usage requirements along with smoothing of the demand profile for the energy supplier was modelled in Almeida et al. (2021). The optimisation of the integration of solar generation in future housing developments using a range of existing and future tariffs for homes possessing solar PV, EV and home battery assets was considered in Gil et al. (2021).

A body of measured residential DR performance is emerging within the scientific literature, and also from grey literature, which includes project reports. The evidence presented here relates to empirical results, in particular, large scale trials (Whitaker et al., 2013; CrowdFlex Phase 1 Report, 2021; Schofield et al., 2014; Langham et al., 2014), trials where homes have LCT assets (Western Power Distribution and Regen, 2017; Gupta and Morey, 2022; Boait et al., 2019; Christensen and Friis, 2017; Gupta et al., 2019; Response, 2022; NEDO Implementation Report for Smart, 2017; Zhao et al., 2015), and trials where there is a particular focus on residential DR at the LV network level (NEDO Implementation Report for Smart, 2017; Zhao et al., 2015; Torriti, 2012). Relevant trials are outlined in Table 1 along with the mechanism by which the response was achieved – either by occupant control of appliances in response to intervention requests or against a TOU tariff, whether manually, with some degree of automation, or by fully automated control, including direct load control by a third party. Trials with a focus on occupant driven, appliance-based DR have shown a measured reduction in peak consumption of between 1% and 11% against ongoing TOU tariffs (Whitaker et al., 2013; CrowdFlex Phase 1 Report, 2021; Schofield et al., 2014). With automated control, a turn-up response of 13% was demonstrated in Western Power Distribution and Regen (2017) against an ongoing TOU tariff compared with 5% for manual control. For two individual UK-wide events of 2 h duration undertaken within the Crowdflex project, homes without LCTs were able to demonstrate a turn-down response of 60% and a turn-up response of 131%, although this level of response may not be sustainable on a daily basis if household consumption was pushed into, or pulled from, other days (CrowdFlex Phase 1 Report, 2021). As concerns the use of LCTs in residential DR, heat pump electricity consumption has been automatically shifted to increase solar self-consumption (Response, 2022; Somer et al., 2017), and home battery storage has been used in combination with solar PV to reduce consumption of grid electricity at peak times (Boait et al., 2019; Christensen and Friis, 2017; Gupta et al., 2019; Response, 2022; Zhao et al., 2015). Coordinated control of home battery and heat pump assets for homes also equipped with solar PV has demonstrated reduction in demand at peak times along with export to the grid, and additionally, absorption of grid electricity during turn-up interventions (Gupta and Morey, 2022).

Although the role of EVs in residential DR is not the focus of this review, the relative size of the EV battery affords a sizeable demand response (Wang et al., 2018). In a standalone turn-up event of 2 h duration, households already on a smart tariff increased their consumption by an average of 11.6 kWh and this was attributed to the use of 7 kW EV chargers (CrowdFlex Phase 1 Report, 2021). Smart control of EV battery charging has been demonstrated within Project Shift (Project Shift Summary Report, 2021) and the FRED project (FRED

Table 1
Relevant trials with empirical results - large scale TOU trials, trials where homes have LCT assets, and trials where there is a particular focus on DR at the LV network level.

Ref	Location/trial period	Number in trial	How DR was achieved	Outcome
Whitaker et al. (2013)	Northern England Oct 2012–Sept 2013	574 test 8415 control	Static TOU. Occupant driven appliance shifting.	1.5%–11.3% reduction in consumption during 4–8 pm
CrowdFlex Phase 1 Report (2021)	UK-wide 6 months within 2020	544	Ongoing dynamic TOU. Occupant driven appliance shifting. No LCT.	Reduced peak loads (4–7 pm) by 0.23 kWh (7%)
CrowdFlex Phase 1 Report (2021)	UK-wide 5 Nov & 25 May 2020	363 turn-down 17,653 turn-up	Financial reward for turn-down, low rate for turn-up. Occupant driven in response to planned events. No LCT.	Turn-down: Reduced peak loads (4:30–6:30 pm) by 0.9 kWh (60%) Turn-up: Increased loads (5–7 am or 2–4 pm) by 2.0 kWh (131%)
Schofield et al. (2014)	London, UK Jan–Dec 2013	1200	3-tier TOU tariff. Appliance shifting.	Reduction in bills over 1 yr for 75% of participants. 5–10% reduction in peak for constraint management events
Langham et al. (2014)	Australia	7000	13 peak rebate events 4–6 h, pricing incentives and/or consumption feedback. Appliance shifting.	Reduction of 0.16 kWh/h
Western Power Distribution and Regen (2017)	Cornwall, UK Apr–Sept 2016	46	Static TOU tariff, reward between 10 am and 4 pm (turn-up). Automated timer for hot water, remote-control switches for appliances. 34% of homes had solar PV.	Percentage of daily consumption occurring between 10 am and 4 pm 13% (automated), 5% (manual).
Gupta and Morey (2022)	Barnsley, UK Mar–May 2017	17	Solar PV 1.3–3.0 kWp. Direct load control of 5 kWh batteries & heat pumps. 22 interventions, single rate & dynamic TOU tariffs.	Turn-down: Up to 1.7 kWh/household (5–7 pm) (85%). Turn-up: Up to 3.6 kWh/household (1–3 pm) (85%).
Boait et al. (2019)	Oxfordshire, UK Dec 2015–2016	48 total 8 with battery	Incentives based on four-tier static TOU tariff. Automated control of 2 kWh battery.	20% reduction in evening peak (6–9 pm) for 8 homes with battery.
Christensen and Friis (2017)	Fur, Denmark. Aug 2015–May 2016.	33 total 5 with battery & solar PV	Intelligent energy storage control unit. 4.5 kWh battery charged from 6 kWp solar PV.	Loads reduced by 35–70% for 1.5–2 h within 5–7 pm. Affected by seasonality.
Gupta et al. (2019)	Oxford, UK Sept 2016–Aug 2017	74	2 kWh batteries charged by solar PV. Smart control of charge/discharge of excess PV generation.	8% reduction (5–7 pm peak) during heating season from battery discharge.
Response (2022)	London, UK Nov 2020–Feb 2022	23 batteries & solar PV, 13 smart control of heating/hot water	4.8 kWh battery. Solar PV 1–4 kWp Economy 7 tariff for electric heating.	Cost savings from business modelling against flat, dynamic ToU and export tariffs based on monitored household consumption.
NEDO Implementation Report for Smart (2017)	Manchester, UK Nov 2016–Mar 2017	550 (4–550 underwent opt-out DR events)	Hybrid and electric heat pumps under direct load control. Turn-down: Within 6:30–8 am and 5–6:30 pm (Average 1 h). Turn-up: 1–2 pm or 3–4 pm.	Turn-down: Aggregate 50–320 kW. Turn-up: Maximum aggregate 438 kW.
Zhao et al. (2015)	Bristol, UK Aug 2014–Mar 2015	11	Energy management system. Battery bank (4.8 kWh) charged from solar PV (1.5–2.0 kWp) & grid.	Batteries exported 20–40% of their capacity to support evening peak demand (4:30–10 pm). Surplus solar generation exported to grid.
Torriti (2012)	Trento, Italy Jul 2010–Jun 2011	1446	Occupant driven appliance shifting. Two tier tariff. Low: 8 am-7 pm. High: 7 p.m.-8 am.	Morning peaks shifted, evening peak demand increased for 31 out of 41 substations.

Flexibly-Responsive Energy Delivery, 2021). The coordinated control of four LCT assets with the potential for DR application has been demonstrated for five UK trial homes, each with a hybrid heating system comprised of an electric heat pump with fossil fuel boiler, home battery, solar PV and an EV (Multi Asset Demand Execution, 2021). The ability to provide flexible power whereby battery discharge could supply heat pump operation and electricity could be exported to the grid was also demonstrated. The DNO (Distribution Network Operator) Western Power Distribution, have published a roadmap for the commercial deployment of their Sustain-H domestic flexibility service, following a trial of 310 dwellings equipped with LCTs (Sustain-H Product Roadmap). The service will use behavioural change from households with at least one ‘high impact’ LCT asset (electric heat pump, home battery, EV) rather than direct load control, to capture a planned twice-daily demand response during peak times from those households where direct load control is not currently available or not desired.

As regards trials with a specific focus on the LV network, smart meter data from 1446 homes in the Trento province, Italy, provided a measure of electricity demand across 41 substations before and after a change to a two-tier TOU tariff (Torriti, 2012). Although householders saved money on the tariff from behavioural shifting of electricity consumption (2.2% over one year), and morning peak loads at the substations were shifted, electricity demand at evening peak times increased for 31 substations. It was suggested that this was in part due to some electricity use being unchangeable in nature. Monitoring of the LV network was deployed within the Sola Bristol project to assess the effect of LCTs on the distribution network. Total changes in demand of 2–4 kW due to battery charging for eight homes on the same feeder equipped with solar PV and home batteries could not be clearly observed from feeder monitoring results (Zhao et al., 2015). This was attributed to the low penetration of trial homes on the feeder, 8 out of a total of 121, and to the variance in demand at the feeder level. At the community level, an ongoing trial in the Netherlands consists of 47 homes connected to the same low voltage/medium voltage (LV/MV) transformer (Reijnders et al., 2020). While some homes have solar PV panels and/or 5 kWh batteries, the remaining homes have no LCT. From smart meter data, households receive feedback on their energy consumption via a mobile app, and this, along with price forecasting, allows them to move consumption to cheaper periods corresponding to times of low network demand. Modelling of 24 batteries showed that energy consumption peaks for this community network can be reduced by 36%. The Customer-Led Network Revolution (CLNR) trial deployed monitoring at the LV feeder level to investigate the effect of heat pumps and solar PV on power quality (Bower et al., 2015). Additionally, the power consumption profiles for ASHPs in eight CLNR dwellings during 14 turn-down interventions at peak times were used to determine that 20% additional electric heat pumps could be accommodated at the network level, accounting for the increased use of heat pumps post-intervention (Jiang et al., 2015). Within the UPGRID project, the ability for the Distribution System Operator (DSO) to control the loads of 50 households during periods of LV network constraints via a home energy management system (HEMS) combined with smart plugs was demonstrated, with power consumption reduced by 18% per household (UPGRID WP4, 2015). To accommodate lower-income groups who may not otherwise benefit from flexibility services, a communal battery (20 kWh) and 37 kWp solar PV array serving a block of flats in London was trialled in conjunction with peer to peer (P2P) services, along with 18 standalone flexibility events whereby the battery was charged with excess PV and discharged only during certain time windows (Urban Energy Club NIA Project report, 2022). Over a year, the four participating households experienced an average reduction in electricity costs of 19.5%. The project also identified other buildings with multiple apartments suitable for the deployment of similar solar PV and battery systems located near to LV substations seeking flexibility services.

Resident engagement is crucial to the success of DR (Davarzani et al., 2021). A systematic review of the requirements and barriers for consumer engagement with residential DR is provided in (Parrish et al., 2020). Aside from financial benefits, familiarity and trust, perceived risk, perceived control, the complexity and effort of participation, and the effect of DR on household routines are all factors which affect enrolment and engagement, as well as lack of awareness about the advantages of DR programmes and inexperience in the use of new technologies (Davarzani et al., 2021; Parrish et al., 2020; BEIS, 2017). The behavioural changes associated with manual shifting require incentivising, ongoing motivation and learning (Kessels et al., 2016), and although automated control may aid engagement compared with manual shifting of consumption, there will still be a certain amount of disruption to the household (Goulden et al., 2018). Householders will require continuous support in the operation of any new technology and systems (Kessels et al., 2016), along with the skills and knowledge to integrate DR into their routines (Christensen et al., 2020). Householders' trust of third parties as concerns transparency for pricing and swift resolution of technology issues is also essential (Parrish et al., 2020). There may be disparity between households as regards the benefits of joining a particular DR scheme. An international review on the residential demand response to pricing found that as household income increased, the size of the response decreased, and that households with major appliances, including heating and air conditioning, were able to provide a greater response (Yan et al., 2018).

The Smart Community Demonstration project evaluated the electricity consumption behaviour of 550 heat pumps installed in social housing across Greater Manchester, providing measured turn-down and turn-up responses under direct load control during the heating season (NEDO Implementation Report for Smart, 2017). A challenge of the project was the maintenance of internet connectivity across a large number of properties. Drawing on the trial, it was found that benefits were more likely in homes where the heating system was constantly on, where householders understood how the heating system worked, including differences from their previous systems, and where there was daytime occupancy (Calver et al., 2022). There was a lack of understanding of how the heat pump worked along with a lack of awareness about direct load control, and there was doubt as to whether the householders could give their informed consent if individual circumstances and practices were not considered in order to determine whether householders would benefit from the system. It was concluded that householders receive tailored energy system advice and that consent standards around DR direct load control require discussion. To encourage engagement in DR, the promotion of smart meters, smart tariffs, storage and automation technologies as a 'DR technology cluster', has been suggested, along with digital comparison tools (DCTs) to inform consumers (Carmichael et al., 2021).

Interest in the practical application of LCTs for residential DR is growing, although trials to date have generally been on a smaller scale than those involving occupant driven shifting of appliances. Turn-up trials, which offer integration of renewables, are not as prevalent as turn-down trials, which aim to reduce consumption at peak times. Although the LV end of the distribution network is the interface between the residential consumer and the electricity grid, and the first point of aggregation of any DR effect at the network level, it has had less attention as regards measurement of the DR response. Resident engagement with the systems and technology supporting DR is key as well as the resident experience of DR interventions themselves. The current study addresses the gap of empirical DR results at the LV network achieved by automated control of domestic LCTs. Results for both turn-down and turn-up interventions are presented, and physical measurement is supported by an evaluation of the resident experience.

3. Methodology

3.1. Research methods and case study dwellings

The research methods had two main areas of focus (Fig. 1).

1) The analysis of time-series monitoring data obtained at the individual dwelling level and at the substation feeder of the local LV network. Data analysis was performed at the aggregate dwelling, individual dwelling and LV feeder levels.
2) The evaluation of the resident experience through qualitative data obtained from household telephone surveys.

The 14 case study dwellings were well insulated, new-build social housing properties within the UK Government funded BREATHE (Bringing Renewable Energy Automation To Homes Everywhere) project on domestic DR. This study describes the second round of DR trials applied to project homes, an earlier round of pilot trials having taken place in spring 2021 (Gupta and Morey, 2022). All dwellings had an Energy Performance Certificate (EPC) rating of B or above. Each dwelling contained a 5 kWh Sonnen battery, a 5 kW Mitsubishi Eco Dan dual purpose ASHP, a Passiv UK PassivLiving Hub smart control system and a solar PV array (1.3–3.0 kWp). All except three of the dwellings were semi-detached two-storey houses, there was a single detached house and two flats. One home was on an Octopus Go[1] TOU tariff, the remainder were on a flat (single) rate tariff. Nine out of the fourteen trial dwellings were connected to the same multi-phase feeder of the local LV network. There were thirty-three dwellings in total connected to this feeder, including seven flats in the same block, two of which were trial dwellings. Real power measurements were available for two single-phase feeders, L1 and L3. The exact number of trial homes connected to each phase was not known since the phases of the two flats in the block of seven were not identified, but it is estimated that the trial penetration for the L1 phase was approximately 31%, and that the trial penetration for the L3 phase was approximately 36%, of the total homes connected to those phases.

There was variation in occupancy, baseline energy consumption levels and daily consumption patterns between dwellings. The number of occupants varied from single occupants in three homes, to families with five occupants in two of the homes, and two or three occupants in the remainder of homes. The majority of households were occupied at the start of the day and throughout the evening, with a reduced or zero occupancy during the middle of the day. During the baseline, the mean

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[1] Octopus Go: A static tariff offering cheap rate electricity between 0:30–4:30 a.m. https://octopus.energy/go/.

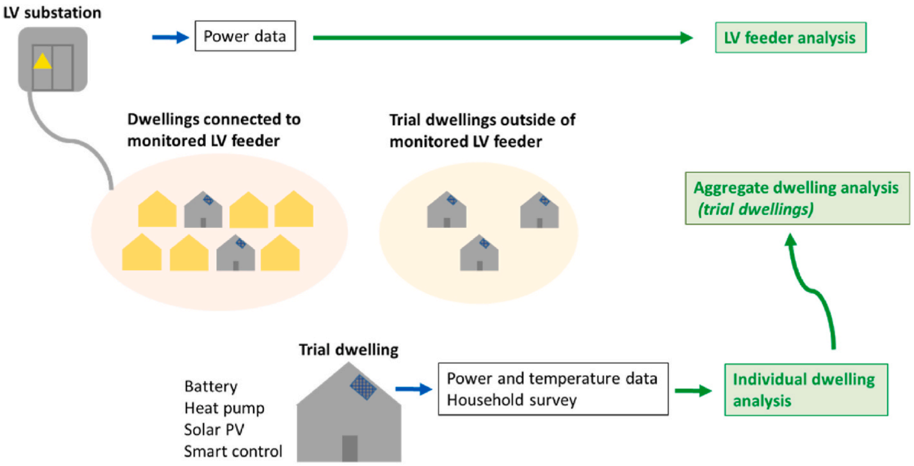

Fig. 1. Schematic of data collection and analysis.

daily whole home consumption i.e. the sum of grid electricity import, solar self-consumption and battery discharge, across the 14 dwellings was 21.4 kWh (SD 8.6 kWh) and ranged from 10.5 kWh for one of the flats with a single occupant to 40.9 kWh for the sole detached house with five occupants.

3.1.1. *Dwelling based data and methods*

At the individual dwelling level, data streams were provided at 5 min intervals by Passiv UK, sourced from the battery and ASHP. The ability to distinguish between the heat pump being used for hot water or space heating was provided. The dwellings were divided into two heating zones, zone 1 (upstairs and flats) and zone 2 (downstairs). Each zone contained a wall-mounted Z-Wave (Secure) SRT 321 electronic room thermostat and temperature sensor[2] with temperature accuracy ±0.5 °C and a 0 °C–40 °C operating range.

A five days matching days baseline approach was used to provide a measure of energy changes due to interventions against usual consumption at intervention times. Daily baseline energy consumption during the 2 h time intervals corresponding to intervention periods (1–3 pm or 5–7 pm) was calculated as the mean of the total energy consumption for the relevant interval over the five baseline days. Similarly, a mean daily average for energy consumption during interventions was calculated for the five days in each trial week. Aggregated results across the 14 dwellings used an aggregated baseline, but to provide energy changes per dwelling, each individual dwelling was also compared to its own baseline corresponding to the trial week of interest.

Two metrics were used for the quantification of the impact of DR interventions on energy consumption, the change in grid electricity import and the change in controllable load with respect to baseline values. Whereas grid electricity import relates to the energy supplied from the grid at the dwelling level (or supplied to grid at times of export), controllable load relates to the controllable home assets, and is the combined effect of heat pump electricity consumption and battery energy. The change in controllable load over a period of time, e.g. over a 2 h intervention period, was equal to the sum of change in heat pump electricity consumption and the net change in battery energy. To distinguish between energy changes for battery charging and discharging, battery charging is positive in sign, and battery discharging, negative. The change in controllable load due to an intervention was calculated as the controllable load change during the intervention minus the controllable load change during an equivalent baseline period.

For interventions which include a heating response, a change in indoor temperature may be an additional effect of DR. For the turn-down trials, for those cases where the heat pump was switched off during the entirety of an intervention, the indoor temperature delta was calculated for each heating zone as the zone temperature at the end of the intervention minus the zone temperature at the intervention start. For the turn-up trials, the indoor temperature delta between the intervention start and end times was calculated for all dwellings and interventions. In case of any delay in heating affecting zone temperatures, the temperature delta was also calculated between the temperature at a time 4 h after the turn-up intervention start compared with the temperature at the intervention start. Onset HOBO MX1101 temperature and relative humidity data loggers[3] with temperature accuracy ±0.2 °C and a −20 °C–70 °C operating range, had been deployed in five dwellings and a comparison exercise was performed between the data logger and thermostat temperature measurements during the period 30/09/20 to 14/07/21. Data loggers were placed in the living room and main bedroom, positioned away from draughts and sources of heat and direct sun exposure. For each dwelling there was a strong correlation between the thermostat and data loggers for each zone, with all Pearson correlation coefficients being 0.84 and higher. Differences would be expected in absolute temperature measurement due to the relative locations of thermostats and data loggers. The strong linear association demonstrated by the Pearson correlation indicates that the thermostats provided a reasonable measure of the *change* in temperature with time for the zone of interest.

Within each five day trial or baseline, only three dwellings had missing power data during the relevant 2 h periods (1–3 pm or 5–7 pm), up to a maximum of 2.5% missing values for any particular dwelling. All 14 dwellings were included in the energy analysis at the aggregate dwelling level, but two of these dwellings were excluded from the temperature delta analysis, one due to a heat pump fault during Trial 3 and another due to an issue with the underfloor heating during Trials 1 and 2.

3.1.2. *LV feeder data and methods*

Power data from the feeder at 10 min intervals was provided by Northern Powergrid. Only data for two out of three phases was available and results for the real power components of these phases, L1 and L3, are presented. Again, a five days matching baseline approach was employed - the mean daily power consumption during the 2 h time intervals corresponding to intervention periods (1–3 pm or 5–7 pm) across five consecutive weekdays provided the baseline, with which power consumption during interventions was compared.

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[2] http://manuals-backend.z-wave.info/make.php?lang=en&type=&sku=SEC_SRT321.

[3] https://www.onsetcomp.com/products/data-loggers/mx1101/.

3.2. Household survey

The externally controlled turn-down and turn-up of heat pump electricity consumption in conjunction with battery operation had the potential to disrupt household routines and residents' comfort. Two surveys were conducted, one during the trials, the other during the week following the trials period, to determine how the trials affected residents in terms of hot water availability, perception of indoor temperature, along with actions taken to change the temperature, noise from the battery and the heat pump, as well as the effect of the trials on household activities. Residents were also given the opportunity to voice any concerns about the trials and general concerns, as well as thoughts about the home energy systems. Of the 14 trial households, 11 households responded to the first survey, and 10 responded to the second survey, with 10 households responding on at least one occasion (71%).

3.3. Trials overview

Three DR trials containing a total of 15 interventions each of 2 h duration were conducted over four weeks during the heating season from January 31st to February 25th' 2022, as outlined in Table 2. Interventions were conducted daily on every weekday during trial weeks. Heat pump usage was subject to temperature comfort limits during interventions (up to ±2 °C from each household's usual set-point schedule). Advance notice of the interventions allowed advance control of the battery and heat pump assets.

Although homes had identical battery and heat pump assets, and were of a similar build construction, there was variation in solar PV capacity, build type and occupancy. Normal daily consumption levels and patterns of consumption varied between households. Ahead of turn-down interventions, batteries in individual dwellings were charged to a level depending upon expected demand for each household. Under normal (baseline) conditions the control system optimised heat pump operation to minimise energy costs while considering thermal comfort and occupants' schedules and preferences by using smart control of indoor temperature set points and the heating and hot water system, in combination with machine learning, a dynamic building physics model of the dwelling and day-ahead weather forecasting. Solar generated electricity was first used to satisfy household demand, then to charge the battery, with surplus solar generation exported to the grid. During the trials, the ability for smart control of the battery was also utilised, allowing charging of the battery using grid electricity and controlled battery discharge to provide the planned demand response against predicted dwelling consumption.

For the Trial 1 turn-down, the control system planned for total controllable load (heat pump plus battery) to be zero and did not account for other appliance/baseload consumption. This was an asset-based turn-down during evening peak times (5–7 pm). In practice, the battery was pre-charged to cover planned heat pump consumption during the intervention, but during the intervention itself, the battery discharged to meet heat pump consumption and other appliance/baseload consumption. For the Trial 2 turn-up, the control system aimed to increase electricity import from the grid by maximising battery charging and heat pump usage during 1–3 pm to simulate a situation where surplus renewable energy was locally available. For the Trial 3 turn-down, the control system aimed to reduce all grid electricity import to zero, regardless of whether usage was asset-based or due to other appliances/baseload, during 5–7 pm.

Table 2
Summary of DR trials schedule.

Baseline/ Trial	Dates	Details
Trial 1	31 Jan-4 Feb 2022	Turn-down 5–7 pm. Target 0 kW controllable load
Baseline	7–11 Feb 2022	Usual operation of battery and heat pump assets
Trial 2	14–18 Feb 2022	Turn-up 1–3 pm. Maximise battery charging and heat pump use
Trial 3	21–25 Feb 2022	Turn-down 5–7 pm. Target 0 kW grid electricity import

During the whole trials period, on aggregate, solar generation was effectively equivalent to solar self-consumption for all analyses. For all but one dwelling, export to the grid for the baseline and trial weeks was ≤0.05 kWh during 1–3 pm and was zero between 5 and 7 pm. The exception was the dwelling with a solar PV capacity of 3.0 kWp, which exhibited 1.2 kWh of grid export during 1–3 pm for the baseline and no grid export during all interventions.

The mean external temperatures for each trial along with that for the baseline are provided in Table 3, calculated as the mean across all hourly values within a particular trial/baseline period.

4. Results

Data analysis at the aggregate dwelling level provides a comprehensive picture of the demand response for all three trials, and results at the aggregate level are presented first, with the inclusion of cross-dwelling analysis. These are followed by a summary of the DR energy changes at the individual dwelling level, along with results from indoor temperature analysis. Results at the LV feeder level complete the quantitative analysis, and these are followed by the results of the qualitative data analysis obtained from the household survey.

4.1. Aggregate dwelling level

4.1.1. Baseline

The average daily power profile for the baseline aggregated over the 14 dwellings (Fig. 2) shows two broad grid electricity import peaks, one during the morning, the other during the evening. During the baseline, compared with daily grid electricity import, daily solar generation was low, although it contributed to supplying demand during the middle of the day, and surplus solar generation enabled the battery to be charged to an average energy level of 17% by mid-afternoon. Across the 14 dwellings, grid electricity import during 5–7 pm ranged from 0.2 kWh to 3.9 kWh, with a mean of 1.9 kWh (SD 1.1 kWh). Grid electricity import during 1–3 pm ranged from 0.02 kWh to 2.7 kWh, with a mean of 0.9 kWh (SD 0.8 kWh).

4.1.2. Turn-down interventions

The average daily power profiles for the Trial 1 and Trial 3 weeks aggregated over the 14 dwellings (Fig. 3) show that the battery was charged by a combination of solar generation and grid electricity import ahead of an intervention. The battery energy levels at the start of interventions varied for individual dwellings depending on their expected household demand during 5–7 pm. Across the 14 dwellings, the battery was charged to 31% on average, prior to the intervention start for Trial 1 (Fig. 3 (a)) to cover the expected heat pump consumption during 5–7 pm, and the battery was charged to 73%, on average, prior to the intervention start for Trial 3 (Fig. 3 (b)) to minimise grid electricity import during 5–7 pm. There was a sharp reduction in grid electricity import at the start of an intervention, and this was more pronounced for

Table 3
Mean, minimum and maximum external temperatures for baseline and trials.

Baseline/Trial	Date range	External temperature °C		
		Mean	Min	Max
Trial 1	31 Jan – 4 Feb	6.0	1.5	9.4
Baseline	7–11 Feb	5.2	0.2	10.4
Trial 2	14–18 Feb	5.2	1.9	11.6
Trial 3	21–25 Feb	4.9	0.3	8.7

Temperature data from Emley Moor weather station (Latitude 53.612, Longitude −1.667).

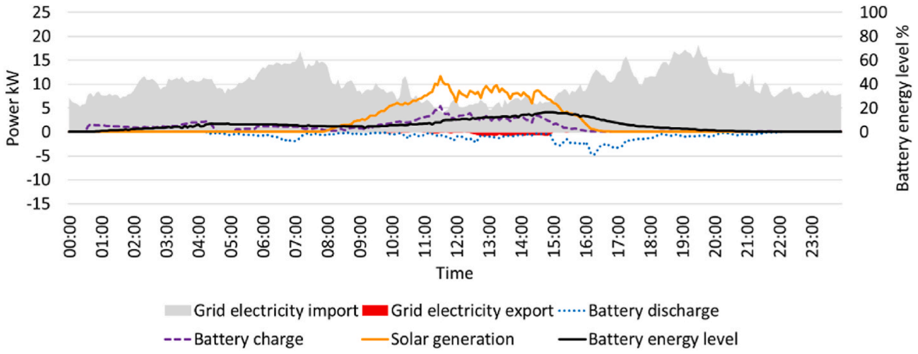

Fig. 2. Average daily power profile for baseline, aggregated over 14 dwellings (Averaged over 5 baseline days).

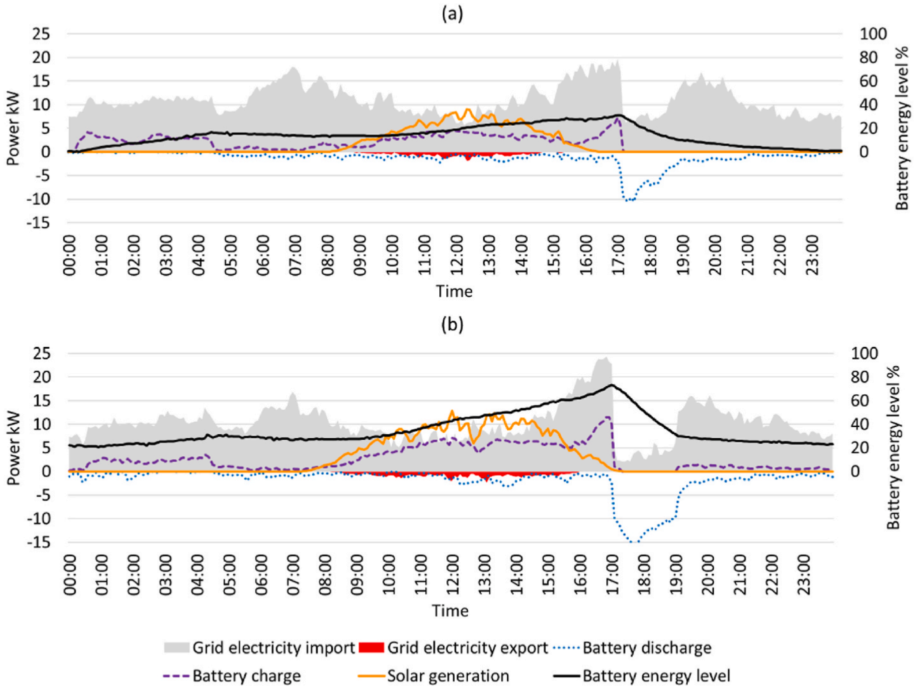

Fig. 3. Average daily power profiles aggregated over 14 dwellings (a) Trial 1 (b) Trial 3 (Averaged over 5 trial days).

Trial 3. Grid electricity import began to increase before the end of the intervention, and this was more apparent for Trial 1. Variation in the amount of solar generation between baseline and trial weeks depended upon cloud cover and solar irradiance levels.

Considering the results of the Trial 3 turn-down (Fig. 3(b)), 0 kWh of grid electricity import was targeted, and batteries were charged ahead of interventions using grid electricity and solar generated electricity, where available, to various levels for individual households, relating to expected levels of demand during 5–7 pm. In practice, household demand could differ from that expected, and the following observations were made for individual dwelling interventions.

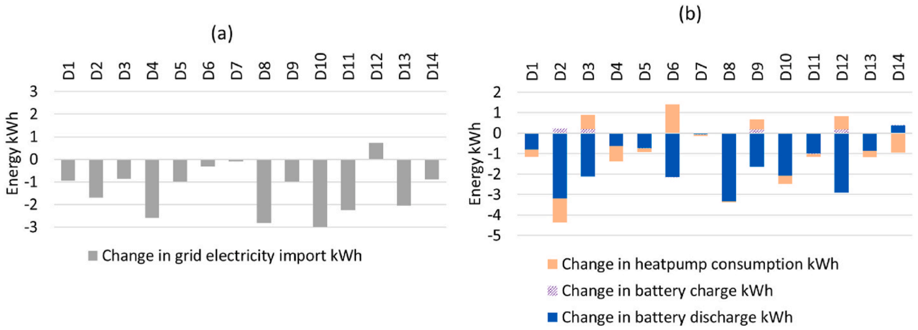

Fig. 4. Intervention 12, Trial 3 turn-down 5–7 pm. Energy changes by individual dwelling compared with the baseline (a) Changes in grid electricity import (b) Breakdown of changes in controllable load.

1) Where individual household demand was lower than expected, the battery was not fully discharged by 7 p.m.
2) Where individual demand was higher than expected, the battery was fully discharged by 7 p.m. and grid electricity import occurred before the end of the intervention.
3) Grid electricity import could occur during an intervention if at any point the rate of electricity consumption exceeded the rate which could be supplied by the discharging battery.

Fig. 4 shows the cross-dwelling response for intervention 12 (Trial 3) as an example of a turn-down intervention, depicting changes in grid electricity import as well as the breakdown of changes in controllable load compared with the baseline. While most dwellings showed a decrease in grid electricity import over 0.8 kWh compared with the baseline, the decrease for dwellings D6 and D7 was only 0.3 kWh and 0.1 kWh, respectively. The baseline grid electricity import for dwelling D6 was fairly low, at 0.4 kWh, and although there was very little grid electricity import during the intervention itself (<0.1 kWh), the low baseline meant that this dwelling would not be able to show a large response in terms of grid electricity import. Battery discharge for dwelling D6 primarily covered heat pump use, which was increased compared with the baseline. Similarly, the usual grid electricity import during 5–7 pm was very low for dwelling D7, a flat with a single occupant, but for this dwelling, there was no need for battery discharge during the intervention since the heating was off throughout. Dwelling D12 exhibited an increase of 0.7 kWh in grid electricity import - this was due to a large spike in grid import around 6 p.m. Dwellings D8 and D10 demonstrated the greatest reductions in grid electricity import, at 2.8 kWh and 3.0 kW, respectively. These were dwellings with high baseline grid electricity import during 5–7 pm (3.9 and 3.1 kWh, respectively) and they had a greater potential for grid electricity import reduction compared with dwellings with usually low consumption. The breakdown of controllable load changes illustrates that heat pump consumption could be increased as well as decreased at the individual dwelling compared with baseline consumption.

4.1.3. Turn-up interventions

The average daily power profile for the Trial 4 week aggregated over the 14 dwellings showed a pronounced turn-up effect (Fig. 5). The battery was charged primarily by grid electricity import, but also by solar generation. At the end of the intervention, the battery was almost fully charged (95%, on average). Typically, following the intervention the discharging battery supplied most of the home consumption requirements until around 5:30 pm. For the majority of dwellings and interventions, the heat pump was used throughout 1–3 pm. During the interventions, battery charging using surplus solar generation reduced the amount of electricity which could be absorbed from the grid, although this effect was small, with solar generation contributing one sixth to battery charging for the dwelling with the highest solar PV capacity (3.0 kWp). This effect will be more pronounced for sunnier months.

Fig. 6 illustrates the cross-dwelling performance for intervention 9, a typical Trial 2 turn-up intervention. Substantial increases in grid electricity import (4.2–9.0 kWh) and controllable load (4.1–5.8 kWh) occurred across the individual dwellings compared with the baseline. The increase in controllable load was mainly due to battery charging, with all home batteries charging between 4.3 and 4.8 kWh during the intervention, but for the majority of dwellings, heat pump electricity consumption also contributed to the increase. The battery was able to provide a consistent and major contribution to the increase in grid electricity import across all dwellings, and this was the case for all interventions. For Dwelling D7, the dwelling with the lowest turn-up response for Intervention 9 (Fig. 6(a)), the battery was fully charged during the intervention, but the heat pump was not used, which was the usual, baseline behaviour for this dwelling, and it was likely that heating control during the intervention was manually overridden by the householder. Dwelling D13 exhibited the greatest turn-up response for Intervention 9 (Fig. 6(a)). The change in battery charge between baseline and intervention was 4.0 kWh, and the heat pump was used throughout the intervention. The demand response was affected by additional household demand which exceeded the expected level.

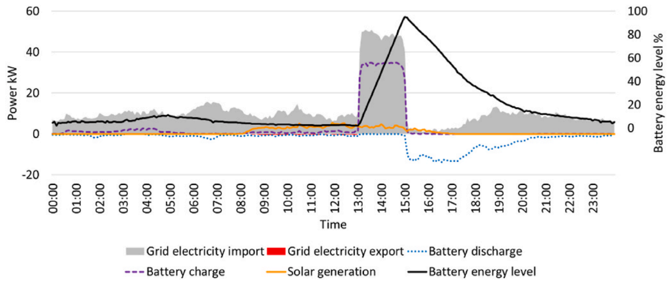

Fig. 5. Average daily power profile aggregated over 14 dwellings for Trial 2 (Averaged over 5 trial days).

4.1.4. Summary of aggregate energy changes

The aggregate daily mean energy across the 14 dwellings for grid electricity import, heat pump electricity consumption and controllable load during the relevant 2 h intervals are provided in Table 4 for the baseline and trial weeks. For turn-down interventions, grid electricity import was reduced by 31% and 67% for Trial 1 and Trial 3, respectively and controllable load was reduced by 140% and 308%, respectively. The reduction in heat pump electricity consumption was similar for both turn-down trials, at 16% for Trial 1 and 17% for Trial 3. For the turn-up trial, Trial 2, grid electricity import was increased by 645%, and controllable load was increased by 560%. The increase in heat pump electricity consumption was 124%. For all three trials, the battery was the main contributor to the changes in controllable load compared with the heat pump, the battery contributing 85%, 85% and 93% to the changes for Trials 1, 2 and 3, respectively.

4.2. Individual dwelling level

4.2.1. Summary of energy changes per dwelling

The mean changes in grid electricity import and controllable load compared with the baseline per dwelling are summarised in Table 5 for energy (kWh) along with equivalent changes in power (kW). The mean change per dwelling per trial was the mean of 70 individual results (14 dwellings x 5 interventions). As might be expected for turn-down interventions, Trial 3 showed a greater impact than Trial 1, i.e. minimising grid import had a greater impact than covering planned heat pump consumption.

4.2.2. Indoor temperature analysis

Individual dwellings were subject to a range of daily heating and hot water schedules based on resident preferences and occupancy, resulting in a range of indoor temperature behaviour. Fig. 7 illustrates the response of zone temperatures to periods of heating for an individual dwelling during a Trial 3 turn-down intervention day. Prior to the intervention, the heating was on from 12:30–5 pm, apart from a period of hot water heating around 3 pm There was a delay in heating affecting the temperature of each zone, and after the heating was switched off at 5 pm, the zone temperatures continued to rise for 1–1.5 h.

Space heating was switched off through the whole of the 2 h duration of turn-down interventions for eight dwellings for Trial 1 and seven dwellings for Trial 3, and Fig. 8 depicts the temperature deltas at the end of these interventions. For both heating zones, all temperatures at the end of the intervention lay within ±1.0 °C of the intervention start temperature, with the exception of one dwelling, a ground floor flat, for which there were two cases where the temperature delta was exactly −1.0 °C.

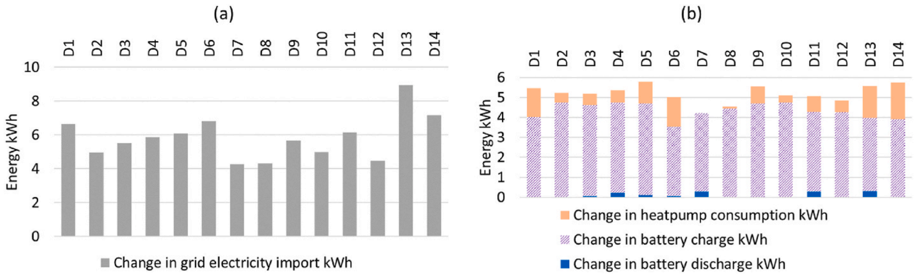

Fig. 6. Intervention 9, Trial 2 turn-up 1–3 pm. Energy changes by individual dwelling compared with the baseline (a) Changes in grid electricity import (b) Breakdown of changes in controllable load.

Table 4
Daily mean energy consumption for each trial compared with baseline, along with battery and heat pump contribution to change in controllable load. Aggregated results for 14 dwellings.

Daily mean energy kWh (during 2 h period)	Baseline	Trial	Energy change kWh Trial minus Baseline (% change)[a]	Mean contribution to change in controllable load[a]
Trial 1 Turn-down (5–7 pm)				
Grid electricity import	26.5	18.3	−8.2 *(-31%)*	
Controllable load	7.2	−2.9	−10.1 *(-140%)*	
Net battery consumption	−2.5	−11.1	−8.6 *(-342%)*	85%
Heat pump consumption	9.7	8.2	−1.5 *(-16%)*	15%
Trial 2 Turn-up (1–3 pm)				
Grid electricity import	12.5	93.4	80.8 *(645%)*	
Controllable load	12.8	84.2	71.5 *(560%)*	
Net battery consumption	4.2	65.0	60.8 *(1460%)*	85%
Heat pump consumption	8.6	19.2	10.6 *(124%)*	15%
Trial 3 Turn-down (5–7 pm)				
Grid electricity import	26.5	8.9	−17.6 *(-67%)*	
Controllable load	7.2	−14.9	−22.1 *(-308%)*	
Net battery consumption	−2.5	−22.9	−20.4 *(-815%)*	93%
Heat pump consumption	9.7	8.0	−1.7 *(-17%)*	7%

[a] Percentages calculated before rounding.

Table 5
Mean change in grid electricity import and controllable load per dwelling compared with baseline consumption by trial (from individual dwelling analysis).

Trial	Mean change in grid electricity import		Mean change in controllable load	
	kWh *(SD)*	kW *(SD)*	kWh *(SD)*	kW *(SD)*
1 (Turn-down 5–7 pm)	−0.6 *(1.3)*	−0.3 *(0.7)*	−0.7 *(0.9)*	−0.4 *(0.4)*
2 (Turn-up 1–3 pm)	5.8 *(1.2)*	2.9 *(0.6)*	5.1 *(0.6)*	2.6 *(0.3)*
3 (Turn-down 5–7 pm)	−1.3 *(0.9)*	−0.6 *(0.5)*	−1.6 *(1.1)*	−0.8 *(0.6)*

†Percentages calculated before rounding.

Fig. 9 depicts the temperature deltas for the Trial 2 turn-up interventions for the 12 dwellings included in the temperature delta analysis. Space heating was on continuously or intermittently throughout all interventions for all dwellings with the exception of just three instances, and all data were included in the analysis. At the end of the 2 h interventions, all temperatures for both heating zones lay within between ±1.0 °C of the intervention start temperature with the exception of one instance where the temperature delta was +1.3 °C (zone 2). The temperature at 2 h after the intervention end point was also investigated, regardless of whether the heating was on or off post-intervention, in case of any delayed effect in intervention heating on the indoor temperature. A slight shift towards higher temperature deltas was apparent at 4 h following the intervention start, and the maximum temperature increase observed was +1.6 °C.

4.3. *LV feeder level*

4.3.1. *Summary of aggregate energy changes*

The mean daily power measurements at the feeder level for the baseline and each trial week for the relevant 2 h time periods are summarised in Table 6. These were calculated as the total L1 or L3 real power during 1–3 pm or 5–7 pm, averaged over the five baseline or trial days. The mean power changes for each set of trial interventions compared with the associated baseline are also provided.

4.3.2. *Turn-down interventions*

Figs. 10 and 11 compare the daily profiles for L1 and L3 real power with the baseline profiles for Trial 1 and Trial 3, averaged across the relevant five day periods. The reduction in L1 real power between 5 and 7 pm was found to be 7% compared with the baseline for both turn-down trials (Figs. 10(a) and Fig. 11(a)). The reduction in L3 real power between 5 and 7 pm compared with the baseline was 2% for Trial 1 (Fig. 10 (b)), but for Trial 3 the effect was more pronounced, with a 21% reduction in L3 real power (Fig. 11(b)). For the Trial 1 L1 and L3 profiles, as well as the Trial 3 L3 profile, an increase in power just prior to 5 pm compared with the baseline was apparent, and this is in step with the power profiles at the aggregate dwelling level (Fig. 3).

4.3.3. *Turn-up interventions*

For the turn-up trial, both the L1 and L3 real power was substantially increased between 1 and 3 pm, 158% and 307%, respectively, demonstrating a clear effect on the average daily profiles (Fig. 12).

4.4. *Resident experience – household survey*

Both telephone surveys were primarily concerned with investigating the resident experience of the DR trials, as well as any general resident concerns with the home energy systems. Additionally, the first survey explored resident opinion towards ongoing DR with automated control by a third party, and the second survey sought to further elicit resident's views on the home energy systems. The first survey was conducted during the week following Trial 1 (the Baseline week), the other during the week following Trial 3.

Across all three trials, 57% (out of 21) responses stated that the indoor temperature felt the same as usual (Table 7). The four responses across the trials where householders felt the indoor temperature was

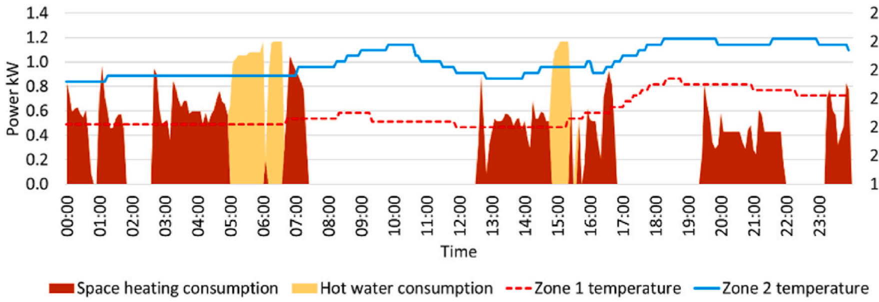

Fig. 7. Intervention 13, Trial 3 (turn-down 1–3 pm) - Indoor temperature behaviour in response to periods of heating on particular intervention days for dwelling D4.

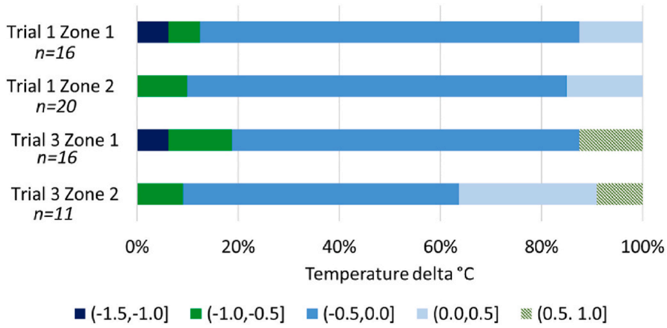

Fig. 8. Trials 1 & 3 (Turn-down) temperature delta between the start and end points of intervention (2 h) for individual dwellings where heating was off throughout interventions. *(n=number of results from five intervention days for all relevant dwellings).*

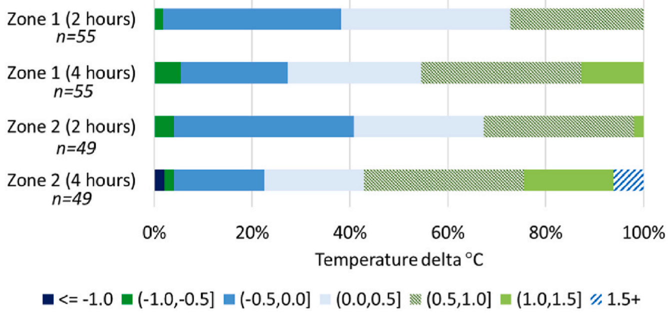

Fig. 9. Trial 2 (Turn-up) temperature delta at 2 h and 4 h from the intervention start for 12 dwellings. *(n=number of results from five intervention days for all relevant dwellings).*

much colder than usual came from two households, both of which had ongoing issues with cold indoor temperatures which were not specific to the trial period. For Trial 1, one household felt that it was sometimes colder and sometimes warmer than usual. No household felt that the indoor temperature was warmer than usual, even during the turn-up trial. For the survey following trials 2 and 3, four households reported that it felt slightly colder than usual, but there was no consensus concerning the timing of the households that noticed this change. Across all three trials, hot water was always or often available for 72% (out of 21) responses. For one household, hot water was not available when required due to a scheduling issue. For three households, hot water was sometimes available – for one of these households, hot water came on with the heating, an ongoing issue, and two households reported that hot water was not available on one or two occasions. Households which noticed changes in indoor temperature or hot water availability during the trials, additional to any reported system issues, were subject to further investigation. Although residents' reports of lack of hot water availability and changes in the indoor temperature (slightly colder than usual) could generally be verified using internal temperature and hot water tank temperature data, the reported changes could not necessarily be attributed to interventions, since there were either similarities with baseline performance, or other explanations, e.g. the heating being off, as controlled by residents.

Table 6
Change in mean daily power (L1 and L3 real power) at the LV feeder level for each trial compared with the baseline during intervention times (Trial 1 & Trial 3 turn-down, Trial 2 turn-up).

Daily mean real power kW *(during 2 h period)*	L1 Baseline	L1 Trial	L1 Power change Trial minus Baseline (% change)[a]	L3 Baseline	L3 Trial	L3 Power change Trial minus Baseline (% change)[a]
Trial 1 (5–7 pm)	299	277	−22 *(-7%)*	172	168	−4 *(-2%)*
Trial 2 (1–3 pm)	148	382	234 *(158%)*	52	213	161 *(307%)*
Trial 3 (5–7 pm)	299	276	−22 *(-7%)*	172	135	−37 *(-21%)*

[a] Percentages calculated prior to rounding.

Noise from the battery did not disturb, or rarely disturbed, householders in the majority of homes, with two householders sometimes being disturbed by battery noise during the evening. Batteries were usually located away from the main living or sleeping space. Noise from the heat pump did not unduly disturb residents.

Regarding indoor temperature, hot water availability, heat pump noise or battery noise, changes during the trial period were either acceptable or householders felt neutral towards them, with the exception of one household where hot water availability was slightly unacceptable, and another household where the cold indoor temperature was unacceptable, although this was a general issue and not specific to the trials. Daily activities were affected during the trial period for two households, one where hot water was not always available and one where the upstairs temperature felt colder than usual. Only one household reported a concern specific to the trials, that the upstairs had felt unusually cold. Seven households had general concerns about their energy systems and five of these related to energy costs, particularly increasing bills, although this was against a backdrop of rising domestic energy prices. A repeated concern was the inability to know what cost savings the battery and solar system were providing. Other general concerns included hot water not being available when it was required for one household (an issue that was resolved during the trials), the indoor temperature being cold for one home, and an issue relating to the mobile phone app heating control not performing as expected.

Residents were questioned in relation to a fictitious scenario,

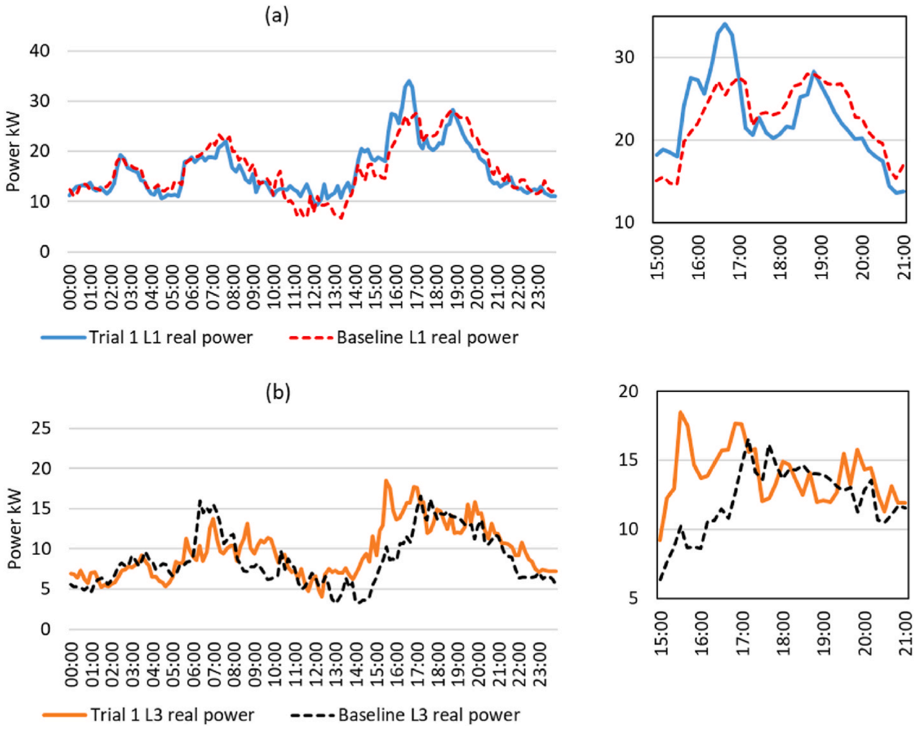

Fig. 10. Average daily profiles for across the Trial 1/baseline five day periods (a) L1 real power (b) L3 real power. Interventions between 5 and 7 pm.

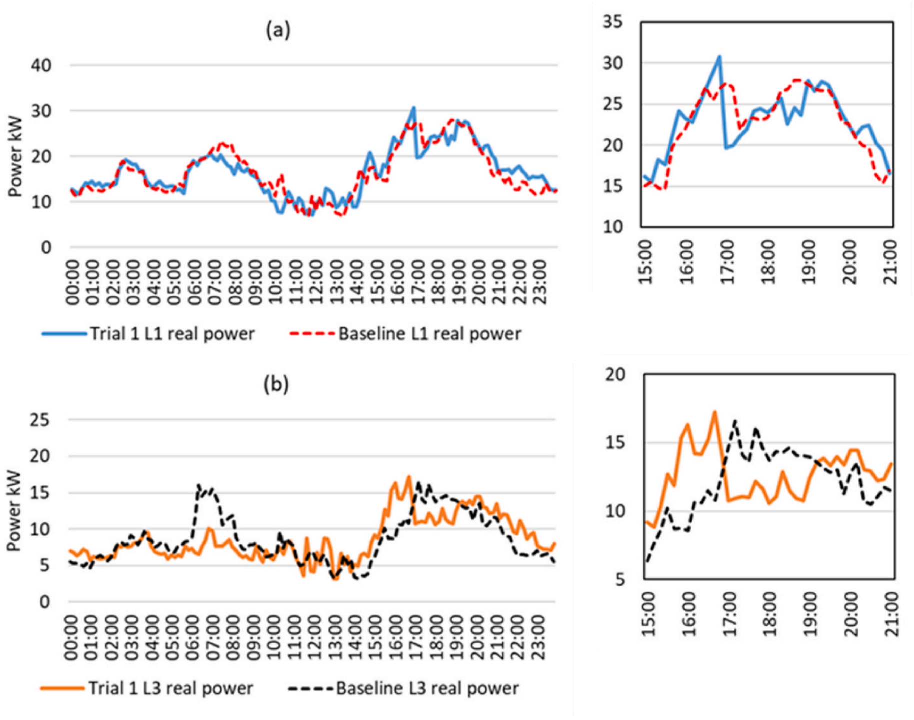

Fig. 11. Average daily profiles for across the Trial 3/baseline five day periods (a) L1 real power (b) L3 real power. Interventions between 5 and 7 pm.

whereby they could receive a financial benefit for allowing control of their heat pump and battery, for short periods of time, similar to the DR trials, but on an ongoing basis. The level of interest in joining such a scheme varied - four households would be interested, five households were not sure, but three of these might be interested with more information, and two households would not be interested. Concerns included such a scheme being new and unknown, that it would need to be without system issues, and that it would not result in costing householders money. Easy transparency for costs would be a requirement for residents.

In response to the question ‘What do you like most about the energy systems in your house?’, six households responded positively, mentioning energy saving or environmental benefits, or the benefit of being able to time heating control using the mobile app. However, four

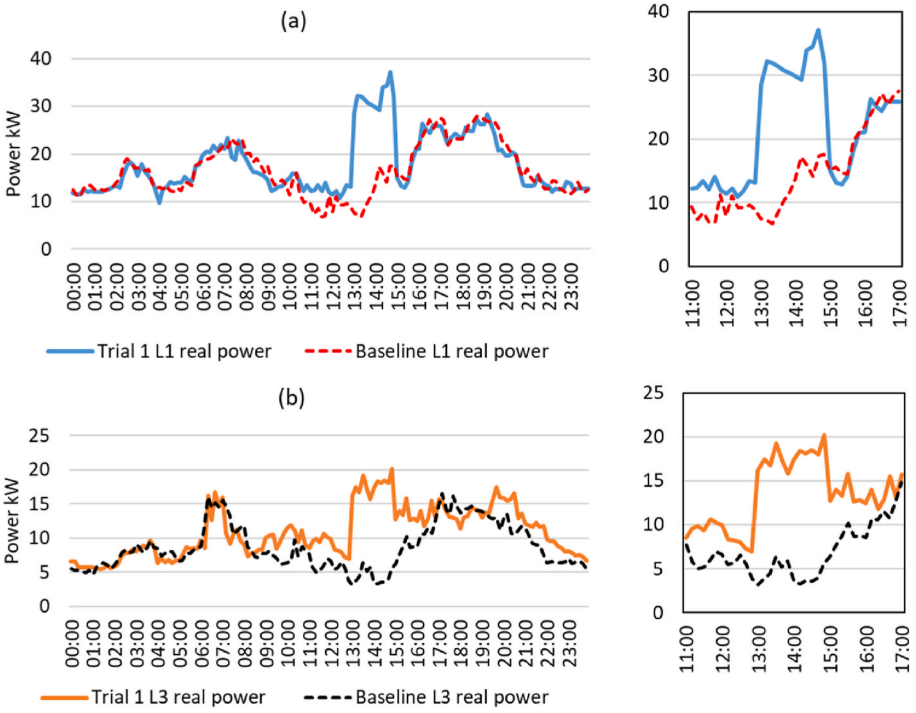

Fig. 12. Average daily profiles across the Trial 2/baseline five day periods for (a) L1 real power (b) L3 real power. Interventions between 1 and 3 pm.

Table 7
Householders' perception of temperature during the trials.

Perception of internal temperature	Trials 1 responses	Trials 2&3 responses	Total responses (out of 21)
Much warmer than usual	0	0	0 (0%)
Slightly warmer than usual	0	0	0 (0%)
The same as usual	8	4	12 (57%)
Slightly colder than usual	0	4	4 (19%)
Much colder than usual	2	2	4 (19%)
Other	1	0	1 (5%)
Total respondents per trial	11	10	21

households which had all experienced heating system issues had no positive reports, with one resident adding that his old system had been 'more instant'. As concerns using the heating system, seven households replied positively, mentioning ease of control and the ability to control the heating when away from home. Three households reported issues with the heating system, including the mobile app not showing the expected heating status. These households had all experienced system issues, and user operation of heating control may have been a factor in some cases. Four households could not think of anything they would like to improve about the home energy systems. Three households wanted to be able to see cost and energy savings from the systems, and three households which had experienced system issues wanted the systems to work correctly.

5. Discussion

5.1. *Monitored response*

The monitored response for each trial was apparent at individual and aggregate dwelling levels, and at the local LV network level where the penetration of trial homes was approximately one third of all connected homes. There is no direct translation between results at the aggregate dwelling level and results at the LV level since only nine out of fourteen of the trial dwellings were connected to the multi-phase LV feeder, and there was some estimation of the exact number of homes on each single-phase feeder. The greatest turn-down response at the LV level (21%), was achieved for L3 when minimisation of grid electricity import was targeted (Trial 3). The increased consumption ahead of interventions observed at the dwelling and LV levels is an interesting illustration of how new consumption peaks may occur. The response for the turn-up trial (Trial 2) was very pronounced at the LV network due to the almost maximal use of battery charging along with a heat pump turn-up for the majority of individual dwelling responses. The observation of a marked response at the network level bears significance since it demonstrates the energy flexibility that clusters of homes with LCTs can provide, an area which is lacking in applied results.

Two types of turn-down interventions were trialled. Trial 1 was asset-based and essentially used the battery to cover planned heat pump consumption, whereas Trial 3 aimed to minimise all grid electricity import. At the aggregate household level, the reduction in both grid electricity import and controllable load for Trial 3 was approximately twice that for Trial 1. A third type of turn-down intervention could involve not only minimising grid electricity import, but using the battery to export electricity to the grid at peak times (Western Power Distribution and Regen, 2017). A question for future DR rollout is which type of response is desirable, and it may be the case that all three types have a place. The Trial 2 turn-up response demonstrates the potential for homes equipped with batteries and electric heat pumps to accept electricity from the grid at times of local surplus renewables generation. Even within similar dwellings (build type and age) with the same LCTs, there was a range of response attributed to the different household occupancy, preferences and varying levels of consumption both at peak times and throughout the day. The battery was found to contribute most to the demand response with the heat pump contribution, on aggregate, a maximum of 15% for the turn-down and turn-up trials. Heat pumps were switched off completely during the turn-down interventions trials for only approximately half the dwellings, with the remaining dwellings using the heat pump intermittently or continuously throughout interventions, enabled, in part, by battery discharge. However, even with a complete turn down for all heat pumps, the battery would still have a greater response potential.

Indoor temperatures were not particularly affected by turn-down interventions with temperatures at the end of interventions lying within ±1 °C of intervention start temperatures in all cases where space heating was switched off throughout the whole 2 h. For turn-up interventions, again, the indoor temperatures at the end of interventions lay within ±1 °C of intervention start temperatures, although post-intervention temperatures tended to rise slightly, and this effect will need further investigation during warmer weather. Thermal comfort limits of ±2 °C from each dwelling's normal set-point temperatures were in place along with the ability to override heat pump control.

5.2. Resident experience

Despite a small number of households noticing changes in temperature (colder than usual), hot water availability or battery noise, the DR trials, consisting of daily, 2 h interventions, were generally acceptable to residents. During the trials, four households had general issues with the heating system, one of which (hot water scheduling) was resolved before Trial 2. Only one household reported a specific *trial* concern, that the upstairs had felt unusually cold. The majority of *general* concerns related to costs and increasing bills – this is against a backdrop of increasing fuel prices. A related concern was lack of visibility of what the energy systems were saving. Control of heating was another concern in terms of the heating system not doing what was expected. However, those residents without ongoing system issues were positive about the ease of use for the heating control, including control using the app. The main suggested improvement to the home energy systems was to be able to see cost and energy savings from the systems. Households with ongoing systems issues wanted the systems to work correctly. In terms of the wider issue of the rollout of DR schemes with automated third party control, several residents would be cautiously interested with more information, transparency of costs and if there were no system problems.

Resolution of issues and general maintenance by personnel experienced with the new systems will be required for the smooth operation of DR schemes along with ensuring residents are satisfied with the performance, control and operation of new energy systems. The battery was a central asset to the DR trials and DR schemes need to plan for the detection and resolution of control and communication issues where home batteries are utilised, as well as for other low carbon technologies. Deployment of large scale DR schemes will require not only the installation of new energy systems and control technology into homes, but a prior capability assessment to determine the suitability of the systems for each individual property. Resident training and ongoing support for user issues is essential following the installation of new energy systems. With few system and control issues, the resident experience can be very positive. However, with ongoing system issues or confusion with the heating system control, residents can be negative about the new energy systems as a whole. Since such systems will be necessary for future residential DR schemes, plans to support the resident in the operation, control and maintenance of new systems should be put in place. User expectation of the heating system performance based on previous experience also plays a part in the resident experience, since heat pump systems can have a longer 'warm-up' time and hot water temperatures may be cooler than gas systems. Visibility of the energy and cost savings due to home energy systems is also important to residents. These findings are in line with those in (Calver et al., 2022), where the personalisation of energy systems to individuals' needs and preferences was highlighted as a key area so that financial, practical and thermal comfort requirements are considered. As stated in a governmental report focusing on DR and small users, the successful implementation of DR will require consumer offerings to be 'straightforward and comprehensible' (BEIS, 2017).

5.3. The wider picture

Appliance-based consumption may not present a sufficient flexible load for widespread DR (although the use of smart plugs and timers may aid the response), and the most likely route for 'engaged and active' DR will be achieved through automation and pricing (BEIS, 2017). Residential LCT offers a potentially higher impact, but its cost is currently prohibitive for many households, unless part of a wider scheme, e.g. social housing provision, or a community project, although the cost of home batteries and heat pumps are expected to decrease (BEIS, 2017; BEIS, 2021b). To enable smart automated control of LCTs in response to real-time electricity pricing, smart meters and reliable Information and Communication Technology (ICT) are also required. There is also a requirement for increased customer awareness of dynamic electricity pricing and opportunities for participation in DR (Hamwi et al., 2021), particularly as such opportunities grow. The UK government aims to put frameworks in place to ensure fair energy prices for all consumers, both those who participate in smart energy schemes as well as those who are unable to do so, with support for those consumers for whom participation may be difficult (BEIS, 2021a; BEIS, 2021b). A key objective is that 'engagement is not a barrier to fair outcomes or net zero', however, this has the potential to limit consumer choice in the move to decarbonisation (BEIS, 2021b). Without regulatory and financial support, demand side management policies may be reduced in their effectiveness (Warren, 2014).

5.4. Limitations and future work

A baseline approach relies on a reasonable match between baseline and intervention weather conditions. All interventions were planned with advance notice given to the control system. Planned interventions allow battery charging ahead of turn-down interventions, and also allow heating to be advanced or delayed if appropriate, and unplanned interventions would be expected to have a lesser impact, on average. The whole trial with baseline period was one month within the heating season, with trials conducted across a small number of homes. A larger trial conducted at different times of the year across a greater range of dwellings would provide additional information on the size and repeatability of the DR impact, and the resident experience, over a longer timeframe. For turn-up interventions, solar generation prior to an intervention can affect the level of battery charge available at the start of the intervention and this, along with solar generation during the intervention itself, can affect the amount of grid electricity that can be imported to charge the battery during the turn-up. Solar generation for the trial period was relatively low, but this may become a more important consideration at other times of the year for such prosumer households.

6. Conclusion

The envisaged role for residential DR is to provide flexibility to support the electricity network in balancing supply and demand and incorporating renewables generation. Residential LCTs offer a meaningful response with the benefit of smart, real-time control, including the coordination of multiple assets in a single household. Such LCTs may occur in local clusters, e.g. on a new-builds housing development, and it is important that their combined effect at the LV level of the distribution network is understood, particularly as electricity generation becomes more distributed with an increased onus on balancing supply and demand at the local level. However, trials involving the DR of residential LCTs are limited in number, and the practical measurement of residential DR at the LV network level is scant.

This study has demonstrated a measured response for turn-up and turn-down interventions at the dwelling and LV network levels using direct load control for dwellings with home batteries, ASHPs and solar PV panels. At the LV network, where trial home penetration was approximately one third, a mean turn-down reduction up to 21% in real power was observed when targeting zero grid electricity import at dwelling level, and for turn-up interventions, a mean real power increase up to 307% was observed. An evaluation of the resident experience of the DR trials found that residents were generally accepting of daily weekday interventions and had experienced little disruption. As regards the general experience (non-trials) of the home energy systems, most residents were positive, although a few households had experienced issues with the operation of the heating system. General concerns amongst households related to costs and the need for visibility of energy and cost savings.

Whilst demand response from TOU shifting of domestic appliance consumption has been demonstrated on a larger scale, DR using residential LCTs sits mainly at the pilot stage. Scaling up from small scale trials to the widespread implementation of DR schemes involving residential LCTs will require

- The increased rollout of TOU tariffs and other financial rewards for consumer provision of flexibility services, along with the supporting structures for regulation, consumer protection and consumer participation being put in place.
- An ongoing focus on the resident experience with support for resident understanding and operation of new systems and their associated technology. This should include maintenance and prompt resolution of issues, in combination with ensuring that individual households have a beneficial financial package which is suitable for the response provision that can be provided with individual energy systems, preferences and daily routines.
- An increased understanding of the measured demand response of residential LCTs, including local clusters of LCTs, and their effect on the LV network with varying degrees of LCT penetration.

CRediT authorship contribution statement

Rajat Gupta: Conceptualization, Methodology, Supervision, Funding acquisition, Investigation, Writing – original draft, Writing – review & editing. **Johanna Morey:** Methodology, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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