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Empirical evaluation of demand side response trials in UK dwellings with smart low carbon technologies

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A R T I C L E I N F O

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A B S T R A C T

Low carbon technologies along with smart control have a role in residential demand side response (DSR) to shift the timing of household energy consumption away from peak times and align it with generation of renewable electricity. This paper empirically evaluates the impact of DSR trials on grid electricity import and resident experience regarding disruption to daily routines, thermal comfort and noise disturbance in 17 thermally efficient social housing dwellings (Barnsley, England). Four types of DSR trials were run through 22 interventions performed in March to April 2021. Each dwelling was equipped with a 5 kWh electro-chemical battery and air source heat pump, and all but one dwelling had solar photovoltaic (PV) panels (1.3–3.0 kWp). Interventions were applied against a flat (single) rate tariff as well as dynamic time-of-use tariffs. On average, secure turn-down interventions between 5 and 7 p.m. resulted in a reduction in grid electricity import of 1.2 kWh per household and a reduction in controllable load (heat pump plus battery energy) of 3.7 kWh per household. The batteries enabled 2.5 kWh per household of electricity to be exported to the grid for these interventions. On average, turn-up interventions between 1 and 3 p.m. resulted in an increase of 2.3 kWh per household in grid electricity import. Individual dwellings showed different levels of demand response depending on the levels and patterns of household electricity consumption.

The resident experience was evaluated by means of a series of telephone surveys. Householders were generally accepting of the trials in terms of changes in indoor temperature, hot water availability, noise disturbance and disruption to household routines. However, some general concerns were raised about the energy systems relating to indoor temperature, hot water temperature and energy costs. The general acceptability of automated DSR, conditional on thermal comfort limits and manual override, is promising for the wider application of residential DSR driven by price signals, although ongoing household engagement in DSR schemes will require a continued focus on the householder experience with training and support in using new technologies. A routine period of inspection should be employed to identify any issues with energy system issues ahead of DSR initiation.

1. Introduction

In the Sixth Carbon Budget, the UK government committed to reducing greenhouse gas emissions with a target of net zero emissions by 2050 and, in the interim, a 78% reduction in emissions by 2035 compared with 1990 values [1]. The future electricity system is expected to consist primarily of wind and solar generation accompanied by other technologies, including nuclear energy and carbon capture usage and storage [2,3]. Achieving net zero will require the decarbonisation of heat and transport and the incorporation of an increasing amount of electricity generation from renewables [3]. As outlined in the 2020 Energy White Paper, the UK energy system will need to be increasingly flexible at a national and local level in order to rapidly respond to changes in supply and demand, incorporate intermittent and variable renewables generation and accommodate an overall increased electricity demand due to the increased use of Electric Vehicles (EVs) and (clean) electricity replacing gas for heating [3]. The ambition for the UK's energy system is for a smarter, more flexible system which is able to provide affordable and clean energy reliably. Flexibility offers solutions to the challenges of variable renewable energy integration regarding flow, stability and balance [4]. A more flexible energy system will not only make optimum use of renewable energy and balance supply and demand, but will be able to satisfy and smooth peak demands while minimising the need for network reinforcement and increased network

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capacity. One component of flexibility provision is demand side response (DSR) whereby consumers alter their energy consumption in response to an external signal. Energy consumption can be reduced or delayed, energy can be stored for subsequent release, and energy can be generated by prosumers. DSR enables the timing of energy consumption to be shifted away from busy peak times and can also be used to increase demand during periods when renewable energy is plentiful. The vision for a smart, flexible energy system is one that will use smart technologies, smart appliances, tariffs and services to offer lower energy costs for consumers [5]. Consumers can reduce their energy consumption away from more expensive peak times and receive a financial reward for supplying flexibility, i.e. the ability to increase or decrease their consumption at particular times. Smart tariffs may include time of use tariffs based on electricity prices, load control tariffs for appliance management, tariffs for users with low carbon technology as well as export tariffs [3].

Homes themselves can provide energy flexibility, i.e. residential DSR, by shifting household consumption, by generation of electricity (e.g. from solar PV panels), and by providing energy storage, whether via home batteries or EV batteries. 'Turn-up' DSR, whereby households increase their electricity consumption, is particularly key for the integration of renewable energy at times when it is abundant. At the local level, an increase in demand can help address constraint issues, reducing the need to limit generation from local renewables e.g. wind generation [6]. Shiftable electrical loads include the use of appliances, which may be smart appliances, able to respond to control signals, electric space and hot water heating, and EV charging. 'Energy storage and flexibility' along with 'Homes' are two of the government's ten priority areas for attaining net zero [3]. 30% of greenhouse gas emissions are due to energy consumption in buildings, and attaining net zero will necessitate the decarbonisation of heat in buildings and require that buildings use energy in a smart and flexible way [5]. The vision for net zero buildings in the future is for well insulated buildings of high energy efficiency, equipped with smart low carbon technologies which can respond to dynamic price signals. Such technologies include energy storage, electric heat pumps, and microgeneration along with smart control. The proposed Future Homes Standard, to be introduced by 2025, will require new homes to be built without heating based on fossil fuel consumption [7]. To aid the decarbonisation of heating, the installation of 600,000 electric heat pumps per year by 2028 has been put forward in The Heat and Buildings Strategy, providing a potential source of residential DSR [8]. Home batteries can be used to receive energy from the grid at off-peak times, or from home solar generation which can be subsequently released at times of peak demand. The UK government intends to support the fledgling domestic flexibility market in the areas of smart meter installation, necessary for half-hourly billing, electric vehicles (EVs), smart tariffs, consumer protection and regulation for flexibility providers [5]. Demand side management (DSM) encompasses not only the response of the end-user, but also the functions of energy providers, network operators and aggregators [9]. Based on international experiences, to be successful, DSM requires support from regulatory policies for energy providers and financial incentives, as well as voluntary programmes and market-based policies such as DR tariffs [9].

Residential DSR can be realised using a price signal or other financial incentive. Time of use tariffs use price signals to shift demand from busy peak periods towards periods of low demand, or towards periods of high renewables generation. Time of use tariffs can be static, offering at least two rates at fixed times throughout the day, or dynamic, with rates changing more rapidly, e.g. at half-hourly intervals in relation to the wholesale electricity price. Changes in energy demand can be achieved by householder driven control of electricity consumption, whether manual, semi-automated using timers or smart appliances, or by fully automated control through a third party [10]. Without some form of automation, domestic control of electricity consumption against a dynamic time of use tariff may be unmanageable, and automation is viewed as crucial for the delivery of response and reserve services for the electricity network [10]. The deployment of low carbon technology to support domestic energy flexibility depends upon a positive reaction from the consumer as well as consumer demand [2], and thus the role of end user, the householder, is key to realising the potential of residential DSR in terms of householders' enrolment, engagement, interaction, and their expectations [11].

Residential DSR is in its infancy. Trials have provided a measure of the demand response, albeit under different conditions, e.g. different tariffs and timings, different household assets and varying levels of control. Potentially, automated control of battery storage or heating offers a greater demand response than manual control of electricity consumption and one which is less onerous to maintain for the long term. This area needs to be further supported with real-world data, particularly where dwellings are equipped with low carbon technologies, along with a focus on the experience of the end-user. DSR trials have rarely included the combination of home batteries, heat pumps, and solar PV panels along with automated control, nor demonstrated both a turn-down and turn-up response for this combination of elements. The current study concerns 17 households with a combination of low carbon technologies, namely home battery storage, electric heat pumps and solar PV panels, along with smart, automated control, all elements which have an envisioned role in the strategy to attain the net zero target. This study seeks to explore the questions - What level of demand response can be demonstrated with a combination of these elements?, What affects the success of a demand response intervention? and What is the householder experience of such a demand response? The study delivers empirical results for turn-down and turn-up DSR interventions using the two metrics of grid electricity import and controllable load. A household survey was used evaluate the resident experience of the trials as regards thermal comfort, hot water availability and noise, as well as any disruption to household routines.

2. Literature review

The forecasting of demand response is complex, involving variables such as electricity pricing, household consumption, renewables generation and weather conditions, and modelling methods are used to optimise cost and energy benefits for the end-user and supplier [12]. A load profile responsiveness index for modelling residential loads, i.e. a measure of load flatness, was introduced in Ref. [13] for smart homes with solar PV and battery storage. The use of virtual power plants (VPPs) can facilitate the management of distributed energy resources and enable system operators to integrate renewable energy as well as incorporate DSR flexibility from end-users [14]. A VPP optimisation model is presented in Ref. [14] based on day ahead market pricing, and a VPP model including smart homes with solar PV and EVs is described in Ref. [15]. Absorption of electricity from the grid (turn-up) has been modelled using a zero cost electricity price at times of excess renewable generation [16]. Absorption by heat pumps resulted in lower carbon emissions than when resistive heaters were used, and annual costs were reduced by 60% for heat pumps and 50% for resistive heater usage, although it was noted that resistive heaters are easier to install and have lower initial costs than heat pumps. A review of energy market optimisation models for prosumers participating in DSR is provided in Ref. [17]. Barriers to the integration of prosumers and DSR programs included the high initial costs of home battery storage and the need to maintain real-time data communications between users and the aggregator. The requirement for improvements to market regulation policies and financial incentives was highlighted, as well as renewable generation incentives.

Recent trials and studies providing a measure of residential DSR encompass occupant driven responses and responses driven by automated control. Trials differ in whether the response was obtained using a static time of use tariff or other financial incentive, against a dynamic time of use tariff or attained using standalone interventions, and additionally, whether low carbon technology (home batteries, solar PV and heat pumps) were specifically used. Time of use tariffs have been found to provide an enduring response, with evening peak loads reduced by 0.23 kWh per household (7%) [18], and between 1.5% and 11.3% [19] when occupant driven. In a London based trial of 1200 homes, occupant driven appliance shifting resulted in 5–10% reduction in peak for constraint management events [20]. In a direct comparison of manual and automated control for turn-up DSR, households with a degree of automation (a hot water timer or remote-control switches for appliances) demonstrated 13% of their daily electricity consumption within 10 a.m. to 4 p.m. compared with 5% for households with manual control [21]. An occupant driven response requires the occupant to be actively involved in the timing of energy consumption. Automated control is desirable where tariffs are complex or unpredictable, but control technologies should be 'mature' so that problems with the control systems should not dissuade users from continuing participation in demand response schemes [22]. With automated control against a four-tier static time of use tariff, eight households in Oxfordshire, UK, with 2 kWh batteries charged from the grid, showed a 20% reduction in consumption between 6 and 9 p.m. [23]. Electric heating presents an opportunity for timed or fully automated control which can be ultilised for DSR. In a study of ten new build homes in Barnsley, UK, equipped with air source heat pumps (ASHPs) under third party automated control, the daily mean heat pump electricity consumption at peak times (4–7 p.m.) was found to be 1.4 kWh, providing a measure of a potentially shiftable load [24]. When two UK-based DSR trials were compared, the demand response per household was around 25 times greater for homes in Manchester which used heat pumps under automated control than for homes in London which aimed to reduce general household consumption at peak times using occupant control, despite a good level of occupant engagement with the latter trial [25]. This was attributed to the comparative sizes of heat pump consumption and household appliance consumption, as well as thermal storage enabling heat pumps to be switched off during interventions. Residential solar PV has demonstrated reduction in peak loads. Consumption data for 300 households equipped with solar PV in Cyprus was used to derive, and then implement, a three-tier TOU tariff resulting in a seasonally dependent reduction of 1.0–3.2% in peak demand [26]. Solar PV in combination with battery storage reduced peak loads up to 70% for five households in Denmark [27], although this was seasonally dependant. In Bristol, UK, solar-charged home batteries discharged to support network evening peak demand [28]. The effect of the combination of home battery storage and solar PV was studied for 15 households in Australia across network peak demand periods [29]. It was found that not all batteries correctly 'load-followed[1]' consumption, with errors such as discharging at a lower rate than demand, charging during peak times, or inactivity, and that real-world home battery systems may under perform compared with modelled results.

Barriers to participation in residential DSR include householders' perceived disruption to patterns of daily living and lack of access to, or understanding of, the accompanying technology [30]. Householders can become disengaged due to 'fatigue' with manual shifting over time, and automation of demand response can support engagement [22,31]. Automation or direct load control can lessen the complexity and effort of the response, but this is conditional upon ensuring the ongoing trust of householders [31]. Trust may be reduced by technology issues if they are not resolved in a timely and transparent manner, or if there is a lack of transparency for pricing and automation schedules. As well as financial incentives, residential DSR requires householder engagement, devices (the home energy systems themselves as well as enabling/-control technology) and competences (the skills and knowledge for householders to incorporate DSR into daily routines [32]. An automated demand response against a dynamic tariff still requires householder acceptance against their individual consumption needs and, importantly, the householder requires continuous support regarding new technologies [22]. Although automation of DSR could avoid the requirement for some engagement, users would still need to 'accept some degree of physical and social disruption to the home' [11].

3. Methodology

3.1. Dwelling characteristics

The dwellings consisted of 16 new-build (2014), well-insulated social housing properties and one post-1950 home situated in Barnsley, UK, as detailed in Table 1. Dwellings were equipped with 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 allowed optimisation of heat pump and battery operation to achieve a least cost outcome whilst avoiding thermal discomfort. This was 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 took into account householders' schedules and preferences.

3.2. Overview of DSR trials

Four types of DSR trials were conducted between 12th March and May 5, 2021 (Table 2) on alternate weekdays. A total of 22 interventions each of 2 h duration was applied. The dwellings were divided into three trial groups (A, B and C). Groups A and B each consisted of six dwellings and Group C contained five dwellings. For Trial 1, all 17 dwellings were subject to turn-down interventions at peak times (6–8 a.m., 5–7 p.m.) against their usual tariff. For Trial 2 (Groups A and B), turn-down interventions at peak times were overlaid on a dynamic Octopus Agile[2] price signal using forecast electricity prices. For Trial 3 (Groups A and B), turn-down interventions were overlaid on a carbon optimisation price signal which was based upon forecast carbon grid intensity for the Yorkshire region.[3] For Trial 4 (Groups A and B) turn-up interventions were applied during 1–3 p.m., to represent times when generation from local renewables (e.g. solar, wind) might be available. For Trials 2 to 4, the original intention was for Group A and Group B to act as alternate test and control groups to eliminate weather variables. However, despite having a similar daily total electricity consumption, there were differences in baseline grid electricity import at peaks times and instead, a

Table 1
Dwelling characteristics.

Build	EPC rating	Usual tariff	Solar capacity	Heating
13 new build, semi-detached	4 homes, A	15 homes, flat (single rate)	16 homes within 1.3–3.0 kWp	14 homes, underfloor downstairs, radiators upstairs
1 new build, detached	12 homes, B	2 homes, Octopus Agile	1 (post-1950) home with no solar PV	2 flats, underfloor
2 new build flats	1 post-1950 home, C			1 (post-1950) home radiators
1 post-1950, semi-detached				

[1] Load-followed: Battery charged using solar PV with subsequent discharge during peak.

[2] https://octopus.energy/agile/.

[3] https://data.nationalgrideso.com/carbon-intensity1/regional-carbon-intensity-forecast.

Table 2
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 a.m. or 5–7 p.m.
2A Octopus Agile + turn-down	A	29 March-2 April	22–26 March	6–8 a.m. or 5–7 p.m.
2B Octopus Agile + turn-down	B	22–26 March	29 March-2 April	6–8 a.m. or 5–7 p.m.
3A Carbon optimisation + turn-down	A	12–16 April	5–9 April	5–7 p.m.
3B Carbon optimisation + turn-down	B	5–9 April	12–16 April	5–7 p.m.
4A Default tariff + turn-up	A	26–30 April	19–23 April	1–3 p.m.
4B Default tariff + turn-up	B	19–23 April	26–30 April	1–3 p.m.

baseline method was used to determine the impact of interventions for each group.

To assess the flexibility of the battery and heat pump system, turn-down interventions aimed to minimise grid electricity import by using battery discharge to meet household electricity demand and reducing heat pump use, as well as maximising grid export. During turn-up interventions, grid electricity was imported for battery charging and heat pumps were used where possible. For all interventions, the variation in temperature was limited to ±2 °C from the household set-point schedule. Additionally, a temporary override was in place whereby householders could alter the upstairs (non-flats) or downstairs temperatures, or boost the hot water system. Interventions were allocated as secure, for which prior notice was given to the control system, allowing changes in battery or heat pump operation prior to the intervention, or 'dynamic', which were unplanned interventions from the control system's point of view. ('Dynamic' when describing an intervention signal sent without prior warning 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).

The external daily temperatures for each baseline/trial period are provided in Table 3.

A baseline method was applied whereby baseline energy consumption was calculated as the average of the energy consumption for the appropriate 2 h time interval over the five baseline days (weekdays). Baseline weeks were adjacent to trial weeks, with the exception of Trial 1 which used the nearest preceding week for comparison which avoided pre-trial test interventions. The method assumes that the average energy consumption and weather conditions, e.g. outdoor temperature and solar irradiance, were similar between baseline and intervention weeks. During 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). Where 'the baseline' is referred to hereafter, it relates to the baseline associated with a particular trial week.

Table 3
External daily temperatures for each baseline/trial period.

Date range	Daily external temperature °C		
	Mean	Min	Max
22–26 February	7.3	4.3	11.4
12–19 March[a]	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

[a] Weekdays only.

3.3. Monitoring

Data streams at 5 min intervals were provided by Passiv UK, sourced from the battery and ASHP (Fig. 1). Internal temperatures were provided at 5 min 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. For a third dwelling, which underwent Trial 1 only, there was a lack of battery response to the control signals. All of these occurrences were taken into account for calculations of energy reduction per household.

Two metrics are used to quantify the impact of interventions, the change in grid electricity import and the change in controllable load compared with the relevant 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 during an intervention, is defined as the change in heat pump electricity consumption plus the net change in battery.

3.4. Household survey

The external control of heat pump and battery operation during interventions had the potential to disrupt household routines and householders' comfort. A series of repeated telephone surveys was undertaken to ascertain 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. 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 at least one response. 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.

4. Results

4.1. Energy consumption during heating season and baseline periods

An indication of energy consumption during the heating season and variability between dwellings is given by Fig. 2 which depicts grid electricity import and heat pump electricity consumption by dwelling for 6–8 a.m. and 5–7 p.m. (ordered by increasing grid electricity import) for November 1, 2020–February 28, 2021. The mean daily grid electricity import ranged from 1.0 to 3.3 kWh and 0.8–5.1 kWh between 6 and 8 a.m. and 5–7 p.m., respectively. The mean daily grid electricity import was found to be 2.0 kWh and 2.7 kWh between 6 and 8 a.m. and 5–7 p.m., respectively, with mean daily heat pump electricity consumption, 0.9 kWh and 0.8 kWh between 6 and 8 a.m. and 5–7 p.m., respectively. The battery discharge energy available from a battery discharge cycle (obtained from a full charging-discharging cycle which was performed monthly) was found to be 4.2 kWh, and therefore the battery would be able to 'cover' mean daily demand during the 2 h peak

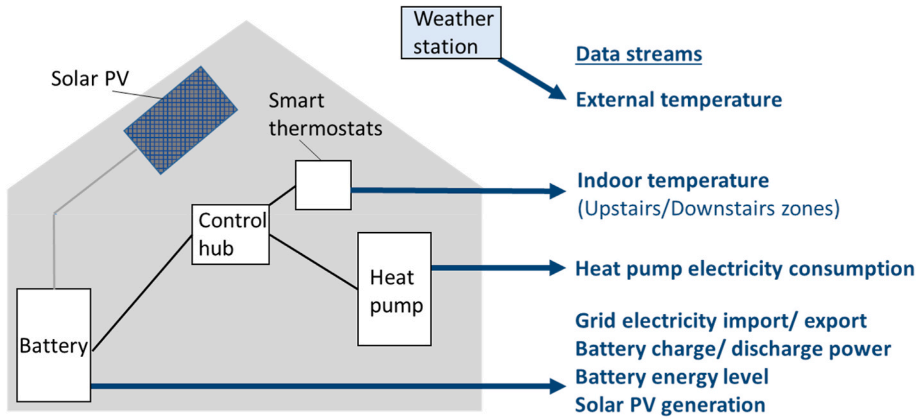

Fig. 1. Schematic of monitoring data collection.

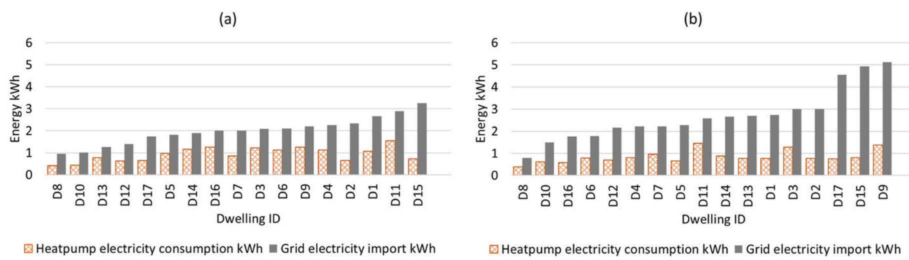

Fig. 2. Grid electricity import and heat electricity consumption by dwelling for (a) 6–8 a.m. and (b) 5–7 p.m. (ordered by increasing grid electricity import) for November 1, 2020–February 28, 2021.

intervals for all but three dwellings during 5–7 p.m., although it might be the case that at certain times, home demand could be greater than the maximum discharge rate of the battery (0.25 kW per 5 min) could supply.

Household consumption during peak times was reduced from the above averages for the various baseline weeks - baseline weeks occurred within the period late February to mid-April 2021. Across the three baseline periods serving 6–8 a.m. interventions, the mean grid electricity import per dwelling ranged from 1.1 to 1.3 kWh between 6 and 8 a.m., and heat pump electricity consumption per dwelling ranged from 0.4 to 0.5 kWh. Across the five baseline periods serving 5–7 p.m. interventions, the mean grid electricity import per dwelling ranged from 0.9 to 2.1 kWh between 5 and 7 p.m., and heat pump electricity consumption per dwelling ranged from 0.3 to 0.9 kWh.

4.2. Aggregate daily power profiles

Aggregate daily power profiles for example intervention days for each Trial are provided in Fig. 3 (turn-down) and Fig. 4 (turn-up) along with the associated baseline profiles, each of which was averaged over the five baseline days to represent usual daily demand. Fig. 3(a) illustrates the aggregate daily power profile for all dwellings during the Trial 1 baseline. Although there was some battery charging, primarily from solar generation, the average battery energy level only reached 18% and battery discharge during the evening peak made a small contribution to home consumption. Fig. 3(b) depicts the secure turn-down intervention between 5 and 7 p.m. for Trial 1 (Intervention 1). On aggregate, the battery was charged overnight and immediately prior to the intervention using grid electricity, and also with solar generated electricity during the middle of the day, such that the battery energy level at 5 p.m. was 89%. Between 5 and 7 p.m., the reduction in grid electricity import was clearly apparent, with battery discharge contributing to home consumption as well as supplying electricity for export to the grid.

Secure turn-down interventions were often more effective than dynamic turn-down interventions due to the higher battery energy level at the start of the secure interventions. Fig. 3(d) depicts a dynamic turn-down intervention between 5 and 7 p.m. of moderate impact during Trial 2 (Intervention 7), for which the corresponding baseline is shown in Fig. 3(c). There was a distinct period of overnight battery charging against the Octopus Agile time of use price signal on the day of the intervention, however, on average, the battery was almost discharged around midday. By 5 p.m., the battery had been charged to an average energy level of 75% by both solar generation and grid electricity import, which allowed subsequent battery discharge to contribute to home consumption as well supplying electricity for export to the grid. Fig. 3(f) illustrates a secure turn-down intervention between 5 and 7 p.m. during Trial 3 (Intervention 11) for which the corresponding baseline is shown in Fig. 3(e). The battery was charged against the carbon optimisation price signal overnight, and only partially discharged during the middle of the day. After further charging ahead of the intervention, on average, the battery energy level at the start of the intervention was 91%.

Fig. 4(b) depicts a secure turn-up intervention between 1 and 3 p.m. for Trial 4 (Intervention 19) during which the battery, on aggregate, was charged with both solar generated electricity and grid electricity import. The corresponding baseline is shown in Fig. 4(a). Prior to the intervention, the battery was charged by solar generation such that by 1 p.m., the battery energy level was 34%, on average. This, along with the fact that surplus solar generation was available during the intervention to further change the battery, affected the amount of grid electricity that could be imported for battery charging during the intervention itself, therefore reducing the impact of the intervention.

4.3. Aggregate daily power profiles

The mean, minimum and maximum values across the relevant groups of individual dwellings for changes in grid electricity import, heat pump electricity consumption and controllable load during each 2 h intervention compared with the appropriate baseline period are

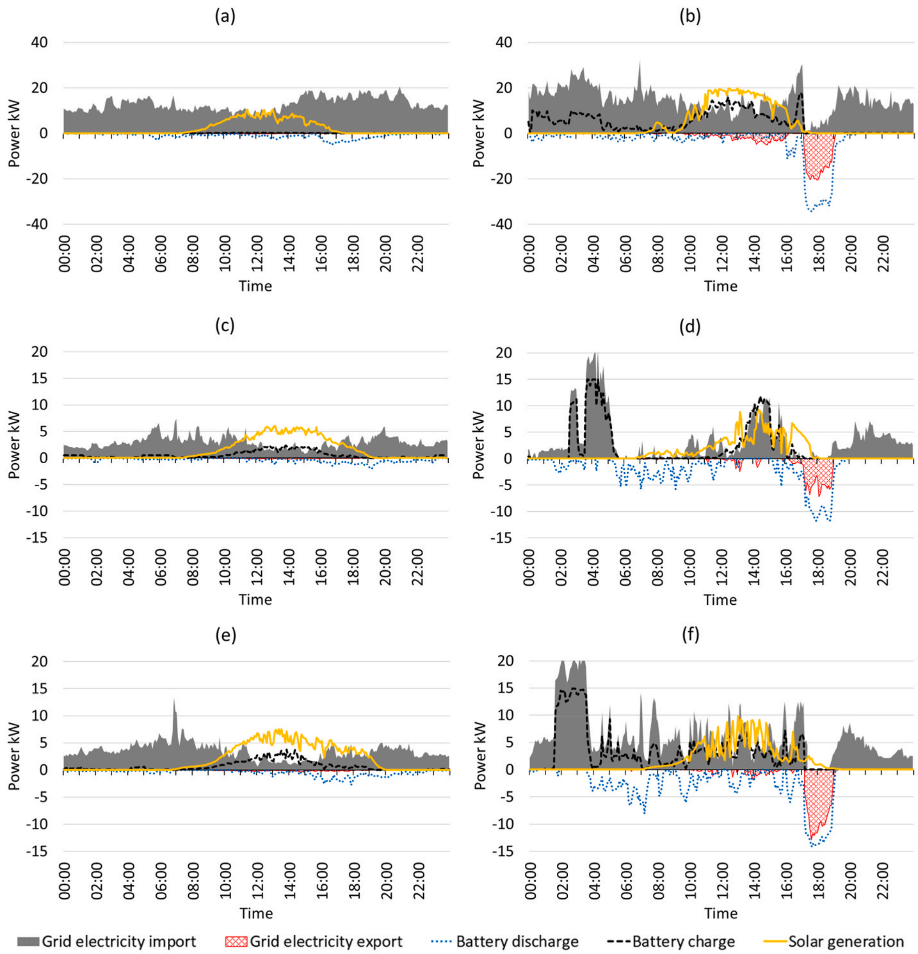

Fig. 3. Aggregate daily power profiles for example turn-down interventions with their respective baselines. (a) 22–26 February baseline - All dwellings, (b) Trial 1, Intervention 1 (Secure turn-down with default tariff, 5–7 p.m.), (c) 29 March-2 April baseline – Group A, (d) Trial 2A, Intervention 7 (Dynamic turn-down and Octopus Agile price signal, 5–7 p.m.), (e) 12–16 April baseline – Group A, (f) Trial 3A, Intervention 11 (Secure turn-down and carbon optimisation price signal, 5–7 p.m.).

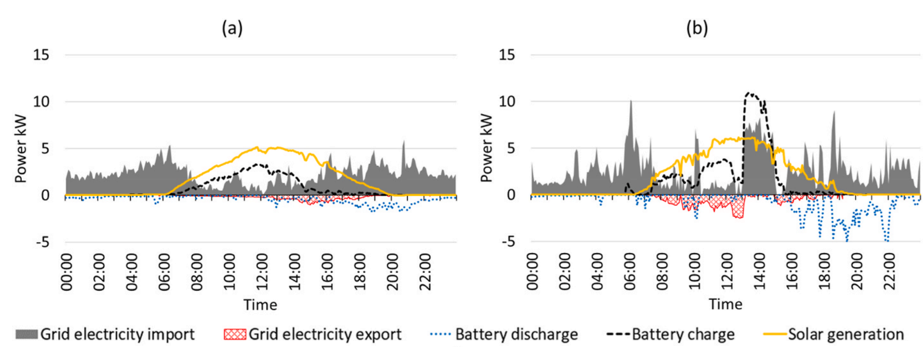

Fig. 4. Aggregate daily power profiles for an example turn-up intervention with its baselines. (a) 19–23 April baseline – Group B, (b) Trial 4B, Intervention 19 (Secure turn-up and default price signal, 1–3 p.m.).

provided in Table 4 for each intervention. Each dwelling's performance was compared against its own individual baseline.

For secure turn-down interventions the mean change in grid electricity import compared with the baseline varied from −0.9 to −1.1 kWh between 6 and 8 a.m. and −0.3 to −1.7 kWh between 5 and 7 p.m. For Intervention 11 (secure), the mean change, at −0.3 kWh, was unexpectedly low and was affected by two particular dwellings (D7 and D8) for which grid electricity import was *increased* compared with the baseline. For D7, there was a 'spike' of grid electricity import at the start of the intervention, and for D8, baseline grid electricity import was very low (0.04 kWh). The mean change in controllable load for this intervention was 3.9 kWh, highlighting the difference in intervention impact between the two metrics. The impact of dynamic interventions was less consistent. The battery energy level, on aggregate, was between 10 and 75% at the start of dynamic turn-down interventions whereas that at the start of secure turn-down interventions was between 87 and 93%, with the exception of Intervention 6 where it was 74%. The mean change in heat pump electricity consumption for all secure turn-down interventions compared with the baseline varied from −0.1 to −0.7 kWh. For dynamic interventions, the mean change in heat pump electricity consumption ranged from increasing by 0.1 kWh to decreasing by 0.7 kWh.

Although all Group B turn-up interventions demonstrated an increase in grid electricity import compared with the Group B baseline (a mean change of 1.6–3.6 kWh), the dynamic turn-up interventions for Group A (Interventions 14 and 16) showed a *decrease* in grid electricity

Table 4
Mean change in energy consumption per household (grid electricity import, heat pump electricity consumption and controllable load) compared with baseline for each intervention.

Intervention	Trial/Price signal	Secure or Dynamic	Time	Number of households	Grid electricity import kWh **Mean** *(min, max)*	Heat pump electricity consumption kWh **Mean** *(min, max)*	Controllable load kWh **Mean** *(min, max)*
1	Trial 1, Turn-down/ Default	S	5–7 p.m.	15	**−1.3** *(-4.2, 0.8)*	**−0.2** *(-0.7, 0.6)*	**−3.4** *(-4.6, -1.0)*
2		D	5–7 p.m.	15	**−0.1** *(-2.8,2.3)*	**−0.1***(-0.6, 1.2)*	**−0.3***(-2.6, 1.3)*
3		S	6–8 a.m.	16	**−1.0** *(-2.7,0.4)*	**−0.3***(-0.9, 0.3)*	**−3.9***(-4.9, -1.7)*
4		D	6–8 a.m.	16	**−0.3** *(-1.3 0.7)*	**−0.1***(-0.6, 0.5)*	**−0.4***(-2.7, 0.5)*
5	Trial 2A, Turn-down/ Agile Octopus	S	5–7 p.m.	6	**−0.8** *(-2.5,0.2)*	**−0.1***(-0.4, 0.7)*	**−3.5***(-4.2, -2.2)*
6		S	6–8 a.m.	5	**−1.1** *(-2.2,-0.1)*	**−0.2***(-0.4, 0.0)*	**−3.7***(-4.3, -2.9)*
7		D	5–7 p.m.	6	**−0.9** *(-2.1,-0.1)*	**0.1***(-0.6, 0.5)*	**−2.7***(-4.1, -1.9)*
22[a]	Trial 2B, Turn-down/ Agile Octopus	S	5–7 p.m.	6	**−1.5** *(-3.3,-0.4)*	**−0.3***(-0.9, 0.1)*	**−3.9***(-4.2, -3.4)*
8		S	6–8 a.m.	6	**−0.9***(-2.0,0.9)*	**−0.3***(-0.7, 0.0)*	**−4.3***(-4.6, 4.0)*
9		D	5–7 p.m.	6	**−0.3** *(-1.3,1.4)*	**−0.2***(-0.8, 1.1)*	**−1.7***(-3.5, 0.7)*
10	Trial 3A, Turn-down, Carbon optimisation	D	5–7 p.m.	6	**−0.8** *(-2.5,0.7)*	**−0.4***(-0.6, 0.1)*	**−3.5***(-4.2, -2.0)*
11		S	5–7 p.m.	6	**−0.3** *(-1.9,1.0)*	**−0.5***(-0.9, -0.1)*	**−3.9***(-4.1, -3.5)*
12		D	5–7 p.m.	6	**−0.6** *(-1.9,0.1)*	**−0.3***(-0.6, 0.3)*	**−2.2***(-3.8, -1.5)*
13	Trial 3B, Turn-down, Carbon optimisation	S	5–7 p.m.	6	**−1.7** *(-2.6,-1.2)*	**−0.7***(-0.8, -0.4)*	**−4.3***(-4.7, 3.8)*
14		D	5–7 p.m.	6	**−0.9** *(-2.2,1.2)*	**−0.7***(-1.2, -0.2)*	**−2.3***(-5.1, -0.6)*
15		S	5–7 p.m.	6	**−1.6** *(-2.2,-1.2)*	**−0.6***(-1.2, 0.0)*	**−4.3***(-5.2, -3.6)*
16	Trial 4A, Turn-up/ Default	D	1–.3 p.m.	6	**−0.2** *(-3.0,1.0)*	**−0.3***(-0.8, 0.0)*	**1.7***(0.6, 3.2)*
17		S	1–3 p.m.	6	**2.2** *(0.7,3.5)*	**−0.3***(-0.8, 0.6)*	**1.6***(-0.6, 2.5)*
18		D	1–3 p.m.	6	**−0.3** *(-3.4,1.7)*	**−0.2***(-0.8, 0.2)*	**1.4***(-1.2, 3.3)*
19	Trial 4B, Turn-up/ Default	S	1–3 p.m.	6	**1.6** *(0.0,3.1)*	**0.1***(-0.7, 0.4)*	**2.5***(1.0, 3.6)*
20		D	1–3 p.m.	6	**3.6** *(3.1,4.3)*	**0.3***(-0.7, 0.8)*	**2.6***(1.9, 3.1)*
21		S	1–3 p.m.	6	**3.0** *(1.7,3.9)*	**0.3***(-0.7, 0.9)*	**2.2***(1.4, 3.2)*

[a] Intervention rescheduled to 5th May.

import compared with the Group A baseline. During the baseline week, solar generation was relatively low, making less of a contribution to home consumption than might be expected, with the overall effect of relatively high grid electricity import between 1 and 3 p.m. It was therefore difficult to show a comparative increase in grid electricity import during interventions on sunnier days with respect to the baseline, and this was the case for the two dynamic interventions. During both of these interventions, a combination of surplus solar generation and grid electricity import was used to charge the battery. Additionally, the daily mean temperature for the turn-up trial week for Group A was 2.7 °C warmer than that for the baseline and there was a reduction in mean heat pump consumption for each intervention rather than an increase.

The mean changes in grid electricity import and controllable load compared with the baseline by trial are provided in Table 5 for secure interventions - this includes repeated measurements for individual dwellings across different interventions. Turn-down interventions between 5 and 7 p.m. showed a similar reduction in grid electricity import across the trials (1.1–1.2 kWh), as did turn-down interventions between 6 and 8 a.m. (1.0 kWh) for Trials 1 and 2. This similarity was due to a similar level of battery charge at the start of interventions. On aggregate, the battery energy level at the start of secure 5–7 p.m. interventions

Table 5
Mean changes in grid electricity import and controllable load per dwelling compared with baseline, across all secure interventions by trial.

Intervention type	Trial	Change in grid electricity import kWh **Mean** *(n)*	Change in controllable load kWh **Mean** *(n)*	Excluding time of use dwellings[a]: Change in grid electricity import kWh **Mean** *(n)*	Excluding time of use dwellings[a]: Change in controllable load kWh **Mean** *(n)*
Secure 5–7 p.m.	1	**−1.2** *(15)*	**−3.4** *(15)*	**−1.5** *(13)*	**−3.7** *(13)*
	2	**−1.1** *(12)*	**−3.7** *(12)*	**−1.1** *(11)*	**−3.7** *(11)*
	3	**−1.2** *(18)*	**−4.2** *(18)*	**−1.2** *(17)*	**−4.2** *(17)*
Secure 6–8 a.m.	1	**−1.0** *(16)*	**−3.9** *(16)*	**−1.1** *(14)*	**−4.2** *(14)*
	2	**−1.0** *(11)*	**−4.0** *(11)*	**−0.8** *(11)*	**−4.0** *(11)*
Secure 1–3 p.m.	4	**2.3** *(18)*	**2.1** *(18)*	**2.3** *(17)*	**2.3** *(17)*

[a] Dwellings normally on a time of use tariff (D1 and D11) excluded.

across Trials 1 to 3 was between 87 and 93% at the start of secure 5–7 p.m. interventions. Trial 1 interventions were found to give a mean change in grid electricity import of −1.5 kWh when the two dwellings on a time of use tariff were excluded. These two dwellings were subject to their default time of use tariff during the baseline period associated with Trial 1, and the resulting battery discharge during 5–7 p.m. affected the calculated difference between baseline and intervention. With the exclusion of the two time of use dwellings, the mean change in controllable load for secure turn-down interventions across Trials 1 to 3 ranged from −3.7 kWh to −4.2 kWh and the secure turn-up interventions resulted in an increase in grid electricity import of 2.3 kWh, on average.

4.4. Grid export

As well as targeting a reduction in grid import, turn down interventions also targeted grid export such that any battery discharge that was not used to meet household demand during intervention times was exported rather than saved to help satisfy post-intervention household demand. For all secure interventions between 5 and 7 p.m., the mean change in grid export per dwelling compared with the relevant was found to be 2.5 kWh with a range of 0–4.2 kWh baseline (there was very little baseline grid export between 5 and 7 p.m.). Dwellings with high baseline consumption between 5 and 7 p.m. exhibited lower grid export, e.g. for the Trial 1 secure intervention between 5 and 7 p.m., there was no grid export for dwellings D9 and D17. Both dwellings were dwellings with high consumption, with baseline grid electricity import of 4.6 kWh and 5.1 kWh between 5 and 7 p.m., respectively. For the Trial 1 dynamic intervention between 5 and 7 p.m., only dwelling D16 (solar capacity 3.0 kWp) displayed grid export above 1 kWh and this was enabled due to the battery being charged with solar generated electricity prior to the intervention. For the Trial 1 secure intervention between 6 and 8 a.m., the mean grid export per dwelling was 2.7 kWh. For the Trial 1 dynamic intervention between 6 and 8 a.m., only the two dwellings on an Octopus Agile tariff displayed grid export above 1 kWh and this was enabled due to the battery being charged with grid electricity import prior to the intervention. For Trial 2 and Trial 3 dynamic interventions between 5 and 7 p.m., battery charging against the time of use tariffs along with prior solar generation meant that grid export occurred for the majority of dwellings, although the mean grid export per dynamic intervention for Trials 2 and 3 was 1.5 kWh, compared with 2.7 kWh for the secure interventions.

4.5. Individual dwelling analysis

To illustrate differences in dwelling response, bar charts of changes in grid electricity import and grid export and a breakdown of controllable load changes (battery and heat pump changes) by dwelling compared with each dwelling's individual baseline are provided in Fig. 5 for Intervention 1, the Trial 1 secure intervention between 5 and 7 p.m. There was no grid export for the associated baseline week during 5–7 p.m.

Dwelling D15 displayed the greatest reduction in grid electricity import. For this dwelling, baseline grid electricity import between 5 and 7 p.m. was high, at 4.5 kWh. The dwellings on a time of use tariff (D1 and D11) showed a small reduction and increase in grid electricity import, respectively, during the interventions compared with the baseline. Grid electricity import was normally fairly low between 5 and 7 p.m. for these dwellings. Dwellings D7 and D8 showed a 0 kWh change and a 0.7 kWh reduction in grid electricity import compared with the baseline, respectively. Baseline grid electricity import between 5 and 7 p.m. was relatively low for both of these dwellings at 0.7 kWh (D7) and 1.0 kWh (D8). There was no grid export for dwellings D9 and D17, and relatively low grid export for Dwelling D15 (0.8 kWh), and all three dwellings normally had high consumption between 5 and 7 p.m. Dwellings D1 and D11 were both on a time of use tariff. Despite battery discharge during the intervention, the difference between the baseline and intervention controllable load was affected by the fact that the battery normally discharged between 5 and 7 p.m. Dwelling D9 also displayed a relatively low reduction in controllable load (−1.3 kWh). For this intervention, the battery at the start of the intervention was only half-charged and it is thought this was due to usually high household demand prior to the intervention. Fig. 5 (b) shows that battery discharge was the main contributor to changes in controllable load for secure interventions, with heat pump electricity consumption playing a lesser role. For 11 dwellings, heat pump electricity consumption was reduced compared with the baseline.

Bar charts of changes in grid electricity import and a breakdown of controllable load changes by dwelling compared with each dwelling's individual baseline are provided in Fig. 6 for Intervention 19, a Trial 4 turn-up intervention between 1 and 3 p.m. applied to Group B dwellings. Dwelling D13 was a low consumption dwelling, particularly during the middle of the day. Prior to and during the intervention the battery was charged solely with solar generation, and during the intervention there was no grid electricity import at all. For dwelling D5, the heat pump was not used during the intervention (the indoor temperature was 22 °C during the intervention), resulting in a reduction in heat pump electricity consumption compared with the baseline. For the other five dwellings, the heat pump was used during the intervention.

4.5.1. Comparison between low consumption and high consumption dwellings

Fig. 7 compares the daily power profiles for the Trial 1 secure intervention between 5 and 7 p.m. (Intervention 1) for two individual dwellings, both on a flat (single) rate tariff, one with normally high daily household consumption, the other with normally low consumption. The high consumption dwelling (D17) was a semi-detached, post-1950 house with two occupants. The dwelling was without solar PV. Baseline grid electricity import during 5–7 p.m. was particularly high, at 5.1 kWh. The battery was nearly fully charged at the start of the intervention (battery energy level 92%), but although the battery steadily discharged throughout the intervention and did not fully discharge until 7 p.m., the

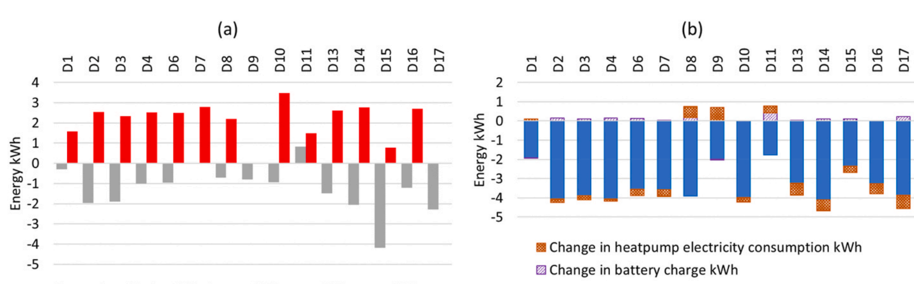

Fig. 5. Trial 1, Intervention 1 (Secure turn-down with default tariff, 5–7 p.m.). (a) Change in grid electricity import and grid electricity export compared with baseline by dwelling, (b) Breakdown of controllable load breakdown compared with baseline by dwelling.

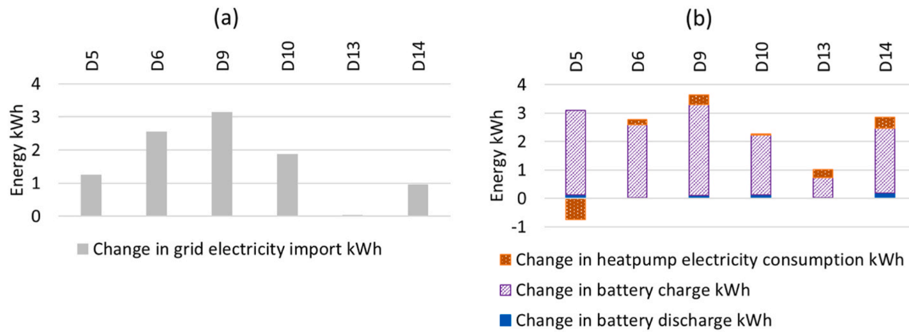

Fig. 6. Trial 4, Intervention 19 (Secure turn-up with default tariff, 1–3 p.m.). (a) Change in grid electricity import compared with baseline by dwelling, (b) Breakdown of controllable load breakdown compared with baseline by dwelling.

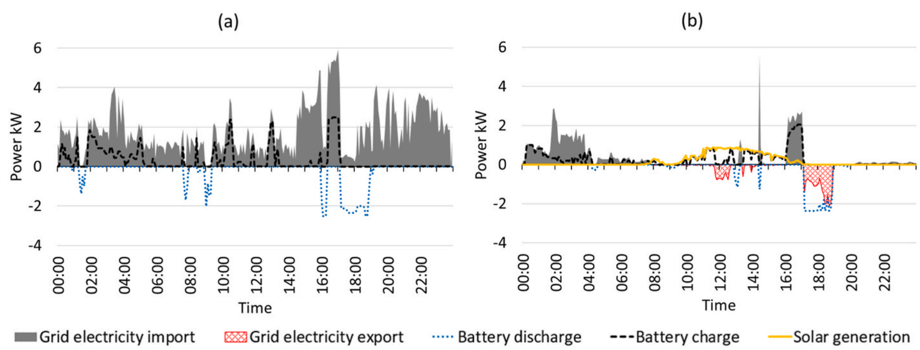

Fig. 7. Individual dwelling daily power profiles for example intervention: Trial 1, Intervention 1 (Secure turn-down with default tariff, 5–7 p.m.), (a) High consumption dwelling (b) Low consumption dwelling.

battery could not fully satisfy household consumption during the intervention. There was 2.9 kWh of grid electricity import with no grid export, and heat pump electricity consumption was low (0.1 kWh). However, compared with the baseline, grid electricity import was reduced by 2.3 kWh. The low consumption dwelling (D8) was a ground floor flat with a single occupant. Baseline grid electricity import during 5–7 p.m. was 1.0 kWh. The battery was fully charged prior to the start of the intervention (battery energy level 96%) by a combination of solar generated electricity and grid electricity import. There was low grid electricity import throughout the intervention (0.3 kWh), although there was heat pump usage during most of the intervention (1.0 kWh). There was export to the grid as the battery discharged.

4.6. Resident experience

The results of the telephone survey comprised the resident experience of specific aspects of the trial along with the overall acceptability of the trials and general feedback.

Across the trials, hot water was always or often available in the majority of households, but sometimes available in two households and rarely in another, although the latter household rarely used the hot water system due to the usual practice of boiling water in a kettle to obtain a higher temperature for washing-up water. Hot water for showering was not affected since homes had electric showers installed.

Across the trials period, 58% (out of 31) responses stated that the indoor temperature felt the same as usual (Table 6). For the remaining households, no pattern could be discerned 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 indoor temperatures being too cold, not specific to the trials period, and for the remaining household, measured temperatures were not colder than usual at intervention times. Only one of the three households which felt much warmer than usual displayed an increase in measured household temperature corresponding to an intervention, the increase occurring ahead of the intervention, suggesting pre-heating. For the turn-up trial, Trial 4, there were no reports of the indoor temperature feeling warmer than usual, as might have been expected if the heating was switched on unusually. However, the daily mean external temperature during the surplus renewables trial was only 10.0 °C and 7.7 °C for the Group A and Group B trial weeks, respectively. During the trials, 58% (out of 31) responses stated that no action was taken to change the indoor temperature, with 39% reporting that the temperature was changed using the heating control (phone) app, although altering the indoor temperature was normal behaviour for many households and could therefore not be attributed 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

Table 6
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

concern. Ten households were rarely or never disturbed by battery noise and eight households were rarely or never disturbed by heat pump noise. Upon being asked 'How were your daily household activities affected by the trial?', no households reported daily activities being affected by the trial itself.

Across the three surveys, 77% (out of 31) responses, stated that the changes experienced during the trials, i.e. to hot water availability, indoor temperatures and noise disturbance from the battery and heat pump, were acceptable or slightly acceptable, or that households were neutral towards them. A breakdown of responses is provided in Table 7. Acceptability of the intervention-related changes was high, even among households who reported some lack of hot water availability, changes in indoor temperature or noise disturbance. For 23% (out of 31) responses the trial changes were considered unacceptable, however these responses came from the three households affected by ongoing issues of low indoor temperatures and this was the overriding reason for unacceptability rather than trial changes themselves.

In response to 'Do you have any concerns about the trial?', only one household had a trial related concern, that hot water was not always available. Nine households reported general, ongoing concerns, not necessarily related to the trial weeks. Six comments referred to electricity costs, however there was no clear evidence of system behaviour that would increase costs and tariff prices had increased for both the time of use and single (flat) rate tariffs during recent months. One comment related to the hot water not being hot enough, e.g. to have a bath. 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 meet their thermal comfort requirements was required.

5. Discussion

Across all secure turn-down interventions between 5 and 7 p.m., regardless of trial, control of home batteries and heat pumps combined enabled grid electricity import to be reduced by a mean of 1.2 kWh per dwelling whilst increasing grid export by a mean of 2.5 kWh per dwelling. A turn-down of 1.2 kWh indicates a potential 44% reduction in grid electricity consumption between 5 and 7 p.m. during November to February. During Trials 1 to 3, where baseline consumption was lower than the November to February average, the reduction in grid electricity import between 5 and 7 p.m. was reduced by 36–86% on aggregate, across secure interventions. Between 6 and 8 a.m., grid electricity import was reduced by 73–84%, on aggregate across secure interventions. There was an average 2.3 kWh turn-up response for grid electricity import between 1 and 3 p.m. for secure interventions. These results show a greater percentage response than the 20% reduction obtained with 2 kWh battery storage for a 3 h evening intervention [27].

Table 7
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

The size of the battery itself is an additional consideration in relation to a particular household's consumption patterns and its ability for self-generation (solar), both from the householder side [33] and from the viewpoint of an aggregated demand response [34].

Battery discharge was the main contributor to changes in controllable load for turn-down interventions, with heat pump electricity consumption playing a much lesser role, reflecting the relative capability of the two assets. Across all secure turn-down interventions between 5 and 7 p.m., heat pump electricity consumption was reduced by 0.34 kWh per household, on average, compared with the baseline, 9% of the 3.8 kWh mean change in controllable load for those interventions. Such a change in heat pump electricity consumption would be a reduction of 13% of the evening peak household demand of 2.7 kWh during the November to February portion of the heating season (Section 4.1), and presents a worthwhile response in its own right.

In terms of the conditions required for a successful DSR turn-down intervention, as might be expected, secure interventions demonstrated greater changes, on average, in grid electricity import and controllable load than dynamic interventions. For secure turn-down interventions, battery charging ahead of the intervention could be planned, and all dwellings demonstrated the capability for a successful intervention in terms of a reduction in controllable load, the main component of which was battery discharge. Where secure turn-down interventions were not so successful, this could be attributed to the battery not being sufficiently charged at the start of interventions, perhaps due to unexpected high consumption prior to an intervention, or, in the case of the two time of use dwellings for Trial 1, attributed to battery discharge during the baseline which effectively reduced the impact of the intervention. The impact in terms of grid electricity import was affected by the usual level of household demand. Irregularly occurring 'spikes' of grid import during baselines or interventions could affect the magnitude of intervention response. Dwellings with normally low household consumption at intervention times were limited as to how much grid electricity import could be reduced compared with the baseline. Dwellings of high consumption were able to demonstrate a greater reduction in grid electricity import, but could be limited in providing export to the grid during interventions.

For dynamic interventions against a flat (single) rate tariff, dwellings relied on solar generation to partially charge the battery ahead of 5–7 p.m. turn-down interventions, hence the response to such interventions was inconsistent. Dwellings on a time of use tariff are able to demonstrate a response to dynamic interventions if times of lower pricing correspond to suitable periods for battery charging ahead of an intervention. With a flat (single) rate tariff, dynamic interventions are not suitable for dwellings without solar PV panels, nor for 6–8 a.m. interventions during the darker months. The single post-1950 dwelling underwent Trial 1 only. Secure interventions were successful in terms of reducing grid electricity import and controllable load - for the secure 5–7 p.m. intervention for this dwelling there was a reduction in grid electricity import of 2.3 kWh, and a reduction in controllable load of 4.3 kWh, compared with the baseline. However, the dynamic 5–7 p.m. Trial 1 intervention had a low impact in terms of controllable load with a reduction of 0.4 kWh compared with the baseline, and grid electricity import was reduced by 0.6 kWh. This was due to the lack of battery charging on a flat tariff, with no solar generation capability. This is in contrast to dwelling D17, which had a solar capacity of 3 kWp, and demonstrated a reduction in controllable load of 2.6 kWh during the same intervention.

Trials 2 and 3 demonstrated how 2 h turn-down interventions could be overlaid on a dynamic time of use tariff. The battery was charged during periods when the price signal was lower. Ahead of 5–7 p.m. interventions, the battery could also be charged with solar generated electricity. The impact of these interventions was determined by comparing grid electricity import and controllable load against a baseline subject to a flat (single) rate tariff for all of the dwellings. The findings provide more evidence as to the magnitude of the impact attainable for these dwellings equipped with batteries, heat pumps and solar PV against a flat (single) rate tariff rather than providing a measured effect of an intervention against ongoing time of use behaviour.

For prosumer households, turn-up interventions were particularly affected by the amount of solar generation prior to and during the interventions, since this affected the battery energy level and therefore how much grid electricity import the battery could accept. Dwellings with a higher solar PV capacity could have a reduced ability to accept grid electricity import on sunny days, particularly if household demand was low during times of solar generation, resulting in a greater amount of surplus generation for battery charging. However, overall the turn-up trial demonstrated the capability to accept, on average, 2.3 kWh per dwelling of grid electricity import in a 2 h period. Future work could assess this capability at other times of day and year to consider the potential for turn-up at times of local renewables generation.

The home batteries demonstrated discharge up to 4.2 kWh. Discharge energy can be used to reduce grid electricity import as well as to export electricity to the grid. For turn-down interventions, grid electricity import was minimised and grid export was maximised where possible, to allow full utilisation of the battery. However, for the 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. The trial dwellings would clearly benefit from a tariff with a low rate period during which the battery could be charged. Since, on aggregate, it was typical for the battery to fully discharge over a 2 h period during secure turn-down interventions, a tariff that is able to reward avoidance of 2 h peak times, or reward grid export at peak times (in addition to any feed in tariff) would also be desirable. A dual rate tariff where the on-peak period lasts for several hours may not be as beneficial. Dwellings with high consumption may be penalised if demand cannot be reduced to that which the battery is able to satisfy, as well as not being able to take full advantage of any reward for grid export. Dwellings of low consumption may have less to gain from avoiding grid electricity import at peak times, but would be able to take advantage of rewards for grid export at peak times. In considering ongoing dynamic time of use tariffs, dwellings with low consumption may be more able to use battery energy to help meet demand during the post-intervention shoulder where rates may still be relatively high. Conversely, dwellings with high consumption may be more at risk of importing electricity from the grid during peak and shoulder times.

DSR changes were generally acceptable to householders. The DSR trials provided four different sets of interventions over a seven week period. Ten of the surveyed households (Groups A and B) experienced thirteen individual interventions of 2 h duration within a seven week period, and two separate weeks (weekdays only) of battery and heat pump operation with respect to artificial tariffs. It should be noted that acceptance of the trial interventions was obtained under the conditions of well insulated homes, a ± 2 °C limit on changes in indoor temperatures and the ability for householders to temporarily override heat pump operation. Heat pump operation could also be enabled by battery discharge where the battery was sufficiently charged. The three households which viewed the trials as unacceptable/slightly unacceptable had general issues with indoor temperatures, and these views did not relate to the trials themselves. The majority of householders' concerns were general to the home energy systems 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 decreasing as expected following the installation of heat pump and battery, rather than increasing costs. For some householders, the expectation of the heating system performance affected their experience, due to a longer warm-up period with the heat pumps compared with householders' previous gas systems or since the hot water temperature was cooler than with former systems. The need for householders to be informed on how the performance of a new heating system could be different from expectations has previously been highlighted [35]. There is a requirement for DSR participation to commence only after new household assets have been routinely operated over a period of time to identify and resolve any system issues which could result in disengagement with DSR itself. Training on the operation and control of new heating systems is essential along with ongoing support.

Trial limitations included the lack of repeated interventions with the same variables, e.g. intervention time, type (secure/dynamic), trial type, and dwelling group. Additionally, although the baseline periods were close to their respective trial periods with the intention that household energy consumption profiles and weather conditions would be similar, the baseline method did not directly account for variation in outdoor temperature and solar irradiance. With interventions conducted at different times of the year, changes may be more noticeable to householders.

6. Conclusion

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. The deployment of low carbon technologies in households is viewed as key for the decarbonisation of heating, as well the realisation of residential DSR. In the transition towards an energy system that is decarbonised and flexible, the role of the householders and their acceptance of smart low carbon technologies are also crucial.

During peak times, 17 dwellings equipped with home battery storage, ASHP and solar PV assets under co-ordinated, third party automated control demonstrated a turn-down effect in grid electricity import along with the ability to export electricity to the grid whilst being broadly acceptable to householders in terms of maintaining householder's thermal comfort, noise disturbance, and without disrupting household routines under the conditions of thermal comfort limits and manual override. Automated control was required for the co-ordinated demand response obtained from the household assets. This need for automation should be considered in plans for the scalability of DSR especially in light of the general acceptance of the trials by householders. Such a demand response could be useful at the local level where households are equipped with similar low carbon technology, as long as there is enough participation to provide a meaningful demand response at the local network. On a larger scale, sufficient penetration would still be necessary. An awareness of the mix of households in terms of the level and patterns of energy consumption is required. Households with low consumption potentially offer less of a turn-down effect, but greater capability for grid export from battery discharge at peak times, with the opposite being likely for households with high consumption. Future work would be to determine the demand response, both turn-down and turn-up, at times throughout the year, as well as investigating the effect at the LV network level for households in the same locality. Among households with similar low carbon technology, there will be different levels and patterns of consumption. It will be important to build up a picture of consumption patterns for homes with low carbon technology assets and their behaviour against tariff structures, particularly for DSR application at the local level if there is a high penetration of such assets.

Requirements for the successful deployment and expansion of DSR schemes using smart low carbon technology include the maintenance of householder engagement with new systems and enabling technology and individual support and training for their operation. Transparency on electricity costs and savings will be required to preserve householder engagement. In-home displays, in communication with smart meters, can provide real-time energy consumption and energy cost information, thereby improving the management and integration of residential DSR. Additionally, there should be a period of routine working for new systems prior to DSR commencement, particularly if systems are retrofitted into existing homes and an older heating system replaced, with timely resolution of any system issues. This will require skilled personnel in the installation and trouble-shooting of household carbon systems, as outlined in the Heat and Buildings Strategy [8]. Obviously, suitable financial recompense would be required with tariffs and pricing structures in place and the technology itself should be affordable in light of the expected benefits. The widespread uptake of domestic DSR will also rely upon the planned government support structures for both flexibility providers and consumers being in place.

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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