Home Response: Domestic Demand Side Response Insights Report

Greater London Authority

March 2022

Element Energy Limited
Suite 1, Bishop Bateman Court
Thompson's Lane
Cambridge, CB5 8AQ

Acknowledgements

The project consortium has had critical support, input, and partnership from several different organisations that have led to the success of this Home Response trial project. In particular, the consortium would like to give many thanks and acknowledgements to the following list of local authorities, housing associations, and additional organisations who have made significant contributions via their involvement in progressing project:

- **Local authorities & housing associations**:
    - Royal Borough of Kensington and Chelsea
    - Camden
    - Waltham Forest
    - Westminster
    - Lewisham
    - L&Q
- **Additional organisations directly involved with project progress**:
    - Connected Response
    - Perfect Sense
    - Carbon3
    - Energy Unlocked
    - Apteno Consulting

Additionally, many thanks to the following groups for their sharing of relevant findings, general guidance and advice, and participation in various engagements with the Home Response Project:

- **Local Authorities & Government Associations**: Lambeth, Islington, Barking and Dagenham, Newham, Southwark, and London Councils.
- **Housing associations**: Clarion Housing Group, The Hyde Group, Metropolitan Thames Valley, Network Homes, Notting Hill Genesis, and Peabody.
- **Other contributors**: Equiwatt, Flexitricity, The Carbon Trust, Sharing Cities DDSR projects, Association of Decentralised Energy, EDF, Smart DCC, SLS, Smart Energy Information Exchange, Energy for London, Future Climate, and G. Birchall

Executive summary

The Mayor aims to make London a net zero-carbon city by 2030. The UK remains the only major economy to have a net zero target enshrined in law – by 2050. To achieve this, huge increases in renewable generation and a significant electrification of the energy-demanding transport and heating sectors are required. Matching this increasing electricity demand to the variable renewable generation remains one of the primary challenges to complete decarbonisation of the electricity network (i.e. the grid).

The relatively new concept of Demand Side Response (DSR) is expected to play a large part in meeting this challenge. DSR essentially involves network customers shifting their usage in response to a signal or incentive from the network operator. Any appliance, device, or vehicle which can shift its electrical consumption with minimal impact to the user can be considered as a potential flexible asset.

The Home Response project was a trial to test domestic DSR solutions in London. Two use cases were investigated:

- Battery installations in households with existing solar PV installations.
- Smart controls and monitoring equipment for existing electrically heated hot water storage tanks on E7 tariffs in flats owned by housing associations or local authorities.

The principal Key Performance Indicators (KPIs) against which the use cases were assessed were: the reduction in energy cost for the customer through shifting or reduction of consumption; the increase in energy system flexibility as measured by the installed capacity (in power and energy terms) and utilisation rate; and the reduction in CO_2 emissions associated with the shift in usage to times of lower grid carbon intensity. A full table of KPIs is available in 1.3. These were assessed alongside an investigation into the viability of commercialisation as assessed by a long-term Cost-Benefit Analysis (CBA).

The pandemic posed a significant challenge at several project stages, particularly in participant engagement and arranging installations, given the restrictions on indoor contact. Despite this, 23 batteries and 35 hot water installations were achieved. The large variation in physical properties of the existing hot water tank installations also posed a challenge for the project at the installation and data analysis stages; these cases required manual examination of the data from each device to infer its properties and understand its behaviour.

This study concludes in the context of the wider energy crisis which has seen unprecedented increased in electricity prices both in the wholesale and (eventually, due to the Ofgem price cap) consumer markets. The rapid increase in prices and the delay in passing this on to consumers has greatly complicated the business case analysis, although the report has attempted to clarify uncertainties where present and suggest likely outcomes for various future scenarios. In general, increased energy prices lead to greater savings and shorter payback times for both use cases.

A smart battery has the potential to create value in several ways:

1. Storing excess PV production in order to reduce grid import later in the day: simulations showed that an average customer on a flat tariff would save £117/year from the battery.
2. Performing price arbitrage, i.e. importing at cheap times and exporting at expensive times if able to switch from a flat to a Time-of-Use (ToU) tariff: simulations showed that the battery plus switching to a dynamic ToU tariff could save £237 per year, or £310 if a customer were able to enrol on an export tariff.
3. Participating in DNO/DSO and National Grid ESO flexibility services: estimations indicate that values on the order of £269/year could be earned.

The CBA concluded that in an 'average' optimism scenario, the battery would present a payback time of approximately 10 years, although this depends primarily on participation in the flexibility services in conjunction with other the value creation methods.

The hot water installations were primarily used for monitoring purposes during the trial, without altering the previously configured heating regime. However, the installations could be used to create value in the following ways:

1. Shifting the heating within the current E7 off-peak to reduce heat loss and improve comfort: considerable scope was identified to shift the consumption to later in the off-peak period. The use of E10 tariffs is another simple method to reduce the chance of insufficiently hot water in the evening.
2. Shifting the heating to times of even lower prices through a dynamic ToU tariff: by simulating a simple heating regime that responds to half-hourly wholesale prices (e.g. via the Octopus Agile tariff), it was found that cost for the customer could be reduced by 50% compared to E7 without changing the total daily consumption, with likely equal or better comfort than the status quo regime, while providing greater flexibility for the grid than the relatively rigid E7 window.
3. Identifying devices that are incorrectly configured for their current regime and allowing a customer or landlord to fix them: several devices were identified as being incorrectly configured or malfunctioning, even in the project's relatively small dataset sample, leading to regular heating outside the E7 window and therefore significantly increased costs for these users.
4. Participating in flexibility services, specifically the Balancing Mechanism (BM) and the potential for a hypothetical demand turn-up service. The potential revenue from these services was found to be small (<£10/year).

The CBA concluded that the revenue from switching to and optimising for a dynamic ToU tariff was significant and in an 'average' optimism scenario could lead to a payback time of approximately 10 years. Further research is necessary to investigate more advanced methods of hot water optimisation for the dynamic ToU tariff.

In summary, both use cases have the potential to offer increased flexibility to the grid. Both present a potentially viable business case but are highly dependent on a range of factors which influence the expected revenue, in particular the prices of the wider energy market. There are several 'quick wins' available, especially in the hot water use case, which merit immediate investigation. The robust data analysis performed for this project can be generalised and may be useful for further studies on these use cases, not strictly being limited to DSR trials.

Glossary

This page provides an overview of definitions and initialisations which are used in the report.

Initialisations:

- **AI:** Artificial Intelligence
- **DNO**: Distribution Network Operator
- **DSO**: Distribution System Operator
- **DSR**: Demand Side Response
- **DUoS**: Distribution Use of System (charges)
- **E7**: Economy 7 tariff (Energy tariff with cheaper rates for seven hours during the night).
- **ESO**: Energy System Operator
- **FiT**: Feed-in-Tariff
- **HR**: Home Response
- **LV**: Low voltage
- **NG**: National Grid
- **NG ESO**: National Grid Electricity System Operator
- **PV**: Photovoltaic
- **SoC**: State of Charge
- **ToU**: Time-of-Use (tariff)
- **UKPN**: UK Power Networks
- **UKPN LPN/EPN**: UK Power Networks London Power Networks / Eastern Power Networks

Definitions:

- **Capacity** (of hot water tank): its volume in litres.
- **Consumption** (in context of the hot water use case): the electrical consumption of the heating element.
- **Dynamic ToU tariff**: A Time-of-Use tariff which changes price on a half-hourly basis according to wholesale energy market fluctuations.
- **Usage** (in context of the hot water use case): the volume of water flowing through the tank to the point of hot water use.
- **ToU tariff:** An electricity tariff which involves price changes throughout the day, these may be pre-determined or variable.

Key insights

This section outlines the key findings of the project, split into the two distinct Demand Side Response (DSR) use cases investigated.

Battery use case

This use case investigated domestic smart batteries which were installed as an addition to an existing solar photovoltaic (PV) installation.

Engagement, installation, operation, and maintenance

- The Moixa batteries (which are homogeneous, unlike the hot water tanks) are reliable and have required minimal remediation work compared to the hot water systems.
- Smart meters would be required for many of the tariffs which were simulated in this report and showed significant benefits for the customer and the grid.

Data analysis

- There is a large variation in daily consumption profile (total daily consumption was 3.9-15.7kWh/day), suggesting that the assumption of a single 'domestic household profile' (commonly used in industry) for all households may cause issues in cases such as this which involve non-linearities.
- There was also large variation in measured PV production between households, and the correlation between this and the nominal PV installation size was weaker than expected (Pearson's r: 0.56), indicating that other factors such as age of PV panels, cleanliness, placement angle, or obstructions causing shade are highly significant.
- The PV production is heavily season dependent, producing 2.7 times as much energy in summer as in winter. Most households were net exporters in summer, while in winter grid exports were rare.
- On average the households consume slightly more energy than they produce from their PV panels (7.55kWh/day vs. 5.67kWh/day).
- The 4.8kWh battery is appropriately sized for these households *on a daily basis,* but not for longer timescales than this – i.e. the battery is not able to store excess solar over a period of several sunny days for use in a period of sustained high consumption days.

Business modelling

Note that most figures assume 'normal market conditions' of the late 2010s, before wholesale energy costs greatly increased in 2021. If wholesale costs do not return, then these revenue figures may be higher. See 2.3.3 for more information.

- A simulation of battery operation on various tariffs showed that the addition of the battery saves £88-£170 per year on average, depending on the tariff.
- If the effect of the battery alongside savings from tariff switching are considered, the potential for savings increases. Three scenarios were envisaged: 'low', 'average' and 'high', which saved the customer £117, £237 and £310 (33%, 67% and 87%) respectively compared to the baseline case of a customer with PV panels on a typical flat tariff.
- For households on a flat tariff, battery savings are strongly dependent on the level of PV production. Households with low PV production which cannot switch tariffs would not benefit from a battery.

- Savings due to the battery on a dynamic ToU tariff were positively correlated with the daily volatility of the import price, indicating that if the wholesale daily volatility increases, so will the potential returns from this use case.
- Using time banding which has a definition of peak time as 16:00-19:00 weekdays (aligned to UKPN Eastern Power Networks DUoS 'red'), the simulation showed that the addition of a battery optimised for a flat tariff does not significantly reduce the peak time grid import. However, when the battery is optimised for a dynamic ToU export tariff under normal market conditions, the household exports an average of 2.1kWh/day during this peak period, effectively offsetting the peak-time demand of 2.5 'regular' households (i.e. without batteries or solar panels).
- The theoretical flexibility potential per battery is 2.4kW for 2 hours, as the power rating is 2.4kW and the capacity rating is 4.8kWh. However, if the batteries are being used normally for price arbitrage, then they will not always have 100% charge available for flex services.
- UKPN Secure / Sustain: To provide this service, using 95%+ capacity of the available fleet, the average cost to the consumer (accounting for the average proportion of required dispatches) ranges from 10 - 16p/kWh. The total cost to a consumer would be between £6 - £10 per kW per year and the revenue for this service is estimated at between £45 - £60 per kW per year.
- UKPN Dynamic: One hour gating to plan for a 30- or 60-minute dispatches were tested. For both services, the cost to the consumer is notably higher than Secure/Sustain, which have longer notice periods. Regarding service delivery, the simulation observed ~100% for the 30-min dispatch and only 50% for the 60-min dispatch. Considering the costs and service provision ability, a fleet derating factor of 33% is recommended for 60-minute dispatches to allow a margin whereby the system would be able to provide the service at a reasonable cost. However, even with this consideration this service is unlikely to be very profitable for domestic consumers.
- Balancing Mechanism: by having a 90-min gating (pre-planning time) ahead of only a 30-min dispatch, tests have shown availability being consistently up to the theoretical max power. For this full provision, cost to the consumer is 18p/kWh for Offers and 2 - 4p/kWh for Bids. The total cost to a consumer would be between £4.5 - £9 per kW per year for Offers and £2.8 - £3.8 per kW per year for Bids. The total revenue is estimated for the Offers is £8.5 - £17 while for Bids is £7.7 - £17.3.
- The CBA analysis indicates that if the technology could be optimised across arbitrage for self-use and participation in DNO/DSO and NG frequency services, the batteries would have a payback time of approximately 10 years under an 'average' optimism scenario.

Hot water use case

This use case investigated adding smart controls and monitoring equipment for existing electrically heated hot water tanks.

Engagement, installation, operation, and maintenance

- Coordination with social landlords, high-density deployment (i.e. focused locations with many installations), and quality installations were key to enable cost-effective deployment of the technology.
- Remedial works were difficult to organise and expensive to conduct.
- There was a large variation in hot water tank physical properties (capacity, pipe location, insulation levels, location of heating element(s), presence of secondary coil, presence of heat exchanger, etc.), which complicated both the installation and the modelling process.
- Communication issues were prevalent, leading to data dropouts. This problem could likely have been avoided if the density of installations had been higher (as seen in other projects), as each building would only require a single communication gateway which would have been more carefully sited.

Data analysis

- Average daily energy consumption for hot water heating was 6.7kWh, of which 6.1kWh was off-peak and 0.6kWh was peak. This is a lower peak consumption than anticipated, as several tenants had reported that they frequently used the 'boost' secondary heating element in the afternoons/evenings.
- There was a large variation in average daily consumption (varying from 3kWh to 12kWh) and inferred water usage (both in volume and time of use).
- Most consumption occurs at the start of the E7 window between 00:30 and 03:00. As the time to heat up varies between 0.5-3.1 hours, there is inherent flexibility allowance to shift a consumer's heating time within the overnight period (e.g. from 00:00-03:00 to 04:00-07:00 for better comfort).
- Consumption is approximately 50% greater in winter than summer, likely due to increased water usage and/or colder mains water feeding the tank.
- The average interval between the median time of heating and median water use varied between devices from 2.5h to 14h, with an average of 9.25h. Some of this variation is as expected from the variation in tenant profiles. The analysis also suggests that the average tank would take 12h to cool halfway from the maximum to the minimum temperature on its daily average profile. This implies that the current tank heating regime is suboptimal in terms of minimising heat loss from the tank. It also implies that that large shifts (>5 hours) in the heating time are likely possible without a negative impact on comfort, especially if insulation were retrofit at the time of installing the smart controls.
- Switching customers to an E10 tariff would likely lead to an improved comfort experience thanks to the afternoon 'top up' charge preventing instances of insufficiently hot water in the evenings.
- There were several examples of incorrectly configured tanks which were not heating primarily during the off-peak window. This is likely unintentional; however, it can lead to significantly increased costs for the customer. Monitoring equipment such as that used in this project could help social landlords to identify and correct such issues, or energy suppliers could leverage meter data to detect these issues automatically.

Business modelling

- The potential benefit of a dynamic ToU tariff was explored by running a simulation of a simple dynamic heating regime: shifting daily consumption to the cheapest time of each day. This was found to reduce costs by 50% (£126) compared to E7, and it is expected that this would deliver similar or better comfort outcomes than the status quo, although further research is needed.
- Turn-down potential: If the ~600,000 hot water immersion heaters in London had smart switches and agreed to participate in potential turn-down or shifting services, this would imply an available capacity of 720 MW between 00:30-03:00 or a 300 MW capacity between 00:30-07:00.
- Based on initial analysis, aligned to trajectories for fuel switching seen in the CCC's 6CB analysis for residential decarbonisation, this 720 MW potential could rise to >750 MW by 2030 and >1.1 GW by 2050. However, it should be noted that it is also possible that (due to fuel switching) this could drop to ~700 MW by 2030 and ~500 MW by 2050.
- The CBA analysis indicated that the majority of potential revenue comes from tariff switching and optimisation for a dynamic ToU tariff, which could lead to a payback time of just over 10 years.
- Scale-up: Rolling out smart controls needs (i) technology standards to ensure interoperability and low-cost integration, (ii) (integration into) large scale landlord driven programmes to ensure low costs of installation, and (iii) smart meters to ensure customers can access better commercial offers.

Contents

1 Introduction

As local and national governments commit to decarbonisation, the push towards a zero-carbon society will require local and national shifts. The Greater London Authority has the goals of achieving zero-carbon emissions by 2050 and to have 15% of London's energy to be renewable by 2030. To support these shifts, electricity system flexibility is a crucial enabler.

As defined by Ofgem, flexibility is "modifying generation and/or consumption patterns in reaction to an external signal (such as a change in price) to provide a service within the energy system". Specifically considering demand-side response (DSR), this involves electricity system customers amending their consumptions patterns to support the system. This type of flexibility offers several benefits including making greater use of renewable generation capacity, improving the stability and reliability of the system, reducing (or deferring) network reinforcement costs, and meeting net-zero more cost-effectively. To put this into perspective, a recent study indicated that a fully flexible energy system could reach net zero while saving up to £16.7bn a year compared to a low (or no) flexibility scenario [1].

In recent years, there has been a significant push to regulate and include additional flexibility into the UK's electricity system. On a federal level, the Government's Energy White Paper suggests the need for increased levels of flexibility in the system to accommodate the acceleration in the electrification of transport and heating [2]. Ofgem's recent Decarbonisation Action Plan notes that "much more flexibility in our energy system and consumption patterns" will be required, particularly to keep costs low; the report also notes how regulation will need to develop to support the transition to net zero [3]. Lastly, both the ESO, via ongoing reform and grid services [4], and DNO/DSOs, as aligned to the DSO implementation plan [5], recognise the need to increase and standardise flexibility services.

1.1 Project description

Home Response was undertaken in partnership with **Element Energy**, **Moixa**, **Repowering London**, **UK Power Networks (UKPN)**, London boroughs and housing associations. It is funded by in part by the **Department for Business, Energy and Industrial Strategy (BEIS)**.

The project demonstrates how electrical hot water heating and solar PV with battery storage technologies can be used in social housing to help Londoners' cut their energy bills, financially reward flexible use of energy, reduce emissions and contribute to a smarter, cleaner energy system for London. By using innovative business models and customer engagement approaches, combined with controlling when and how hot water heating and batteries are used and energy efficiency support, additional flexible electrical power can be provided to local and national electricity networks. This will increase low carbon electricity capacity and improve security of supply to meet Londoners' variable demands for power, i.e. at peak times of the day.

1.2 Project objectives

The objectives for Home Response were to:

- Engage and recruit households by using innovative engagement methods that have been tried, tested, and improved upon through the development of community energy projects.
- Remotely control households' flexible demand for electrical hot water heating and solar PV combined with battery storage technologies by using Moixa's GridShare software and hardware technologies.
- Give households a share of the profits received from energy trading.
- Have Moixa manage everything for households: once a resident signs up to GridShare, there should be nothing further required (Moixa sells the energy, collects payments from network operators, and once a year send customers their share).
- Develop and trial business models that provide replication potential for commercial energy businesses and community energy organisations.
- Meet UK Power Networks' need for local level electricity grid capacity flexibility (which includes increasing supply and reducing demand for electricity) at times of critical need for Londoners (i.e. peak times of the day between 4pm and 7pm).
- Demonstrate and disseminate to communities with similar opportunities how to implement domestic demand flexibility by producing detailed materials, events and learning experiences.
- Provide greater levels of demand flexibility by controlling electrical technologies and testing the usefulness of smart meters in social housing households, manged by housing associations and London Boroughs.
- Create new business and customer engagement models to reward Londoners' flexible use of energy.
- By demonstrating and disseminating project learnings and opportunities, kick-start household flexibility markets by demonstrating and disseminating project learnings and opportunities.
- Realise a range of energy system benefits.
- Deliver the Mayor's policies and proposals to develop clean and smart, integrated energy systems utilising local and renewable energy resources.
- Accelerate collaboration and partnerships between energy users, technology and supply chain providers, researchers and policy makers to provide technical, commercial and environmental solutions and benefits.

1.3 Project Key Performance Indicators (KPIs)

Table 1 below outlines the KPIs to which this project aimed to align throughout the duration of the trial and data analysis.

Table 1. Overview of project KPIs, measurable indicators, and potential data collection methods

KPI	Measurable indicators	Data collection methods
KPI 4: Business relationships	Number of new business relationships and collaborations established	Project partner and client interviews
KPI 5: Technology advancement	TRL level (and progression) for each technology being used	Partner insight and trial progress
KPI 6i: Additionality of funding	Potential revenue available for domestic DSR provision	Partner insight and experience
KPI 6ii: Follow-on funding	Number of follow-on projects and amount of funding received	Project records
KPI 7i: Reduced energy costs	Bill savings and potential future savings to customers	Energy billing / meter data coupled with business modelling simulation
KPI 7ii: Reduced total energy demand	Potential future savings to customers and reduction/removal of supplementary heating	Energy billing / meter data coupled with business modelling simulation
KPI 7iii: Increased energy system flexibility	Installed capacity and frequency/duration of use of flexible assets	Trial data and energy modelling
KPI 8: Steps towards commercialisation	Dissemination statistics and number of products (and potentially services) sold in UK and overseas	Partner records & dissemination plan
KPI 9: CO_{2e} emissions reductions	Calculation of potential to accommodate more intermittent renewable generation due to DSR and thereby avoid of high carbon generation	Emissions modelling and NG carbon level

1.4 Impact of COVID-19

The unprecedented Covid-19 pandemic had a significant impact on this project. Particularly, as resident engagement was a key component of the project, many of these activities were either not possible, or required severe workarounds that were less effective. The main effect was on the delivery timelines (particularly the installation schedule) which had to be initially paused and eventually extended substantially. This had a knock-on impact on other activities including the number of final installations, gathering of sufficient time-series data, allotted period(s) for DSR testing, and available time for analysis and reporting.

2 Trial design

This section discusses the data monitoring, tenant engagement, and research methodology, which were all key aspects of a successful trial.

2.1 Use cases

Two distinctly different types of domestic storage asset were investigated: batteries, installed as an addition to an existing solar photovoltaic (PV) installation (i.e. household with a smart battery and PV panels); and smart controls for existing electrically heated hot water tanks (i.e. household with a smart control for its electrical hot water immersion heater).

2.1.1 Battery

Smart battery systems were to be installed in 30 London homes with existing solar PV installations on their roofs. However, due to delays and difficulties in engagement and installation caused by the COVID-19 pandemic, this was reduced to 23, which were installed between January and June 2021.

Figure 1: Diagram of Moixa's smart battery system installed in a house with PV panels.

Designed and supplied by consortium partner Moixa, the system (shown in Figure 1) consists of a smart battery which is connected into the household fuse box (3 in the figure). The battery uses current transformer (CT) clamps to measure the energy generated by the solar panels and imported from the solar grid. The battery controller is networked and communicates with Moixa's GridShare platform.

Value creation

The battery controller optimises for electricity prices using information on the customer's tariff along with artificial intelligence (AI) predictions of consumption patterns, based on historical usage, and likely solar availability.

The inclusion of a smart battery to a household has three distinct strategies for creating value for the customer. The first two are already fully exploited by Moixa's battery as a commercial product:

1. Take advantage of the difference between import and export price: in practice this means minimising unnecessary export to the grid. Instead of needing to export the excess energy during a period of high PV production, the battery is charged, and the energy is used later to reduce grid import. This value method is employed to some extent under all tariffs; for tariffs without an export payment, the export price is effectively zero. This is the only method of value for customers who remain on a flat tariff and is based on self-consumption rather than a DSR service.
2. Take advantage of the difference in price throughout the day, known as *price arbitrage* (time-of-use tariffs only): This involves shifting the import or export to the time of day which is most favourable. Only two devices in the trial are on Time-of-Use (ToU) tariffs and therefore exhibit this behaviour, but it has also been simulated for all devices in section 4.2.1.

Additionally, we have explored the following as an opportunity for further value creation (via simulation), pending the development of the necessary technology:

3. Participating in flexibility services: the National Grid Electricity System Operator (NG ESO) and local Distribution Network Operators (DNOs) both offer avenues for flexible assets (i.e. the battery in this case) to earn revenue via the provision of a defined service; for this study, UK Power Network's (UKPN's) Secure, Dynamic, and Sustain services were considered alongside the NG ESO's Balancing Mechanism and Frequency Services.

Battery specifications

The batteries used in the trial were an identical model manufactured by consortium partner Moixa. They have a capacity of 4.8kWh, a maximum power of 2.4kW, and are guaranteed by Moixa for 10 years of operation. The battery is pre-set with a limit to not go below 10% State of Charge (SoC) as this could negatively impact the performance and the lifetime of the battery. The SoC is estimated by the battery controller using the method of 'Coulomb counting'.

PV specifications

The 23 households had existing PV panel installations of varying sizes. The average size was $2.4kW_{peak}$ (i.e. sized in relation to the theoretical peak generation of the system) but ranged from $1.0kW_{peak}$ to $4.0kW_{peak}$. Data is missing from three of the households.

Household information

A survey was developed and sent to participants to gather data about the demographic and socioeconomic profile of the residents, their current energy use, and their level of satisfaction with their current energy trial installations.

It is important to note that the profile of the households in the battery trial is quite different to the hot water trial. Of the 10 respondents, seven own their home, six are employed with only one reporting to be unemployed, and the dwellings are all houses rather than flats.

Information about electricity tariffs was crucial to the optimisation of the battery and this was collected separately to the main survey. Of the 23 households in the trial, 20 were on flat tariffs at varying rates, one was on an E7-style tariff (Octopus Go), one was on a dynamic ToU tariff (Octopus Agile) with a fixed export rate (Octopus Outgoing Fixed), and one was on an unusual daily variable tariff (Octopus Tracker) for which the battery controller could not be specifically optimised and therefore was treated like a flat tariff throughout.

Therefore, it is only confirmed that one household is paid anything for their export to the grid. It is possible that more are on a Feed-in-Tariff (FiT) which they failed to report, as this tariff generally does not require any grid export meter readings, and the FiT may belong to the landlord rather than the tenant. The FiT is split into a generation and an export payment. It is not permitted to receive an export FiT payment alongside other forms of export payment such as the Octopus Outgoing tariff, so this would exclude these households from some of the tariffs explored in this study.

Monitoring variables

This section introduces the data variables that were monitored and analysed for the battery use case.

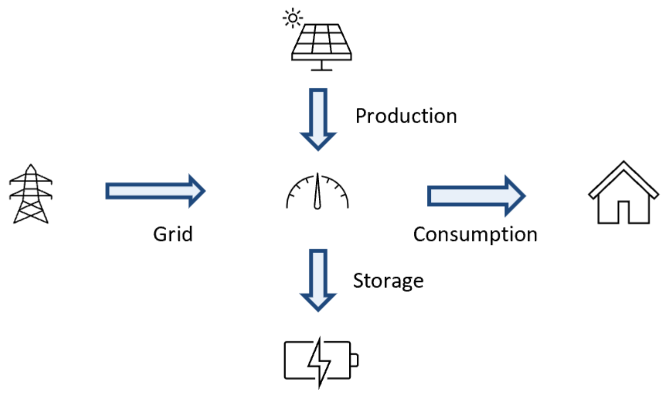

Figure 2: Diagram of energy flows in a household with solar PV (top) and battery (bottom) installed and grid (left) and consumption (right) illustrated, indicating the terminology and sign convention in relation to the meter (centre) used in this report.

The data from the batteries contains the four variables shown in Figure 2, and a further variable: the State of Charge (SoC) of the battery, expressed as a percentage. Three of the variables shown in Figure 2 are directly measured (grid, production, and storage) and one is inferred (consumption) using conservation of energy. The sign convention is indicated in the figure, with arrows indicating the direction of a positive energy flow. The battery controller measures the data at 30s resolution, and the tariff switching simulation in 4.2.1 was performed at this resolution, however the remaining analysis was performed on aggregated data in intervals of 30 minutes.

2.1.2 Hot water

The Home Response project planned to install smart controls, meters, and temperature sensors on the hot water tanks of a total of 130 homes in London, primarily flats owned by housing associations. Due to a range of factors discussed in the data availability section 3.2.1, only 35 sets of equipment were successfully installed between November 2020 and June 2021.

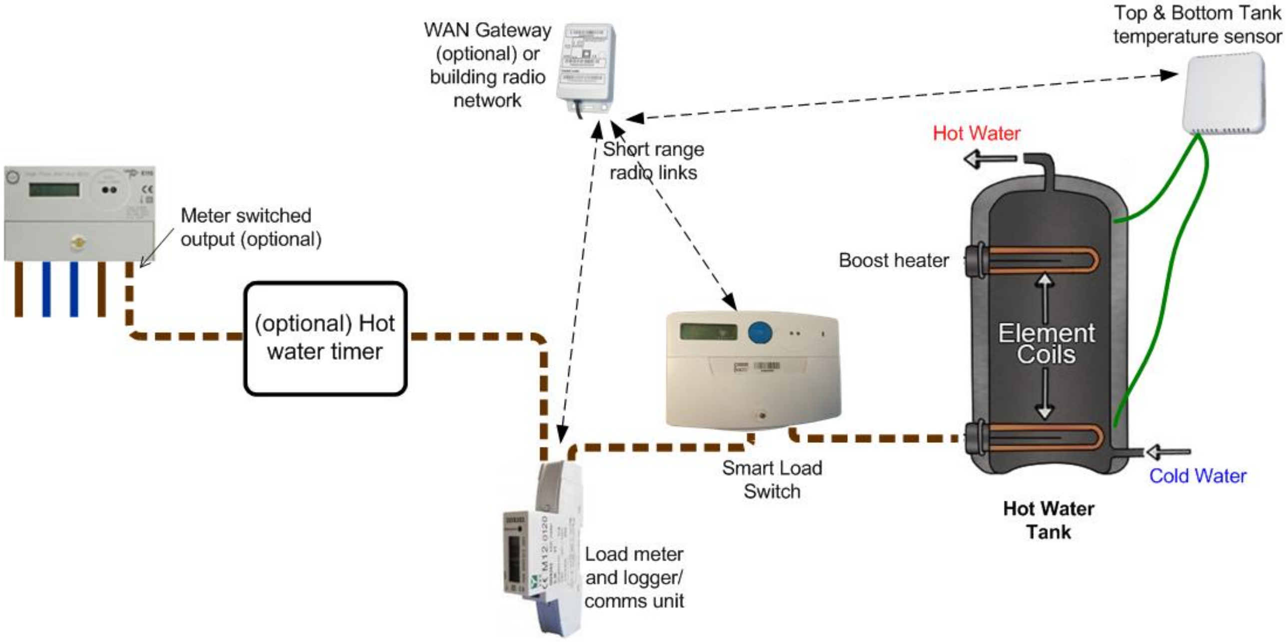

Figure 3: A diagram of the Connected Response smart control and monitoring system attached to a 'typical' hot water tank; some existing electrical equipment such as the off-peak timer circuit is not shown.

Figure 3 shows a diagram of the hot water smart control and monitoring system used in the project. Note that the tank shown in Figure 3 is a 'typical' tank, but there was large variation as detailed below. The system was designed and supplied by Connected Response as a variant of its electric storage heating and domestic hot water control system. The system provides electrical consumption metering and real time control of the water heating circuit(s). In addition, a water tank temperature sensing unit was included with two temperature sensors for attaching to the outside of the top and bottom surfaces or pipework of the hot water storage cylinder. These sensors provided a measure of the stored water temperature, from which the volume of hot water usage could be approximately estimated.

This type of smart control system is typically fitted in multiple properties in multi-dwelling buildings and uses a low power short range radio mesh network to communicate within the building to an installed gateway unit. For this project's mostly individual property installs, a small GPRS gateway was installed to provide the continuous remote connectivity to the metering and control equipment.

The equipment could either be installed on the meter board or next to the hot water storage tank. As only hot water was being controlled, the installers found it easier to install everything next to the water tank.

For most of the test period the system was used just to collect metering and temperature data, no heating control was implemented in addition to the existing meter or timer control. As the Connected Response smart controller was installed in series with the existing control it could only potentially provide control within the 'on' periods provided by the existing system.

Value creation

The hot water tanks with immersion heaters were originally designed to be used with an E7 tariff. This type of tariff was first introduced in 1978 [6] with the intention of encouraging domestic users to shift their usage from peak times to times of lower usage, specifically during the night, to take advantage of cheap electricity provided by the nuclear base generation. Although the generation mix has shifted and much of the night-time electricity is now provided by wind, the principle remains valid and wholesale electricity prices remain much lower at night, along with estimated grid carbon intensity.

As the hot water load was already (theoretically) avoiding the peak hours of the day, it was hypothesised that the opportunity for value creation would be limited. However, the following opportunities were nevertheless identified for exploration:

1. Time-shifting to improve comfort: providing hotter water to the resident at times when the hot water may have cooled unacceptably under the current regime, ideally without heating at peak times.
2. Time-shifting to times of even lower prices: in comparison to the E7 tariff, this would require switching to a dynamic ToU tariff to create value for the energy supplier (as it reduces their costs), which could be passed on to the end-user; there is also value in the potential to reduce carbon emissions.
3. Fixing incorrectly configured tanks: in many cases, residents may be unaware of pre-existing issues with their hot water tank configuration, energy supply, or usage; intervention via the installations and subsequent monitoring may provide awareness on poor configurations which can then subsequently be corrected. It was previously unknown to what extent this was a problem.
4. Participating in flexibility services: akin to the battery case, flexibility service provision for the grid was considered; applicable to this use case, a demand turn-down and/or turn-up service was considered in addition to participation in the Balancing Mechanism, both of which would provide value to National Grid which could then be passed on to the end-user. It was expected that this would be limited due to the small fraction of such requests that are typically issued at night.

Hot water tank specification

Although Figure 3 shows a ‘typical’ tank with two immersion heating elements, there was a very large variation in the physical properties of the hardware:

- The tanks in the trial had differing capacities.
- Some were a bare cylinder while others had a metal case which prevented easy attachment of temperature sensors.
- Some had a heat exchanger to provide a more consistent temperature output, while most had bathing water pumped directly through the cylinder
- Some had a single immersion heating element while others had two, the secondary element being for additional ‘boost’ use during peak times.
- The placement of the heating elements in the tank also varied: most commonly the primary (off-peak coil) was at the bottom of the tank and the secondary (‘boost’ or on-peak coil) near the middle, but some tanks had a primary at the top.
- While most tanks had an inlet pipe at the bottom and an outlet pipe at the top, some tanks had up to 4 pipes connected, making it difficult to interpret the flow direction.

For the tanks that have two separate heating elements, these are usually on separately controlled off-peak (primary) and ‘boost’ (secondary) circuits. However, a few used only one water heating circuit for both off-peak and boost. In these cases, the installed system is metering both off-peak and ‘boost’ consumption.

Unfortunately, many of the physical properties of the tanks (capacity, pipe location, heating element location, metering arrangement) were not recorded at the time of installation. Only at later stages in the project did it become apparent that this information would be useful (e.g. for estimating water flow); however due to the inconvenience and associated cost of site visits, it was infeasible to comprehensively collect the missing information and much of it had to be inferred through data analysis.

Smart switch specification

The Smart switch has two 100A contactors that are typically used to independently control the storage heating supply and the off-peak water circuit. In this project only the off-peak water control contactor was used. The smart switch has a boost button for optionally providing extra water heating. The switch also measures the AC frequency to 3mHz which can be used in demand response applications to auto shed load.

Metering specification

The 3kW (max) immersion heating load is metered by a small MID-approved (Measuring Instruments Directive approved meter, suitable for fiscal settlement) meter with logger/communications unit to connect the rest of the system. By default, the logger records consumption every 30 minutes but could be configured to provide real time (every few seconds) power usage.

Temperature sensor specification

The temperature sensors attach to the outside of the water storage tank or nearby pipework to give temperatures to the nearest 0.5°C. When suitably installed and lagged they give a good indication of the water temperature at that point, without having to directly contact or break into the water circuit. By default, the readings are also logged every 30 minutes.

Household information

The resident survey illustrated that the socioeconomic profile of the residents in the HOT WATER study was very different to the battery study, with five of the 15 residents unemployed, seven having a household income of less than £20,000, and only five holding at least an undergraduate degree. All the dwellings are flats owned by a housing association, except one which is owned by the local authority. All respondents said that their primary motivation for joining the study was a potential reduction in their energy costs, whereas in contrast some battery participants cited carbon emissions reductions or expressed an interest in learning more about their usage.

This is relevant because the relative precarity of many of these households may influence their willingness to accept the risk associated with some of the variable tariffs considered in this study. Furthermore, the residents are unlikely to invest in smart technology equipment unless the payback time is considerably short, or they are sponsored by their housing association for the capital cost.

Monitoring variables

Data from the hot water systems consisted of the electrical consumption of the heating element (‘consumption’), temperature at the top of the tank (‘$Temp_{Top}$’), and temperature at the bottom of the tank (‘$Temp_{Bottom}$’). Usually, this consumption refers to the primary heating element which was controlled by a user-configurable timer to heat during the off-peak hours, and if a secondary ‘boost’ heating element is present then this was not metered. However, in some instances the secondary element consumption was also metered as part of the same variable. The data was recorded at half-hourly intervals.

2.2 Tenant engagement

Residents were recruited as project participants using flyers, calling campaigns, and liaisons with social housing organisations such as L&Q. Participants were then contacted with a customer engagement package, including an Expression of Interest (EOI) form with GDPR consent, which included arranging a visit to their property to assess the suitability for this study's project equipment.

Once the suitability of the property was confirmed and a date for equipment installation was agreed, the participants signed the agreement and were officially recognised as Home Response project participants. The installation was then coordinated with the participant.

Remedial works on faulty hot water installations (e.g. depleted temperature sensor batteries, offline kWh meter, poor signals) were coordinated with the participant by Repowering, after which L&Q, Carbon 3 or Connected Response attended the property to carry out re-installation to resolve the issues.

Table 2 gives an overview of all steps undertaken regarding the tenant engagement.

Table 2: Chronological overview of the steps undertaken regarding the tenant engagement.

Step	Description
1	Participant receives a communication (in person, letter, email) from Home Response (HR) Team.
2	HR team follows up initial contact with bespoke customer engagement package, including Expression of Interest (EOI) form with GDPR consent.
3	HR team reviews information received by a resident to confirm as a suitable participant and identifies any specific needs. HR team checks with the client customer team to determine any additional risks. HR team invites the customer to participate in the project (in person, by letter, and/or email as required).
4	HR team gains the trust of the customer and build confidence in trying something new.
5	Participant agrees to sign up for HR Response trial (no cost to the customer). Other energy services may also be agreed upon, such as energy efficiency advice.
6	Date agreed with customer for equipment installation.
7	Following installation, HR team checks customer expectation(s) and experience is satisfied.
8	Remedial visits are coordinated where needed; participants are contacted via email, phone, or text.
9	Select sample of participants shortlisted and contacted for flexibility service provision testing and hot water load shifting trial.
10	Resident is informed of project end and equipment decommissioning options.
11	Resident receives 50 GBP payment or voucher of the same value as a participation reward.
12	HR equipment is decommissioned or left in place according to resident preference.

A discussion of the lessons learned in tenant engagement can be found in 7.4.3 in the conclusions.

2.3 Analysis methodology

For each of the use cases, the data was analysed considering the KPIs and the intended strategies for value creation introduced in 2.1. The analysis sought to fully understand the data, including any relevant unexpected findings. Therefore, various segmentations of the data were explored (by weekend/weekday, season, month), and average profiles were considered alongside full time-series data. Devices which behaved unexpectedly were discussed with the whole of the consortium to pool expertise to understand the issue.

For the hot water case, more modelling was necessary as there were many relevant unknowns which needed to be inferred from the consumption and temperature data (capacity (L), water usage, secondary 'boost' heating, physical properties of the tanks).

2.3.1 Battery analysis methodology

For the battery case, leveraging the comprehensive measured device power flow data, the following properties were estimated:

- Capacity (kWh): estimated using the rate of change of SoC compared to power in and out.
- Standby power consumption: estimated from the power consumption when SoC stayed constant.
- Efficiency (including and excluding the standby power consumption): estimated by dividing the gross power out of the battery by the gross power in.

The detailed methodology is available in Appendix A: Detailed modelling methodology.

2.3.2 Hot water modelling methodology

For the hot water use case, only consumption and temperature sensor data was available. Information about the physical properties of the tanks (which varied greatly – see 2.1.2) was not available.

The 'standard model' for the hot water tanks was assumed (and validated) to be as per the 'typical' tank shown in Figure 3: the primary heating element at the bottom, the secondary element halfway up the tank and not metered, the inlet pipe at the bottom and the outlet pipe at the top. The sensors were assumed to measure the water temperature at the top and bottom of the tank. Many devices did not fit this model, so the analysis code was adapted to allow for some (but not all) of the variations.

The following tank properties were estimated:

- The capacity of the tank: assessed using the rate of increase of temperature with consumption.
- The cooling parameters of each tank (ambient temperature and exponential cooling coefficient): these parameters were calculated by fitting an exponential decay curve to periods of cooling where no water usage occurred.
- Estimated manually based on an in-depth revision of the time-series data:
    - Whether a secondary heating element was present
    - The positions of the primary and secondary heating elements (if applicable)
    - The position of the intake pipe.

The following additional quantities were also estimated:

- Electrical consumption for heating (when not metered): secondary 'boost' heating elements were usually not metered, so the amount of secondary consumption had to be approximately determined from the increase in temperature and the estimated capacity of the tank.
- Water usage (in litres): this was estimated using an energy balance model based on the drop of temperatures observed, the location of the inlet pipe and the capacity as estimated above, and several key assumptions.

The detailed methodology, including the key assumptions made, is available in Appendix A: Detailed modelling methodology.

2.3.3 Tariff testing

This sub-section details the tariffs that were explored in this report. Time-of-Use (ToU) tariffs allow consumers to benefit from the value they provide to the grid by shifting their usage, and therefore are integral to several of the value strategies identified in 2.1 for both the battery and the hot water usage case.

Table 3: Commercial domestic electricity tariffs investigated as part of this report

Tariff name	Description	Import price (£/kWh)	Export price (£/kWh)
Flat	A typical flat tariff from 2021.	0.184	0
E7	A typical Economy-7 tariff from 2018. E7 is a ToU tariff which encourages night-time consumption.	0.094 (off-peak 23:30-06:30) 0.190 (peak 06:30-23:30)	0
Go	Octopus Go tariff, a ToU tariff conceived for Electric Vehicle (EV) users (prices for new customer in May 2021).	0.05 (off-peak 23:30-03:30) 0.159 (peak 03:30-23:30)	0
Agile	Octopus Agile dynamic ToU tariff at the time of the trial (Jun-Dec 2021). This tariff exposes customers to wholesale market fluctuations.	Variable on half-hourly basis, capped at 0.35, typically 0.19 at night and 0.35 at evening peak	0
Agile + Outgoing	As above but with Octopus Agile Outgoing dynamic ToU export tariff.	As above	Variable on half-hourly basis, typically 50% of the import rate
Agile 2019	Octopus Agile dynamic ToU tariff from exactly 2 years prior to the trial period (Jun-Dec 2019).	As above but with 2019 rates (lower)	0
Agile + Outgoing 2019	As above but with Octopus Agile Outgoing export tariff (Jun-Dec 2019).	As above	Variable on half-hourly basis, typically 50% of the import rate
E10*	A similar tariff to E7, but with 3 additional hours of off-peak during the day.	As an example: 0.1 (00:00-05:00) 0.2 (13:00-16:00 & 20:00-22:00)	0

** The E10 tariff was not included in any simulations but has been discussed elsewhere in this report so is included in the table for completeness.*

When comparing between different types of ToU tariffs, it is desirable for all these tariffs to have similar profitability/viability for the energy provider, so that any savings that are observed can be attributed to genuine efficiency improvements provided by the customer's flexibility. Unfortunately, this is difficult, as there is no single provider providing all the tariff types above, and it is also infeasible to determine the commercial viability of each tariff. Providers such as Octopus promote their innovative reputation and may want to offer an 'experimental' tariff to attract enthusiasts and publicity rather than strictly generate profit.

Tariffs were all taken from the period 2018-2021, however this period (particularly the latter end) saw a large increase in wholesale prices and much volatility in the tariff market. Many providers, unable to raise their tariffs due to fixed tariffs or the OFGEM price cap, admitted to making sustained losses on many of their customers. Therefore, in tariff comparisons, attention should be paid to the tariff rate in addition to the total cost.

The 'Agile' tariff saw a large rate increase in 2021 as it reflected the wholesale increase, while most other consumers were protected by fixed tariffs or the price cap, meaning it was likely the only tariff to represent commercial viability in 2021. The Agile tariff has been retained in this report for interest, however comparisons with the other tariffs are therefore largely skewed based on this context. The fact that the Agile rate reaches the imposed cap of £0.35/kWh frequently also negates its usefulness as a dynamic tariff.

For this reason, the 'Agile 2019' tariff was introduced, which takes prices from exactly 2 years earlier, before the current energy crisis led to sharp price increases. Interestingly, the Agile rate in 2019 is cheaper than the E7 9.4/19.0p for a large proportion of the time (leading to the savings in section 4.3.1), even at night. This means it is usually cheaper than both E7 9.4/19.0p and Flat 19.0p even without consumption shifting, unless consumption is particularly concentrated at peak times.

In this report, the flat and E7 tariffs are often compared to the Agile 2019 tariff as a fair comparison of tariff types under 'normal market conditions'. However, it is uncertain whether the energy market will ever return to these prices. If prices remain elevated, it is expected that all revenue figures are likely to change accordingly.

Battery tariff simulation

For the battery case, it was expected that the greatest benefit would be realised when the battery was combined with a dynamic ToU tariff, as the battery controller is aware of the tariff prices and is able to optimise accordingly. However, all but two households in the trial were on flat tariffs, making meaningful comparison with 'real' data infeasible.

Therefore, it was decided to simulate the behaviour of the batteries on various tariffs over a fixed period of time. The 'real' production and consumption data from the trial was used, but the battery input/output data ('storage') was discarded. The battery behaviour was then simulated. The parameters of the simulation were as follows:

- The simulation period was six months from June to December (21/06/2021 - 21/12/2021). This was a period when most devices were online. The solstice dates were chosen so that the solar irradiation would be representative of the whole year.
- The simulator used a non-linear efficiency curve that was parameterised to best emulate Moixa hardware under different operating conditions, resulting in a mean efficiency in general usage in the range 65-70%. This range matches the efficiency measured from the trial data.
- The tariffs chosen for the simulation are presented in Table 3.

Hot water tariff simulation

It is expected that the hours which are considered peak and off-peak may continue to vary in the future, in ways that are difficult to predict, as grid decarbonisation progresses, and new demands are incorporated (e.g. electric vehicles). The E7 tariff and its equipment, which is the default for the hot water use case, is relatively rigid and may fail to evolve to the changing grid.

Therefore, to imagine a more future-proof system, a simple heating regime based on a dynamic ToU tariff was devised and simulated: for each day (midnight to midnight), the total consumption (measured and inferred) was taken and shifted into the cheapest half-hour Agile periods of the day, maintaining the constraint of the maximum heating power, thereby keeping the consumption magnitude constant.

Implementation of this regime in practicality would require knowledge of the Agile price for the following 24 hours; fortunately, this information is available, as Agile prices are published daily one day in advance. Therefore, this regime would be quite possible to implement using the current equipment.

This theoretical regime was simulated for the whole hot water data period.

2.3.4 Flexibility testing

As with the tariff testing, running many physical tests on the installed systems to understand their performance for grid services was neither necessary nor practical.

Each battery in the program had been onboarded onto Moixa's AI platform, which generates the lowest cost set of actions for the battery, based on the participant's unique tariff and predictions of home load and PV generation. This is done typically in the evening of the preceding day for any given day's plan. The algorithm can also take requests for additional actions, such as preparing and discharging for a flexibility event and providing the batteries capability to do this and the additional cost incurred by altering the optimised behind-the-meter plan. These availability and cost figures can be recorded without the plan actually being pushed to the device (i.e. simulated without having any adverse impact on the trial participants).

Therefore, by requesting flexibility events at appropriate time ahead gates (e.g. 24 hours ahead for UK Power Networks Secure), then the fleets capability to perform against various services can be captured. This can be used to understand the costs of delivering flexibility services (alongside operational and capital costs) and compared with the revenues available from various services suitable for the systems. In this way a potential revenue stack can be created.

For the hot water case, the analysis was simpler as it could be assumed that there was no behind-the-meter cost for shifting load within the low tariff period and, if the customer comfort levels were not impacted, the load would free to shift around as required.

Therefore, the appropriate services were evaluated for the number of events per year that would line up with the periods when participants had flexible load in the tanks, and from there an estimate of the types and number of services that could be bid into made.

3 Data analysis

This section presents the data collected during the Home Response project, the issues that arose during its analysis, the key findings in relation to the project objectives, and several interesting, unexpected findings.

3.1 Battery

3.1.1 Data availability

A total of 23 batteries were installed into houses with existing solar PV installations between January and June 2021. Data was collected between the date of installation and project conclusion in February 2022. A total of 6456 days of data was collected, although this was reduced to 5335 days after cleaning. The data spans around 9 months, with a slight weighting toward summer months. Both monthly and seasonal segmentation of the data has been performed where relevant.

3.1.2 Data cleaning

The battery data was largely ready to be used, without significant interruptions, erroneous readings, or duplicates. However, there were many periods when one element of the system was offline – usually either the PV panels or the battery. These periods were identified and removed for each relevant device.

One device displayed a fundamental behaviour shift midway through the trial - this was because the battery controller had been reprogrammed to optimise for the Go tariff. The periods were considered separately as different devices. The same device, by coincidence, had very low PV production. Despite the low production, we decided to include the device, given that no fault had been identified by the customer or installer and so there was no reason to believe this was unrepresentative.

3.1.3 Typical profiles

All aggregated profiles are an 'average of average profiles', meaning that all devices have equal weighting despite some devices having more data than others (between 83 and 349 days). Quantiles, where shown, indicate the variation between device averages, rather than the variation between all days in the dataset. On average, the households produce 5.67kWh/day (min: 0.09, max: 10.45, std: 2.37) from their PV array and consume 7.55kWh/day (min: 3.9, max: 15.65, std: 2.93). All profiles shown are averaged over the entire trial period unless stated otherwise.

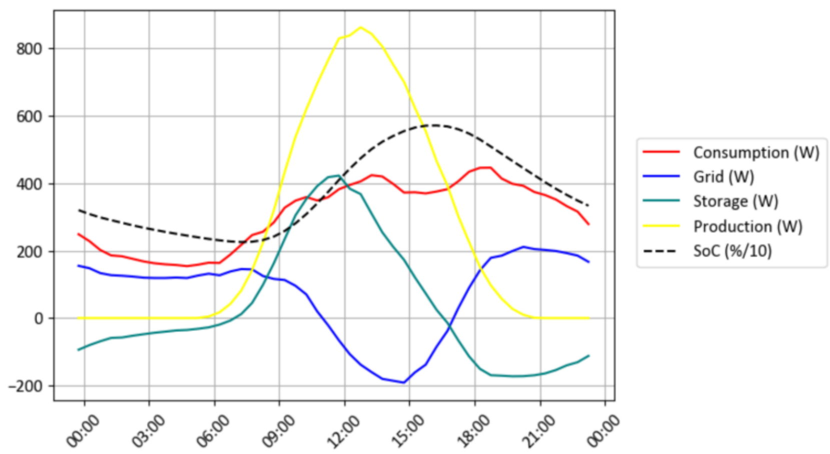

Figure 4: The average daily profile of the 21 battery devices on flat tariffs over the whole trial period.

As discussed in Trial design, most of the devices are on flat tariffs and are optimised as such. The average daily profile is shown in Figure 4. It should be noted that the production well exceeds the consumption at the solar peak, which would lead to a significant export at peak times without a battery.

It is also important to note that the graph shown in Figure 4 is an *average* daily profile, in contrast to a *typical* daily profile. Figure 4 appears to show a grid export occurring between 11:00 and 17:00, despite the battery not being full (SoC does not exceed 60%). Examining the full data day-by-day, this never occurs, since the battery would not allow any export unless it were full, or the excess PV production were greater than its rated power of 2.4kW (very rare). An average profile would not show an SoC of 100% at any time of day unless the batteries were *all* at 100% *every day* at that time.

Examination of the full data reveals that export does indeed occur only when a battery has reached full capacity. While this occurs frequently enough to cause the afternoon export seen in Figure 4, it predominantly occurs during sustained periods of high PV production over several days, as happens frequently in summer. This suggests that the 4.8kWh batteries are capable of storing a single day's excess production, but not of addressing energy imbalances on a longer timescale.

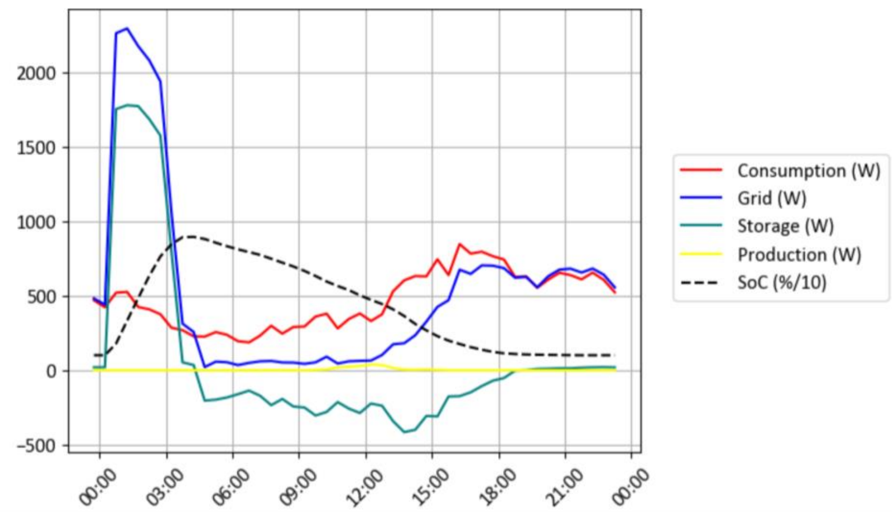

Figure 5: The daily profile (81 days) of the single battery on the Octopus Go tariff. Coincidentally this device has the lowest PV output of the fleet.

The two devices on ToU tariffs behave differently to the majority on flat tariffs. Figure 5 shows the distinct battery behaviour ('storage') on the Octopus Go (ToU) tariff, which involves charging at night. Similar overnight charging behaviour is seen in the device on Octopus Agile (a dynamic ToU tariff).

3.1.4 Segmented profiles

These figures show the data segmented by season, by weekend/weekday and by month. In some figures, quantiles are shown to emphasise the variation between devices.

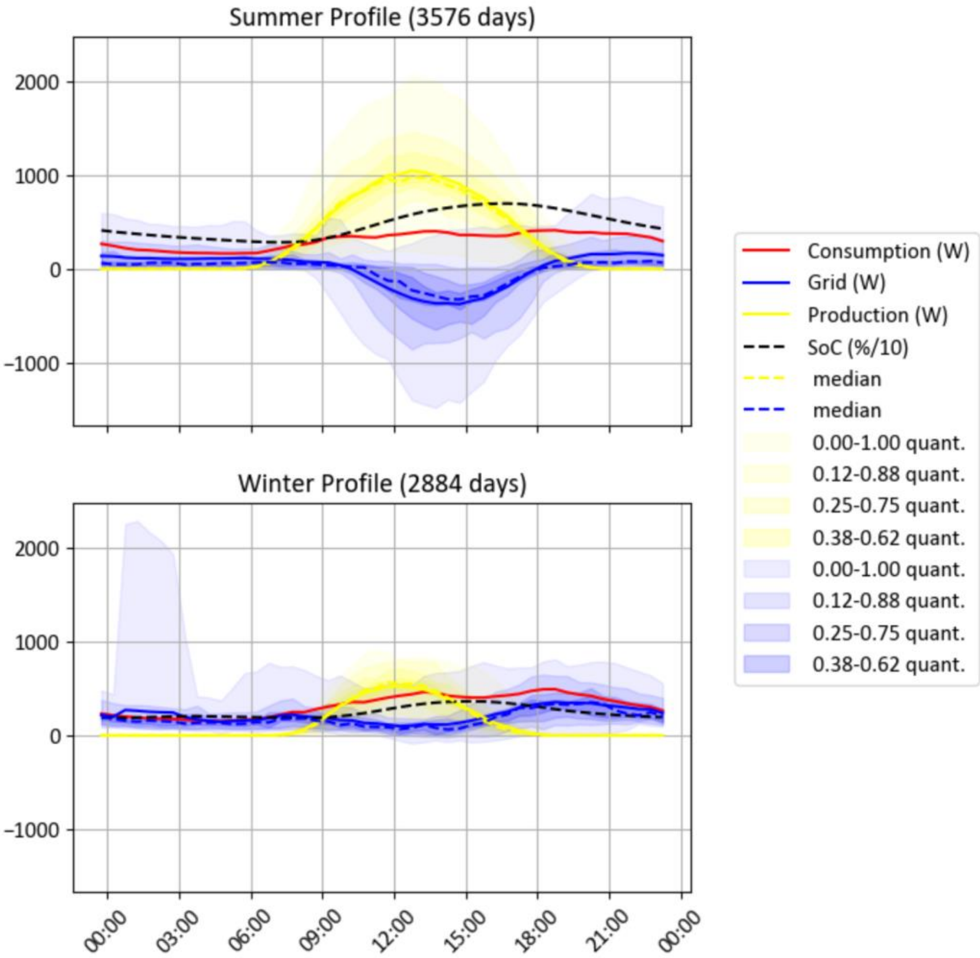

Figure 6: Battery data segmented by season, with quantiles for the PV production (yellow) and the grid (blue) showing the variation between devices. The large winter night-time import on the outer quantile is due to the single household on Octopus Go.

It should be noted that the full Home Response dataset is slightly biased towards summer. Therefore, to analyse solar PV production, it is sensible to segment the data by season as in Figure 6. The summer peak production is approximately twice the winter production on average, while the total production is 2.7 times as great (more daylight hours also being a factor), leading to 14 out of 23 devices being net exporters in the summer.

Even in summer there is a large variation in PV production between devices: the smallest has an average daily peak of 180W while the greatest has a peak of 2070W. The nominal size of the PV array is unknown for the smallest producing device, so it is unclear whether the low production is caused by a fault. The correlation between the nominal PV installation size and the measured production was much weaker than expected (Pearson's r: 0.56), indicating that other factors such as age, cleanliness, placement angle, or obstructions causing shade are highly significant.

It is also relevant that the State of Charge (SoC) of the battery is very low in winter, with the peak of the SoC average profile being 36%, compared to 71% in summer. This may limit the ability of the batteries to participate in grid flexibility services during the winter if solely relying on solar production (rather than also charging during off-peak times).

As discussed in 3.1.3, continuous periods of high PV production led to the battery frequently hitting capacity, which is seen in the high average SoC in summer and the large average export (380W peak) in the afternoon. In winter, this is not the case – the battery rarely hits capacity and there are no devices which have an average export in the afternoon in winter.

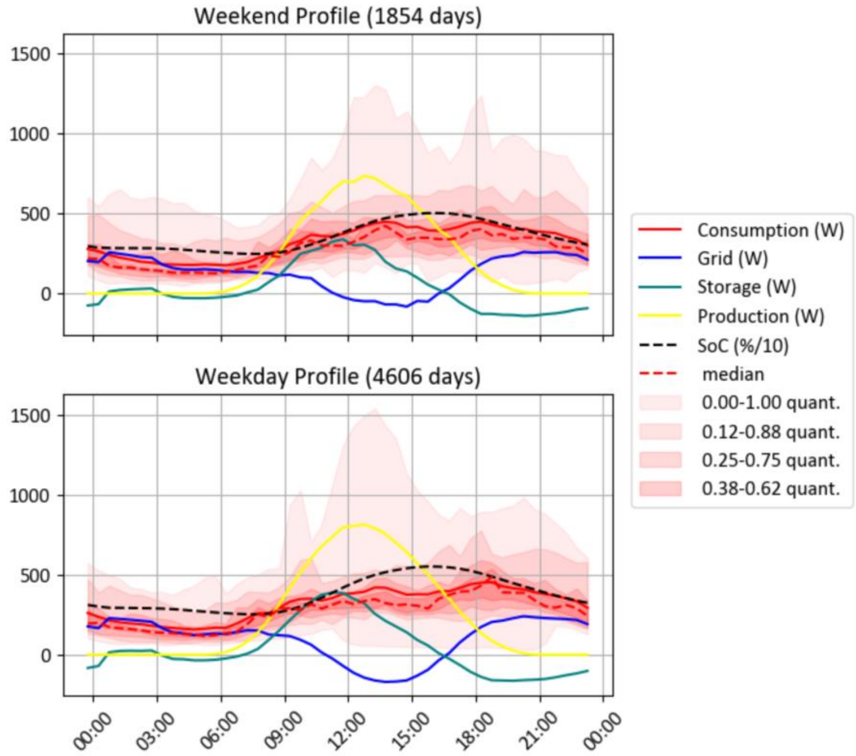

Figure 7: Battery data segmented by weekend/weekday, with quantiles shown for the consumption.

There is a large variation observed in the household consumption, as seen in Figure 7. Total daily consumption varies between 3.9kWh and 15.65kWh, with varying usage patterns evident from the full time-series data. There was no significant difference in consumption observed on weekends. This data indicates that an 'average domestic profile' may be an over-generalisation that does not capture the uniqueness of a household. When installing a battery, matching the size to the production and consumption needs of an individual household is important.

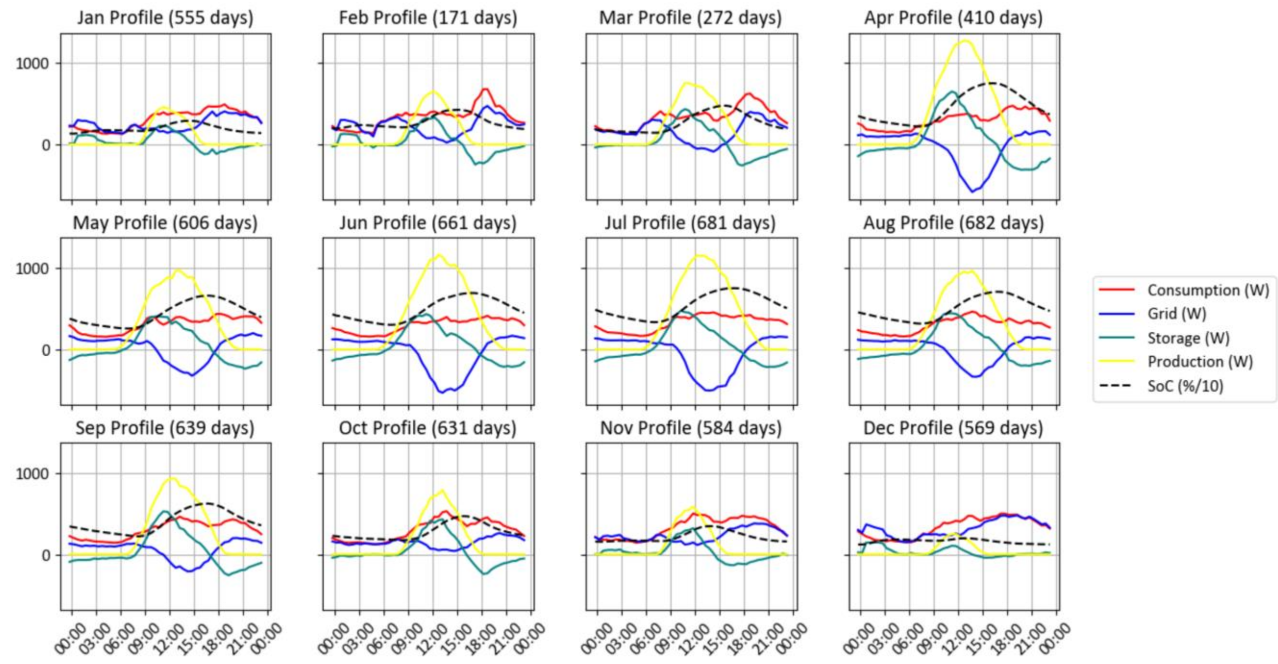

Figure 8: Battery data segmented by month.

Figure 8 shows the battery data segmented by month. The data almost spans an entire year, with only February having significantly less data than average due to delays in getting the devices operational. As expected and as seen in Figure 6, there is significantly more PV production in the summer months, causing a large grid export despite the batteries. Excluding the months with significantly less data, there are no trends in the consumption profile that could be confidently attributed to the month.

3.1.1 Battery properties

It was found that the nominal capacity of the batteries, 4.8kWh, was highly accurate. Estimations from the data gave a capacity of 4.5kWh (min: 4.2kWh, max: 4.8kWh).

The efficiency of the batteries was also estimated. They were found to have a 'total' efficiency (energy out divided by energy in) of 66% (min: 47%, max: 73%). It is notable that the batteries have a significant standby consumption of 12W – if the effect of this is negated, the batteries have a 'charge/discharge' efficiency of 76% (min: 68%, max: 79%). This implies that the batteries become more efficient the more they are used and leaving a battery sitting idle should be avoided (although the capital cost of the battery is a more significant reason to avoid this).

3.2 Hot water

3.2.1 Data availability

Although the project aimed to install smart controls, meters and temperature sensors to hot water tanks in 130 homes, delays brought on by the COVID-19 pandemic meant that only 35 systems were successfully installed between November 2020 and June 2021.

In addition to this, the data from the 35 devices was not consistently usable, resulting in fewer devices being used for aggregated analysis.

The variation in hot water tank devices (as detailed in 2.1.2) was a significant issue. Sensors could not be placed in a consistent way, sometimes being placed on casing or pipework which led to data which was difficult or impossible to interpret. The difference in pipe and heating element placement meant that the 'standard model' in 2.3.1, used for estimating water flow, could not be applied without modification.

Furthermore, the communication gateways experienced frequent mobile network communication issues due to the often-poor signal environment adjacent to the water tanks and the standard gateway antennas originally fitted. The Connected Response equipment is typically installed at higher densities within a building, using its Zigbee mesh radio network to communicate with a single gateway in the building, which can be more carefully sited for good connectivity and cheaper overall install costs. This is evidenced in the supplemental dataset, where every dwelling was retrofit with the smart devices and only a few communication issues were noted.

Both the installations and the remedial works, necessitated by the aforementioned issues, were delayed by the COVID-19 pandemic, with additional tenant engagement issues (as detailed in 0) further stalling progress.

As a result, of the 35 sites where smart controls were installed, three had significant signal issues which were not resolved, 14 had other issues with the installation, such as poorly placed or flat batteries in the sensors, and one was repaired but too late to collect sufficient usable data. Of the 17 devices remaining, 4 were charging principally during peak hours, indicating a problem with the existing charge control (such as a meter with incorrect time) that the owner either could not or did not know how to resolve. This leaves 13 devices remaining for aggregated analysis of 'normal' hot water tank operation. These devices have a total of 2674 days of data, reduced to 2296 after cleaning.

One hot water tank was reconfigured midway through the trial, leading to a fundamentally different profile being observed. This was considered as two separate devices in the analysis.

3.2.2 Data cleaning

In contrast to the battery data, there were many periods of missing data from the hot water devices, caused by the aforementioned communication issues with the Connected Response gateway installation. To mitigate this, missing periods of <3 hours in temperature or consumption meter data were linearly interpolated (dashed grey line in Figure 10).

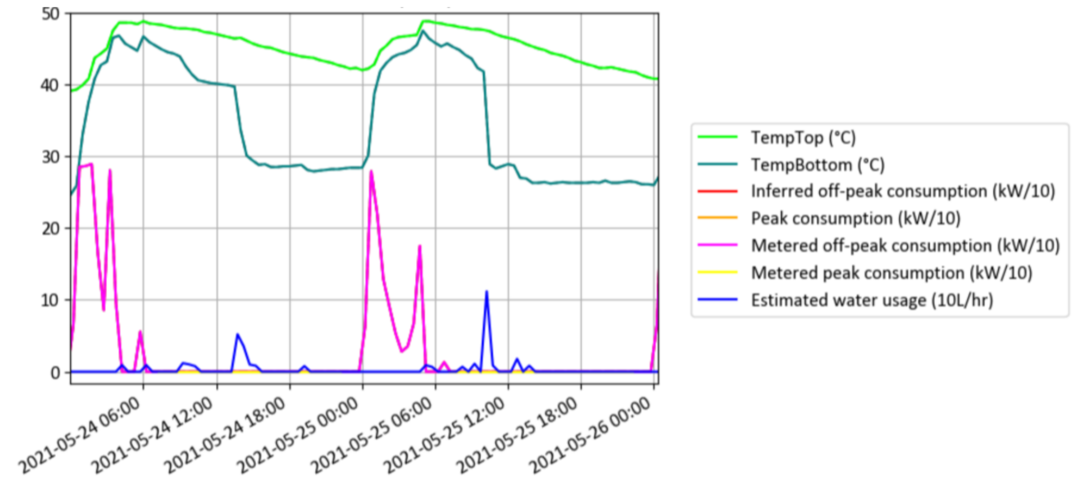

Figure 9: A two-day excerpt from a hot water device which exhibits the 'normal' profile.

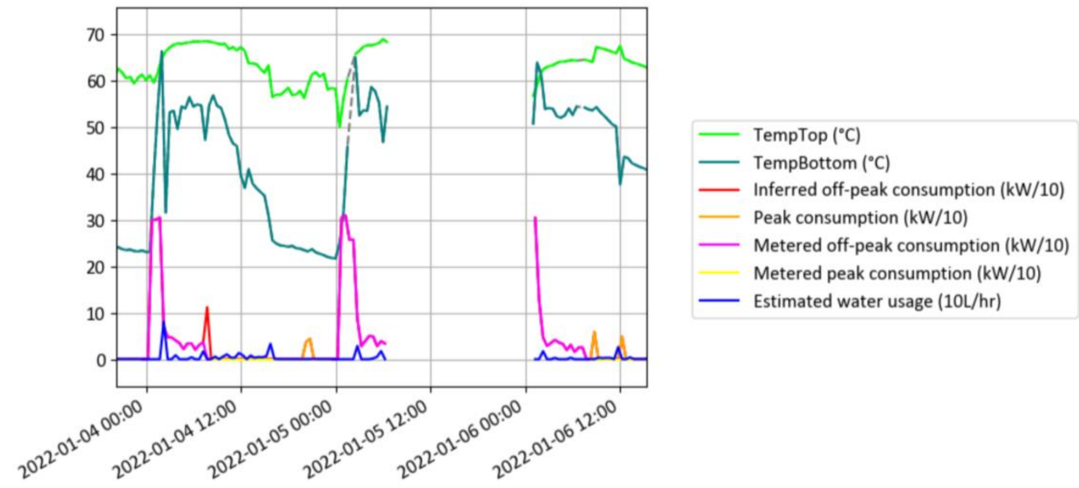

Figure 10: A two-day excerpt from a hot water device with irregular and noisy data.

Noise in the temperature sensor data was a further problem: compare Figure 10 to the normal, expected profile in Figure 9. The spikes and troughs in the temperature curves cannot be explained by water usage events unless we assume that the sensors have been placed on the pipes near the tank rather than on the tank itself. Some photographic evidence from installation reports indicates that this was the case for some devices. This device's data could not be used for aggregated analysis.

All data was manually examined for irregularities. Any devices or periods of highly unusual behaviour that was suspected of being due to incorrectly configured tanks or monitoring equipment was either considered separately or discarded.

3.2.3 Typical profile

In this section and throughout, 'consumption' refers to electrical consumption for the purpose of heating water, whereas 'usage' refers to the flow of water out the tank. As in the PV section, all aggregated profiles are an 'average of average profiles', meaning that all devices have equal weighting despite some devices having more data than others (min: 21, mean: 164, max: 413). Quantiles, where shown, indicate the variation between device averages, rather than the variation between all days in the dataset.

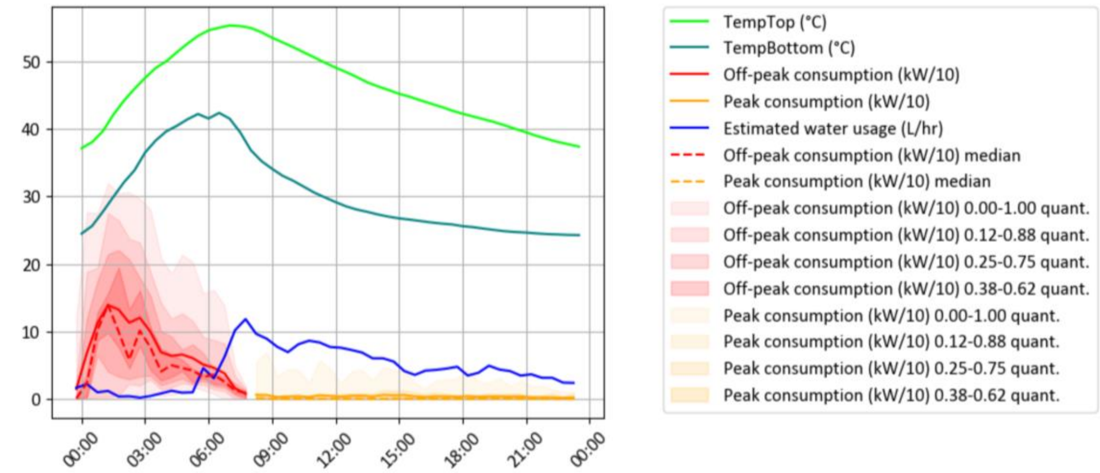

Figure 11: The average daily profile for the 14 well-understood hot water devices, with quantiles shown for the consumption.

Figure 11 shows the daily profile for the 14 devices which are well understood, i.e. they appear to be correctly configured, the data is relatively clean, and the temperature curves are free of noise. Average daily consumption is 6.67kWh (min: 3kWh, max: 12kWh), of which 6.08kWh is off-peak and 0.59kWh (min: 0kWh, max: 5kWh) is peak (although it should be noted that peak usage is largely unmetered so has been approximately estimated). This is a lower peak consumption than was anticipated, as several tenants had reported that they frequently used the 'boost' secondary heating element in the afternoons/evenings.

Most heating occurs between 00:30 and 3:00 after the E7 off-peak period has started. Consumption tails off once the tanks have reached the setpoint although heating is still required to maintain the setpoint until the end of the off-peak period. All devices except one show negligible consumption for the rest of the day.

3.2.4 Water usage profiles and heating-usage intervals

In this sub-section the water usage is analysed, and this is compared to the profile of water heating, to explore the link between heating-usage interval and insufficiently hot water.

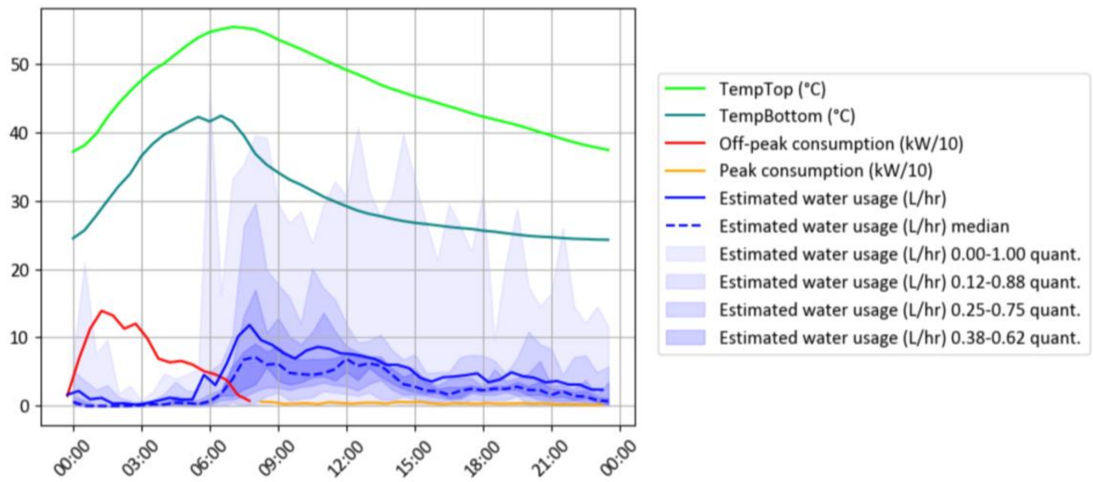

Figure 12: The daily profile of the hot water devices, with quantiles shown for the estimated hot water usage.

The estimated (not directly measured) amount of water usage varies greatly (mean: 108L/day, min: 36L/day, max: 432L/day). Some of this difference can be attributed to residents' profiles as reported in the residents' survey. For example, a household with average usage of 50L/day is a single employed female (Figure 13), whereas a household which uses an estimated 132L/day (10.6kWh/day of consumption) is a comparatively large household of 2 adults and a child.

From Figure 12 it can be seen that 90% of devices usually use hot water between 08:00-13:30, and that 90% of devices use negligible quantities of hot water between 01:00-04:00.

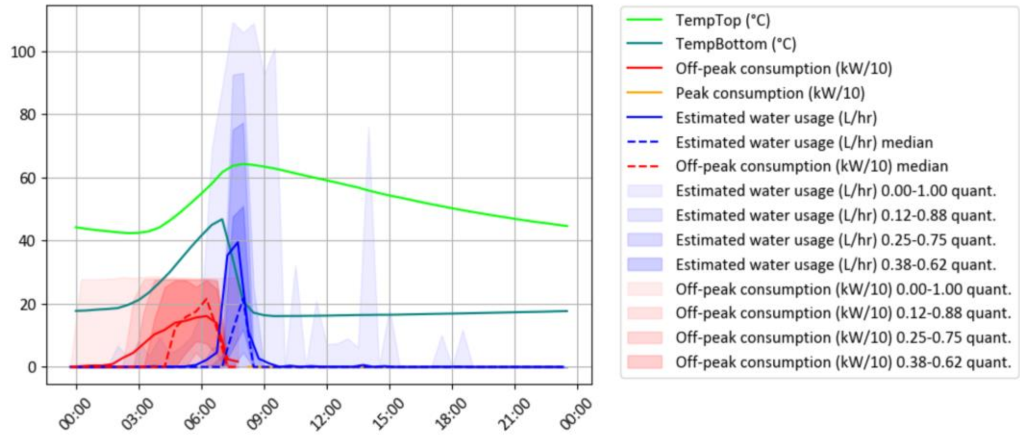

Figure 13: A household with consistent morning hot water usage. Belongs to a single employed female. This is the optimal usage in terms of minimising heat loss through the tank.

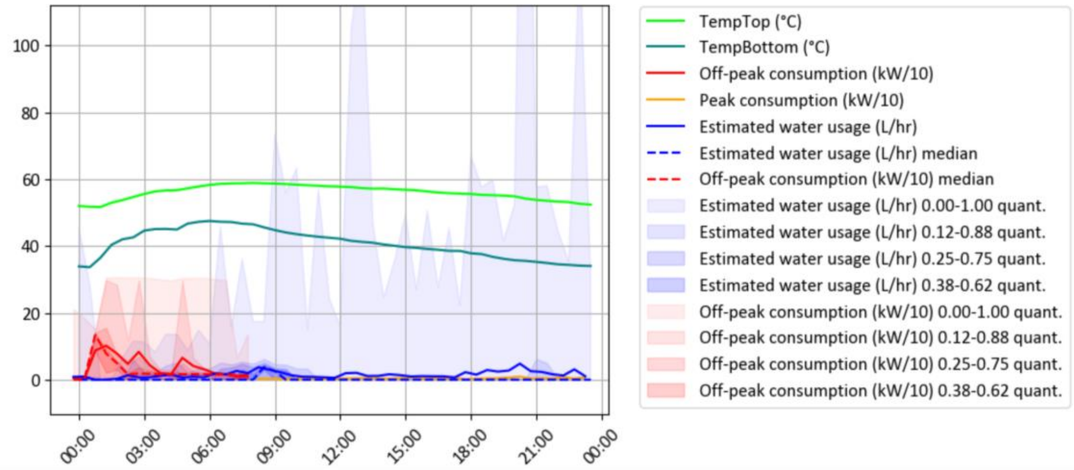

Figure 14: A household with significant water usage in the evening. The median time of water usage is 18:15, which is 14 hours after the median heating time.

In general, it is desirable to minimise the time between heating and usage, because the energy lost through the tank by conduction and radiation increases with the temperature of the tank. Ideally, the tank would remain at the required usage temperature for as little time as possible. In practicality, the randomness of usage events is likely to limit the degree to which this may be optimised.

In the Home Response dataset, the time of water usage also varies greatly. The occupant of the household in Figure 13 uses her hot water strictly in the morning at 8:00 (median usage time), and the device has been modified by Connected Response to heat at 5:15 (median heating time), leading to a heating-usage gap of 2.5h. Conversely, Figure 14 shows a household with water usage spread throughout the day, with a median usage time of 18:15 and a heating-usage gap of 14h. This implies suboptimal heat loss, and this tenant responded that their hot water is ‘often not available’, presumably due to depletion or cooling of the tank. The average interval was 9.25 hours (min: 2.5h, max: 14h).

3.2.5 Segmented profiles

These figures show the data segmented by weekend/weekday by month and by season. Consumption quantiles are shown to emphasise the variation between devices.

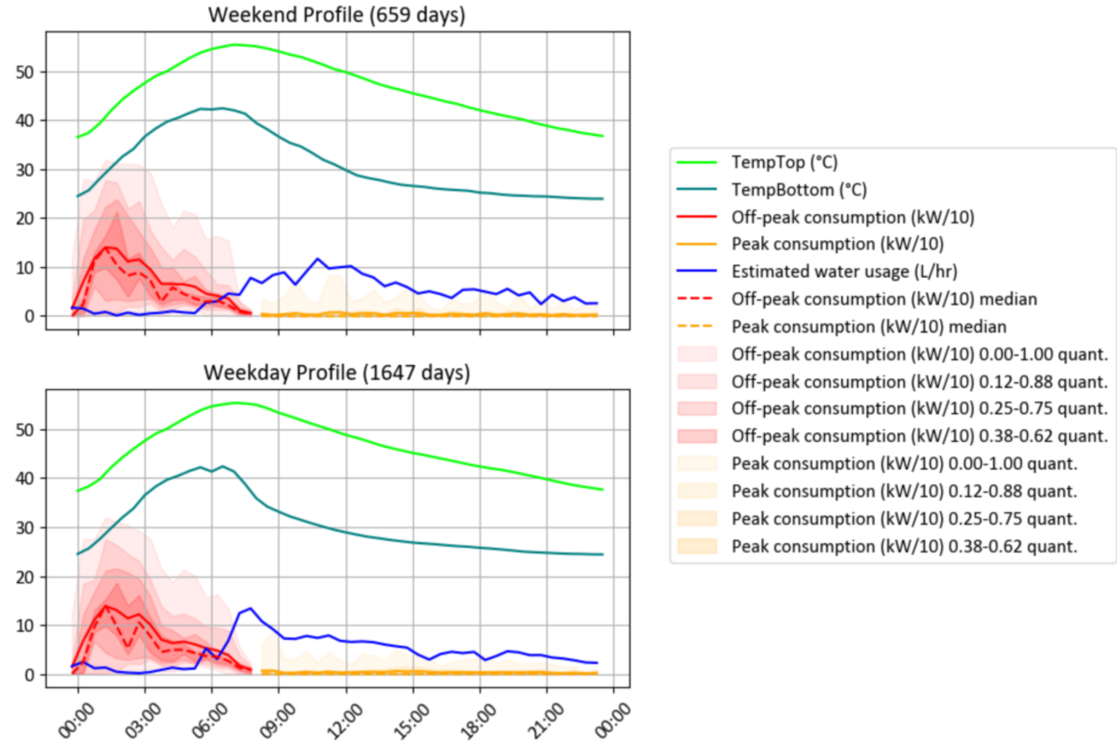

Figure 15: The hot water data segmented by weekend/weekday, with quartiles for water usage [to change].

The differences between the two are minor – there is slightly less of a 07:00-08:00 peak in water usage on the weekend, as could be expected.

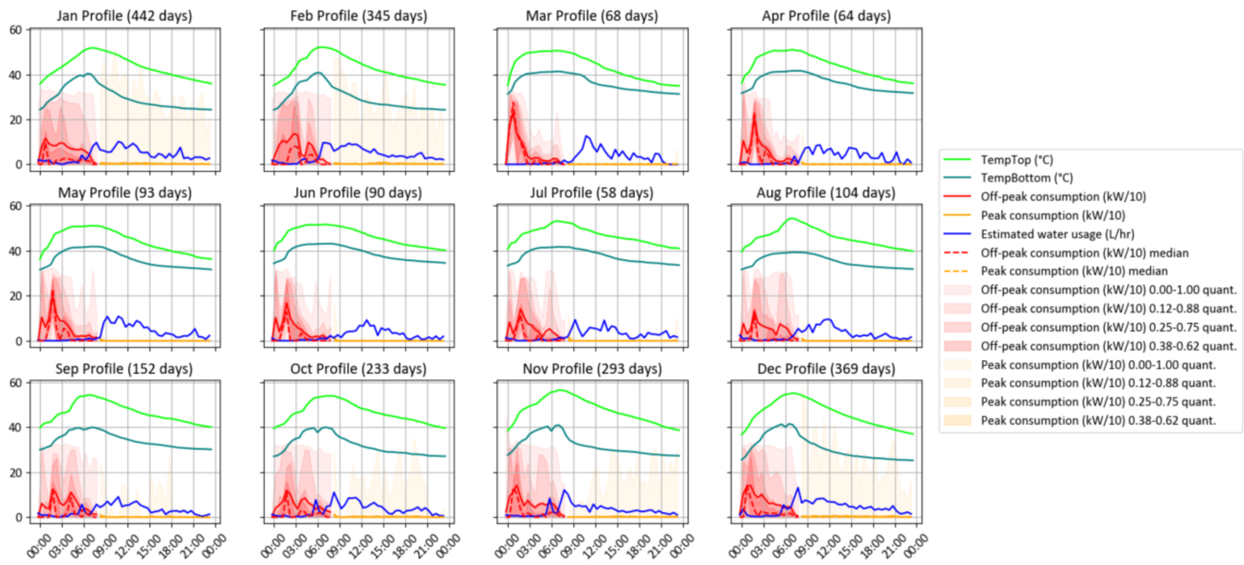

Figure 16: The hot water data segmented by month, with quartiles shown for consumption.

Figure 16 shows the variation between months for the hot water devices. Unfortunately, as some months have more data than others (especially March-July is only including data from two or three devices), most of the variation between months can be attributed to variation between devices rather than month-dependent trends.

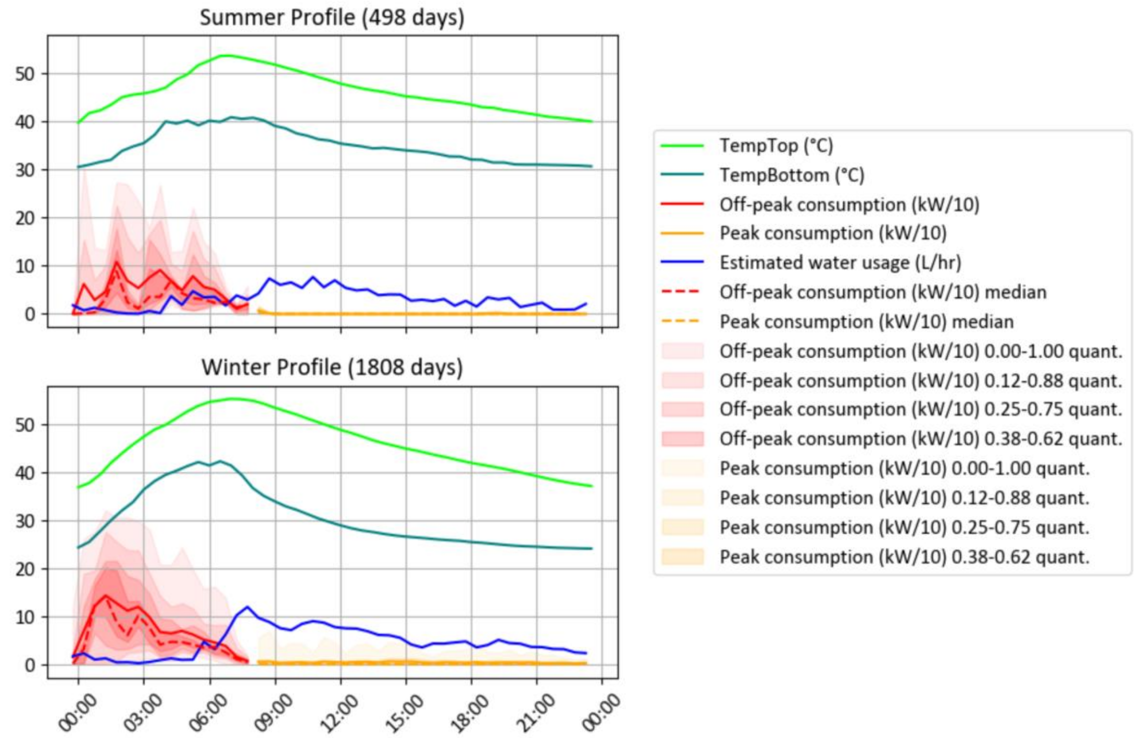

Figure 17: The hot water data segmented by season, showing slightly higher consumption in winter than summer.

Figure 17 shows the data segmented by season for all devices, showing that the consumption is approximately 50% greater in winter than in summer. This is possibly due to increased water usage, which is also increased in winter. Another factor may be the temperature of mains water fed into the tank, which varies between 11-21 degrees from winter to summer [7]. It should be noted that there is uncertainty over this result due to the small dataset and the fact that many devices were not online for the full year making comparisons over this timescale difficult.

3.2.6 Temperature observations

These figures concern the measurement of the temperature at the top of the hot water tanks.

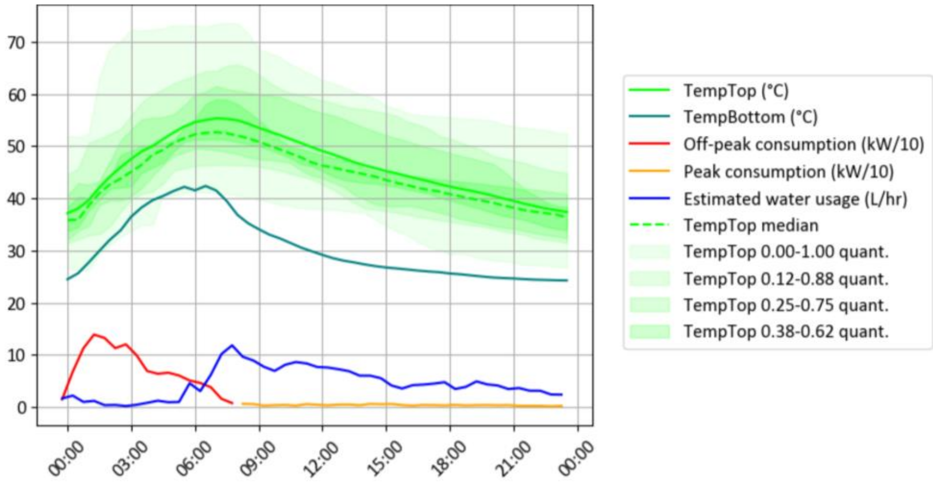

Figure 18: The daily profile for the 14 well-understood hot water devices, with quartiles showing the variation between devices of the top temperature sensor.

Figure 18 shows that the peak of the $Temp_{top}$ profile varies between devices from 41°C to 74°C. For context, recommended water temperature for bathing is 40°, and it is recommended to regularly heat a tank to 60°C at least once a week for legionella compliance. There is some uncertainty as to the extent to which $Temp_{top}$ represents the true water temperature in the tank, as this may be higher if the sensor was not directly in contact with the metal of the tank. Furthermore, the final water temperature at point of use may be lower than the tank temperature if there is significant uninsulated piping between tank and bathroom. These uncertainties make it difficult to draw firm conclusions about the appropriateness of the configured temperature setpoint, although the hottest tank, at 74°C, is difficult to justify. It is very likely that this hottest tank temperature can be attributed to a faulty thermostat or the resident setting the temperature too high.

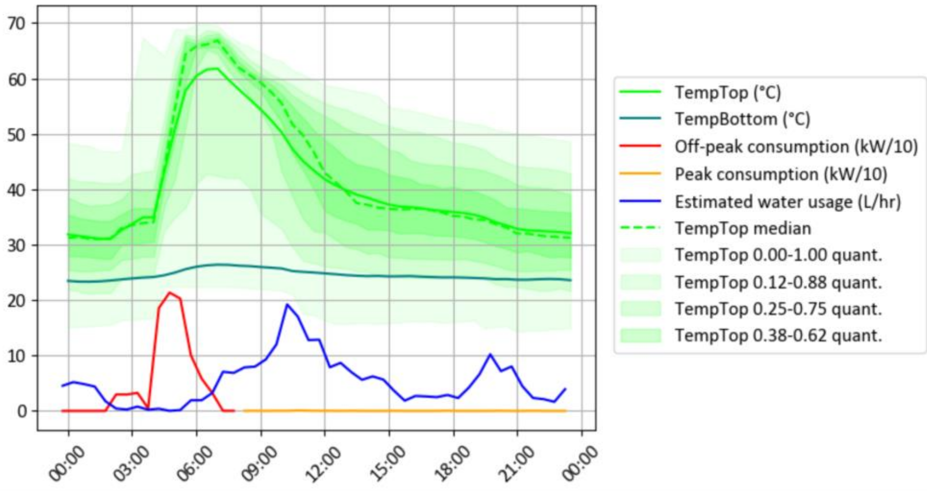

Figure 19: A hot water tank which is apparently undersized.

Figure 19 shows a device which is apparently undersized for the household. The temperature $Temp_{top}$ drops significantly by midday and is unlikely to be able to provide water at the point of use at a comfortable 40° past this time. The heating element appears to be located at the top of the tank meaning $Temp_{bottom}$ never approaches the setpoint – this contributes to its poor energy storage capability.

3.2.7 Incorrectly configured devices

A significant proportion of devices appear to be incorrectly configured, leading inevitably to greatly increased costs for the tenants. At least four devices are regularly heating at the wrong time, either due to the secondary 'boost' element being left on, or an incorrectly configured timer on the primary element. This suggests that it may be worthwhile for stakeholders such as housing associations or energy suppliers to monitor the consumption of households on E7 tariffs to notify them if an incorrect configuration is suspected. Energy suppliers could do this with the peak/off-peak meter data they have already, or housing associations could analyse consumption using smart controls such as those used in this trial.

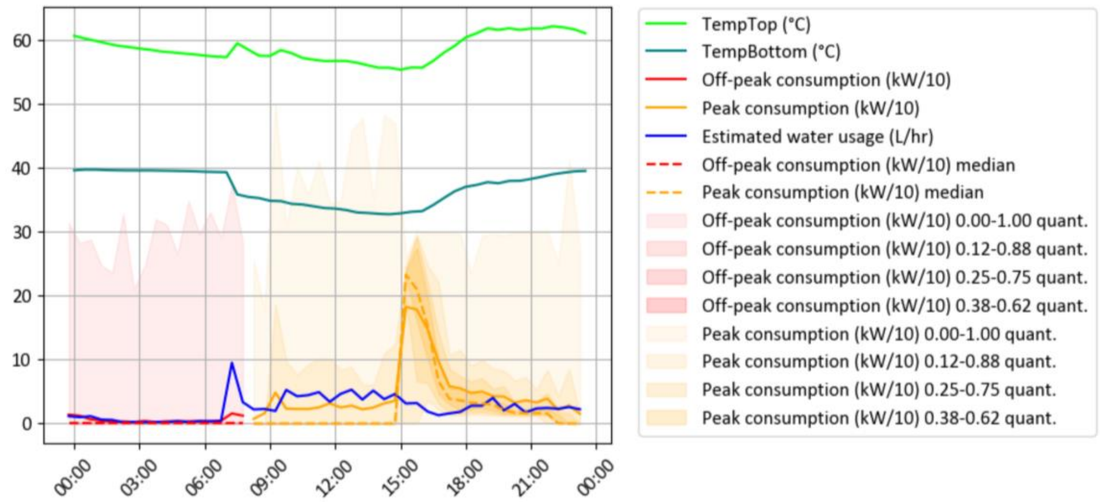

Figure 20: An incorrectly configured hot water device profile whose clock appears to be out of sync.

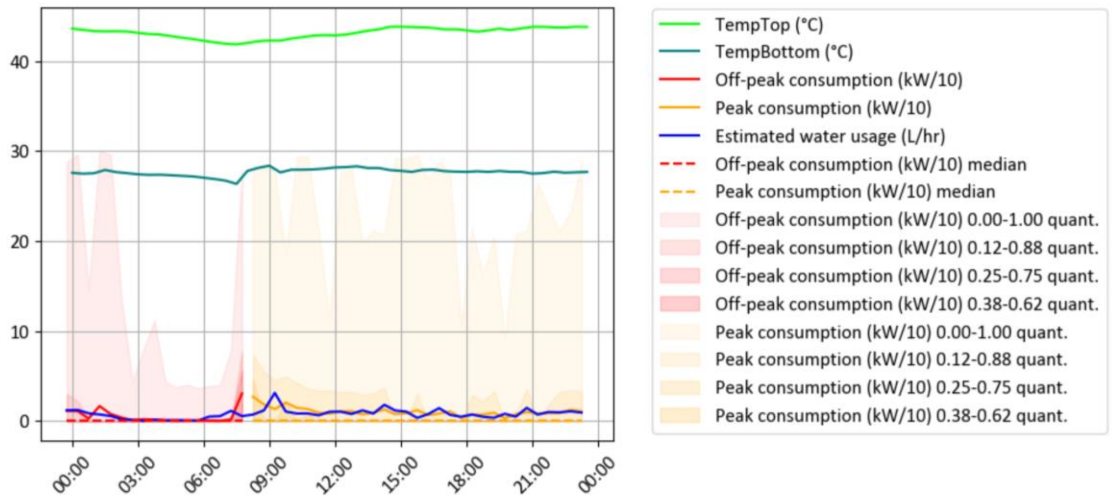

Figure 21: An incorrectly configured hot water device profile which appears to consume at all peak times.

Figure 20 shows a hot water device whose clock appears to be out of sync, such that consumption starts at 15:00 and continues during peak hours. This may cost the tenant at least double compared to the correctly configured case if the timing is downstream of the meter. In some cases where the incorrect timing is done by the meter (typical of legacy 5 terminal meters) then the tenant would not pay but the network is effectively subsidising off-peak energy use in on-peak times. This device has been excluded from aggregated statistics.

Figure 21 shows a different issue: the heating occurs during all peak times, rather than off-peak times. We see the peak of the heating occurring at 08:00. Heating continues at a low level throughout the day to maintain the temperature at the setpoint. This device has also been excluded from aggregated statistics.

3.2.8 Tank heating and cooling properties

To fully understand the potential for shifting the heating time, it is necessary to understand how long it takes the hot water tanks to fully heat up, and how long it takes them to cool through conductive and radiative heat losses. Using the known electrical immersion element power, an estimated tank capacity, and the average day's temperature drop for each device, the theoretical time to charge is estimated to be 1.38 hours (min: 0.5h, max: 3.1 hours) for the trial devices. This is roughly the duration of the bulk of the heating in the consumption profiles.

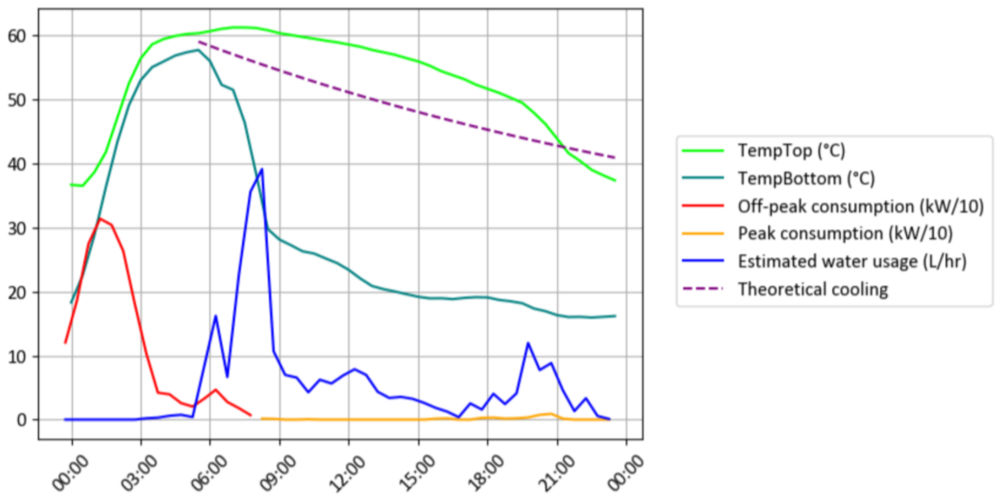

Figure 22: A daily profile for a single hot water device, with the dashed purple line showing the predicted cooling without any water usage. The ambient temperature for this device is estimated at 23 degrees.

To determine the rate of cooling, a script was written which identified long periods of cooling with no water usage and determined the cooling coefficients (exponential decay coefficient and ambient temperature) for each tank, assuming conduction is the dominant method of heat transfer (full methodology in appendix). Only 11 devices have sufficient data to do this. Of these, the average estimated exponential decay coefficient 'k' was 0.04/h (min: 0.025/h max: 0.070/h), indicating that it typically takes 17 hours for the difference in temperature between the tank and its environment to halve. Thus, it can be predicted how the devices would cool from their maximum temperature, with an example given in Figure 22. It should be considered that while most of the tanks in the study have some insulation, they are not insulated to modern standards and as such there may be scope for improvement with insulation retrofits.

It is difficult to know at which temperature to define the point where the tank is unusably cool, due to the previously mentioned uncertainties regarding the relationship between measured tank temperature and point-of-use water temperature. Therefore, a variety of metrics are offered in Table 4 to display the results.

Table 4: Results of hot water tank cooling calculations

Cooling metric **Time to cool from daily average profile max to:**	**Time to cool with no usage (hours)**		
	Min	**Mean**	**Max**
25% of the way from the maximum to the minimum temperature on the daily average profile.	3.1	5.3	7.3
50% of the way from the maximum to the minimum temperature on the daily average profile.	7.1	11.9	16.1
100% of the way from the maximum to the minimum temperature on the daily average profile (large uncertainty here as approaching ambient temp).	20.1	34.6	52.2
50% of the way from the maximum temperature on the average profile to the estimated ambient temperature (analogous to a radioactive half-life).	9.9	19.9	29.7

3.3 Supplemental hot water data

Connected Response provided a large, anonymised dataset of consumption data from a previous installation of smart controls in a social housing estate in the City of Westminster. The dataset contains combined hot water and space heating consumption for 780 installations over a period of four years (2016-2020). These customers are on a custom tariff, similar to an E10 tariff, which provides three cheap off-peak windows per day. From the data, we can be confident that these periods are 01:00-06:30, 13:00-15:30 and 18:00-19:30.

As the hot water and space heating were combined, and only hot water is of interest to this report, only data from July and August has been analysed, with the assumption that negligible space heating would occur during these summer months.

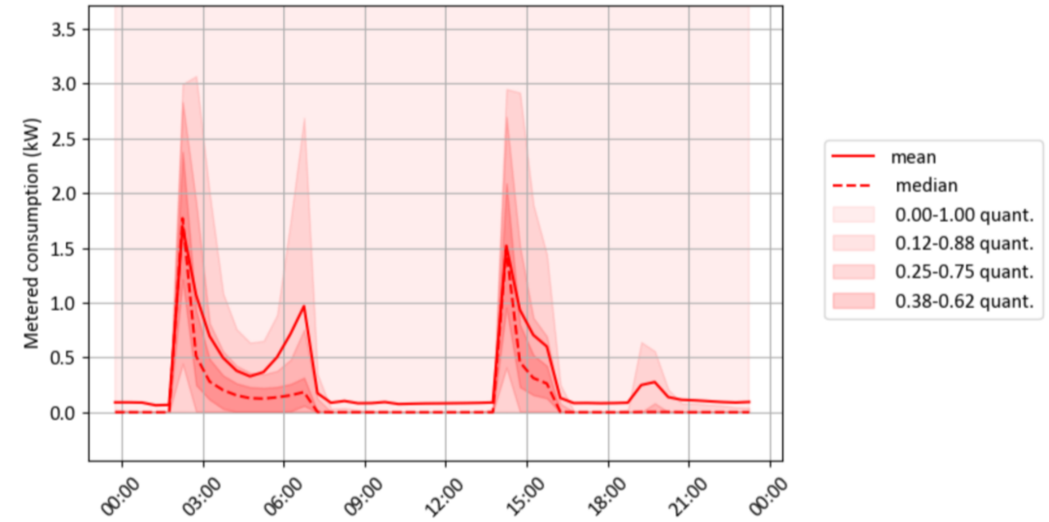

Figure 23: Supplementary hot water consumption data from Westminster on a custom E10-like tariff, with quartiles showing the variation between *all days in the dataset*.

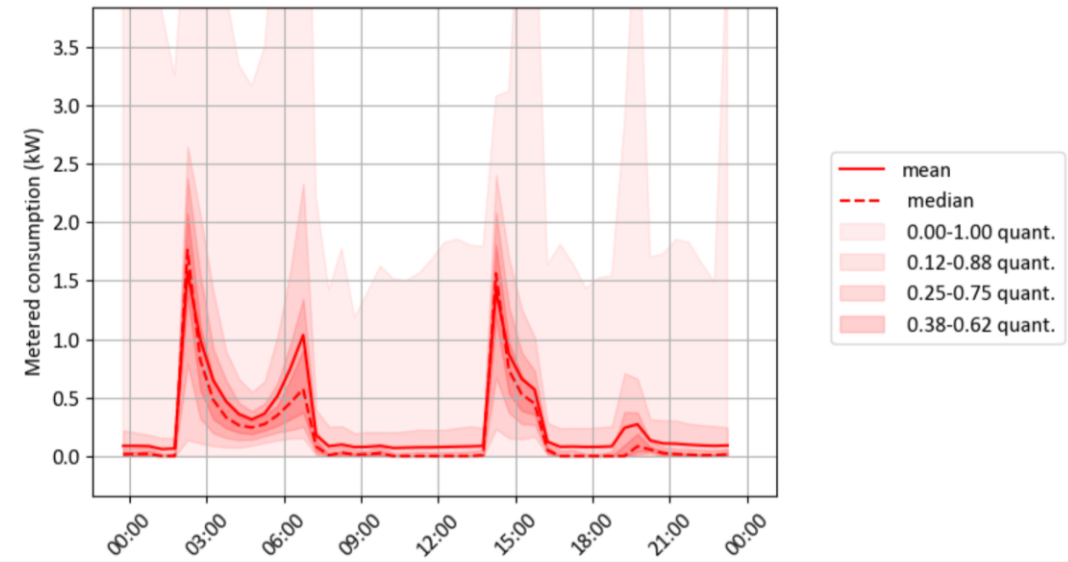

Figure 24: Supplementary hot water consumption data from Westminster on a custom E10-like tariff, with quartiles showing the variation between *device average profiles*.

Figure 23 shows the profile for the Westminster data, with quantiles showing the variation between all days in the dataset. Firstly, it is noted that the maximum quantile line is off the y-axis scale and is greater (17kW at times) than the assumed immersion element power of 3kW. This can be explained by occasional use of the space heating system, which is a small fraction of the time and so should not significantly affect the averages. As expected, there is a large spike of 1.8kW at the start of the overnight off-peak period, with many devices reaching their maximum of 3kW, as the tanks heat up to their setpoint. The consumption then tails off as the setpoint is reached. There is a second spike in the mean line towards 06:00, although the median line remains flat. This can be explained by occasional use of the hot water before 06:00 and the subsequent reactivation of the heating element as cold mains water enters the tank. There is also a significant spike in the afternoon at 14:00, present in almost all devices, indicating that the tanks have cooled below their setpoint by this time. This suggests that the afternoon off-peak window (which is not present in an E7 tariff) can be worthwhile from a comfort perspective. There is a small spike in the evening off-peak window, although at least 50% of the time there is no heating in this window at all.

While Figure 23 shows the variation between days in the dataset (i.e. mean and quantiles of all days of data ignoring which device they come from), Figure 24 shows the variation between device averages (i.e. mean and quantiles of each device's average profile). Comparing the two clarifies whether occasional trends are seen throughout all devices or just in a few differing devices. For example, the 0.1kW baseline consumption at all times is due to a small number of devices – at least 75% of devices have no consumption between 08:00-14:00. However, while the 05:00 and 19:30 spikes are seen on less than 50% of days, a majority of devices do occasionally participate in these spikes, hence they appear in their averages.

4 Business modelling

This section explores the methods of value creation presented in section 2.1 for both the battery and hot water case and analyses the potential for profitability on various timescales given the capital and ongoing costs associated with the equipment.

4.1 Literature review

A brief literature review was conducted to understand the potential revenue streams that would be applicable for each of the battery and hot water use cases. This included identifying the type of options available (i.e. DNO/DSO services, NG ESO services, or tariff switching & optimisation), understanding the requirements to participate and applicability, and the potential value (i.e. savings or availability and utilisation payments) to be gained from the service. The below tables summarise the narrowed down set of possibly applicable revenue streams. Various commercial domestic electricity tariffs were also investigated as part of this report – these are presented in Table 3 in section 2.3.2.

Table 5. Summary of key applicable revenue streams and services investigated as part of the larger literature review

Category	Revenue Stream / Service	Description
DNO / DSO	Secure [8]	- Used to manage peak demand on the network and preventively reduce network loading; windows for provision are schedule a week-ahead. - Paid for availability (£/MW/h) and utilisation (£/MWh) as bid. - Commit to service window ~6 months ahead.
DNO / DSO	Sustain [8]	- Used to manage peak demand on the network and preventively reduce network loading; windows for provision are scheduled and fixed at the point of contract. - Paid a fixed (£/MW) service fee. - Commit to service window delivery 1 month ahead (option for 1 week).
DNO / DSO	Dynamic [8]	- Required following a network fault; participants are expected to be ready to respond to utilisation calls within 15 minutes, but windows for provision are declared a week-ahead. - Paid for utilisation (£/MWh). - No fixed service windows.
NG ESO	Balancing Mechanism (BM)	- Used to balance electricity supply and demand close to real time. - Access through Virtual Lead Party, VLP - Paid for utilisation (£/MWh) at a variable price based on current rate. - No fixed service windows.
NG ESO	Fast Frequency Response (FFR)	- Used to rapidly (<2 s delivery time) provide power increases or decreases to balance electricity supply and demand. - Paid for availability (£/MW/h) and utilisation (£/MWh) as bid. - Differing service windows.

Time shifting	Wholesale price arbitrage	- Based on day-ahead wholesale market which gives an hourly price per MWh of electricity the day before the electricity is used. - Value is to be had by shifting demand to lower price periods and/or importing (purchasing) energy at times of low prices and exporting (selling) at times of high prices) aligned to the fluctuating price throughout the day.

4.2 Battery

This section concerns the business case for the battery use case, in relation to the value strategies introduced in section 2.1.1. The tariff switching simulation explores the optimal tariff for value strategies 1 and 2, followed by an exploration of value strategy 3: the possibility of participating in NG and DNO/DSO flexibility markets. Value is considered for the customer, the DNO/DSO, the national grid and the wider environment. Lastly, a cost-benefit analysis is performed with an optimised revenue stack combining all value strategies.

4.2.1 Tariff switching simulation

The results of the six-month tariff simulation described in section 2.3.3 are presented in this sub-section.

Financial savings

A summary of the financial results of the six-month tariff simulation is shown in Figure 25, with an example of the simulated battery behaviour in Figure 26. It is important to recall that the battery controller behaves differently on each tariff.

Firstly, the value of the solar PV panels (without a battery) was examined. The panels decrease the cost by a significant margin in all cases. For the non-export tariffs, the PV panels decrease the average cost by a consistent 25-30%, largely irrespective of whether the tariff is flat or ToU. The greatest benefit of the PV panels is unlocked when export tariffs (e.g. Outgoing) are used, with the PV panels reducing the total cost by over 54% for both 2019 and 2021 versions of Agile. This is unsurprising, as it can be recalled that for most households in the trial, the production well exceeds the consumption at midday (see Figure 26). For the Agile + Outgoing 2019 tariff, the 54% saving due to the PV is made up of 26% from offsetting consumption and 27% from exports. In absolute terms, this export is worth £78/year on average, up to £163/year for the largest producer. As discussed in section 2.1.1 (Household information), some households may be ineligible for an export tariff due to already being in receipt of a FiT export payment.

Secondly, the value of the batteries was assessed. The addition of the battery saves a further £88-170/year on average, depending on tariff, shown in green in Figure 25. This represents 31-66% of the cost with PV panels but without the battery. There is variation between devices, especially on flat tariffs – some devices on flat tariffs will gain as little as £3/year from adding a battery while some gain £179/year depending on the output ‘production’ of the PV panels.

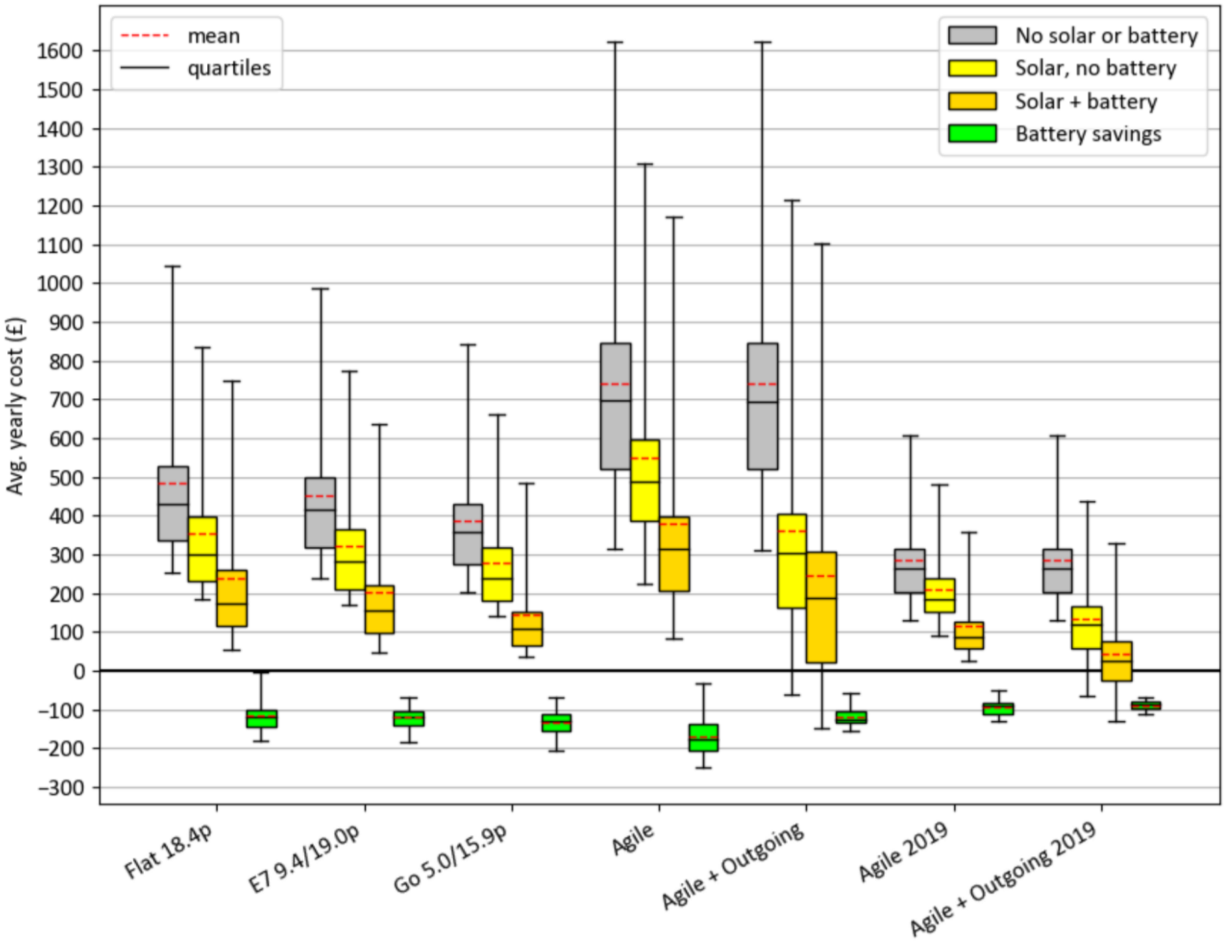

Figure 25: Simulated electricity costs on various tariffs using six months of Home Response consumption and production data, showing the spread of costs across the fleet. 'Battery savings' is the difference between the 'solar, no battery' case and the 'solar + battery' case.

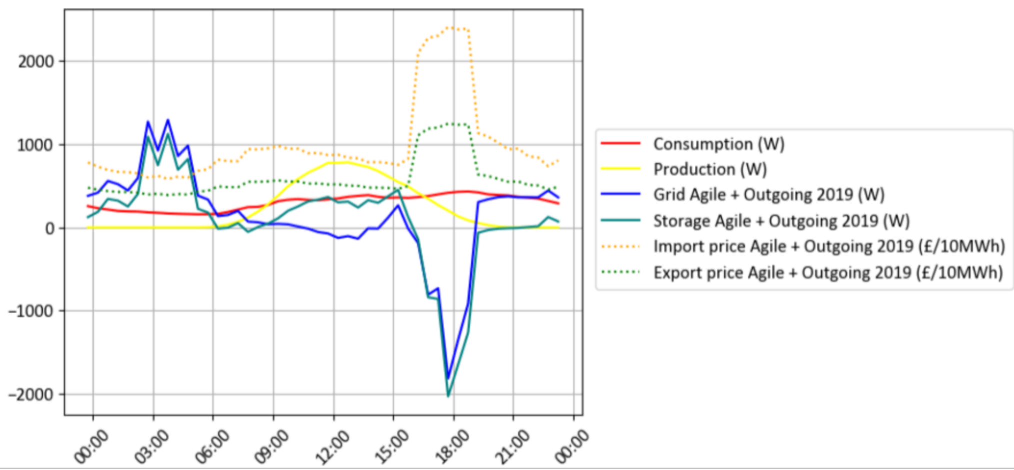

Figure 26: The simulated battery behaviour responding to the Agile + Outgoing 2019 prices, averaged over all devices. The addition of the battery reduces the average cost on this tariff by £88/year down to just £44/year.

Lastly, for the business case analysis, we have considered the average savings in three 'scenarios', which include savings from battery installation and tariff switching:

- ***Low***: A customer with PV panels on a flat tariff (Flat 18.4p) buys a battery but is unwilling or unable to switch tariff. The customer can expect savings of **£117** or 33% (although lower savings are possible if PV production is low).
- ***Average***: A customer with PV panels on a flat tariff (Flat 18.4p) buys a battery and decides to switch to a dynamic ToU tariff under normal market conditions (Agile 2019), without an export tariff as they lack the required paperwork or already benefit from a FiT. They can expect savings of **£237** or 67%.
- ***High***: A customer with PV panels on a flat tariff (Flat 18.4p) buys a battery and decides to switch to a dynamic ToU import and export tariff under normal market conditions (Agile + Outgoing 2019). They can expect savings of **£310** or 87%.

Due to the complexity in comparing tariffs (as discussed in 2.3.3), especially during a period of unprecedented price rises in the energy market, there is an inherent uncertainty in figures which involve tariff switching.

Factors affecting savings

In some cases, the variation between households was very large. It was hypothesised that matching the battery to the household in some way would provide a greater saving. This sub-section explores the correlations that were observed between savings and household and price market factors.

The variation in battery savings between devices on the flat tariff is principally dependent on the level of solar production (Figure 27). This is because on a flat tariff the battery only minimises export (value mode 1) as discussed in section 2.1.1 (Value creation) and for small PV arrays there is no export to minimise. A strong correlation (Pearson's r = 0.83) is also seen for the Agile tariff (Figure 28), however this is due to the energy crisis causing the price in 2021 to frequently hit the £0.35/kWh cap and therefore strongly resemble a flat tariff.

However, when a ToU tariff with an export payment is used, the battery is able to utilise the temporal difference in import price (value mode 2 as discussed in section 2.1.1) to create value by charging at cheap times, irrespective of the size of the solar array. For Agile + Outgoing 2019 (Figure 29) we see minimal correlation, because minimising export is no longer a significant benefit of the battery when export is compensated. For Go 5.0/15.9p (Figure 30), which is not an export tariff, we see a weak correlation because both value modes are at play. It should also be noted that the greater battery savings for Go 5.0/15.9p are due to the benefit of both value modes (which does not signify lower overall costs for this tariff).

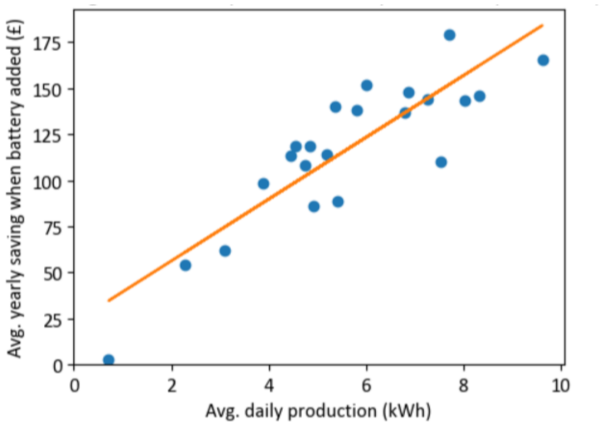

Figure 27: Savings due to the battery on the Flat 18.4p tariff against average daily solar production, showing a strong correlation (Pearson's r = 0.87)

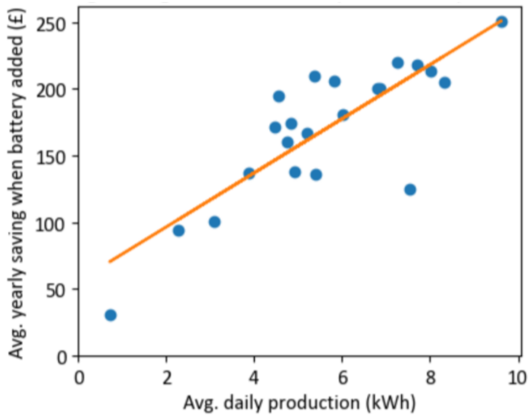

Figure 28: Savings due to the battery on the Agile tariff against average daily solar production, showing a strong correlation (r=0.83)

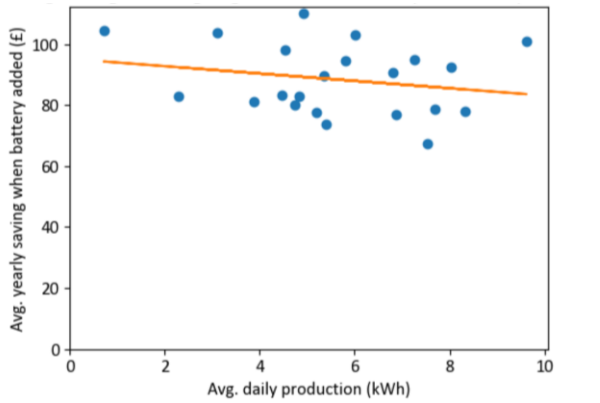

Figure 29: Savings due to the battery on the Agile + Outgoing 2019 tariff against average daily production, showing no significant correlation (r=-0.22)

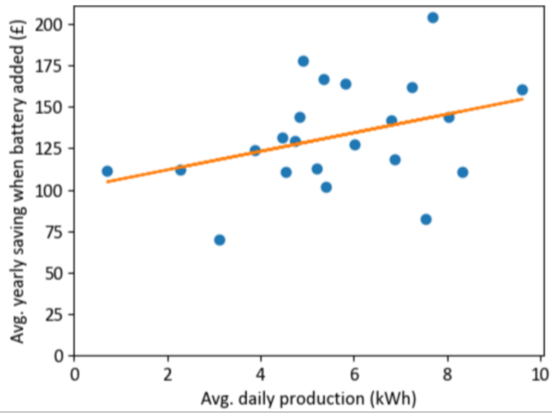

Figure 30: Savings due to the battery on the Go 5.0/15.9p tariff against average daily production, showing a weak correlation (r=0.37)

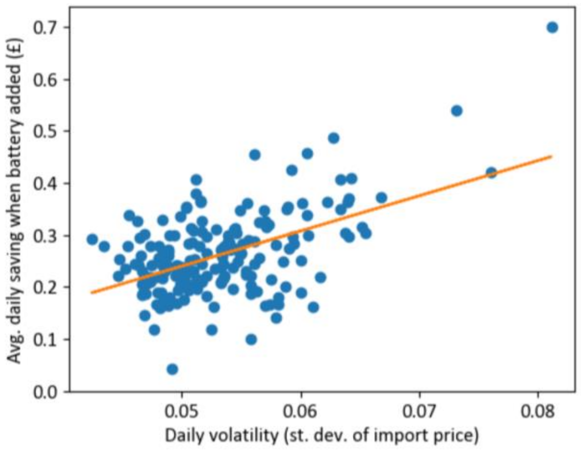

Figure 31: Battery savings versus price volatility for Agile 2019 tariff (Pearson's r = 0.48)

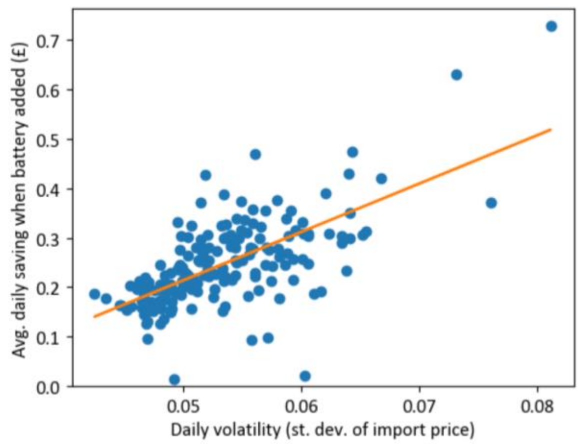

Figure 32: Battery savings versus price volatility for Agile + Outgoing 2019 tariff (Pearson's r = 0.66)

For the dynamic ToU tariffs, rather than being correlated with the volume of production, the savings are instead correlated with the volatility of the price. Figure 31 and Figure 32 show the savings due to the battery on each day of the trial, averaged across all devices, against the import price volatility on that day. The positive correlation in both cases implies that if the import price volatility increases (as may occur in the future, due to the further adoption of variable renewable energy generation), the savings from using a battery are likely to increase relative to a non-battery case.

The results from the Agile 2021 tariffs are not shown as they are highly distorted by the effect of the price frequently hitting the £0.35/kWh import cap, and the supranormal profit caused by occasional Outgoing price spikes of >£2/kWh in September 2021.

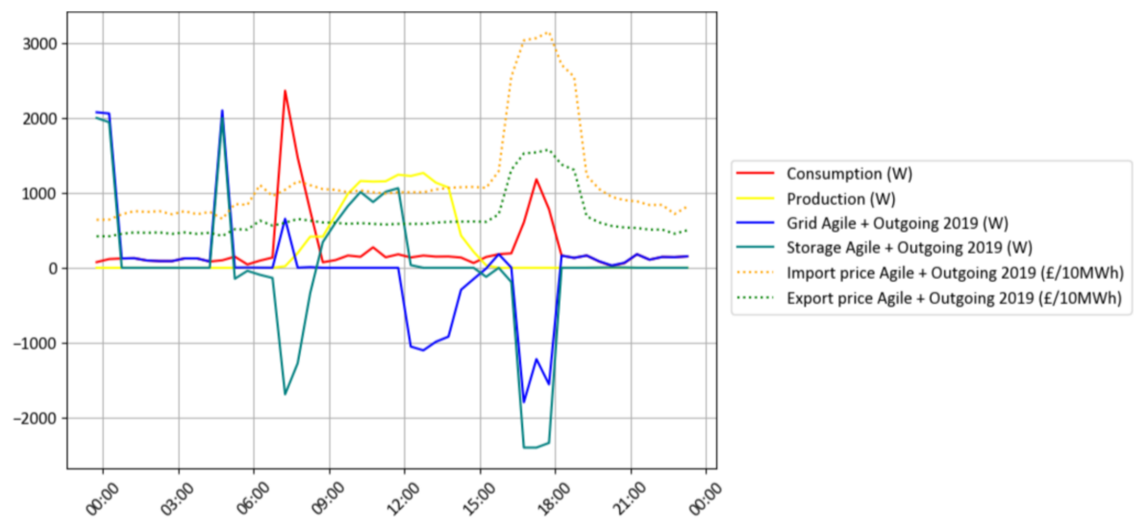

Figure 33: A highly volatile day on the Agile + Outgoing 2019 tariff, in which this PV + battery device saves £0.60 due to the battery, and the fleet saves an average of £0.42.

An example of a relatively volatile day which leads to large battery savings is shown for a single device in Figure 33. The battery is able to charge from the grid in the morning as well as from the solar generation, preventing two large import events at the morning and evening peaks, and even enabling an export during the evening peak.

Surprisingly, no significant correlations were observed between household consumption and savings on any tariff.

CO_2 emissions impact

A CO_2 emission impact analysis (from the grid perspective) was performed, using half-hourly grid average carbon intensity figures from National Grid ESO. Only grid *average intensity* figures are calculated and published. It is likely that *marginal intensity* (the emissions associated with the production of an additional small unit of power on top of the real power level at a particular time) would be more accurate, however a reliable source for this data could not be found.

This is not a lifecycle analysis (LCA) as it does not include emissions from the manufacture of the battery, only emissions associated with the household's electrical import from the grid.

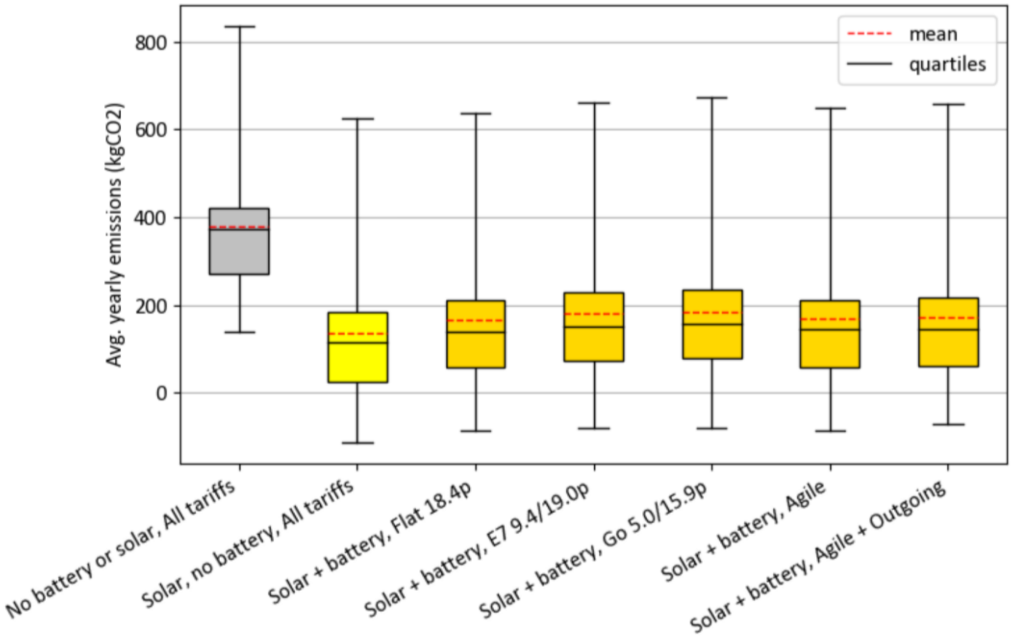

Figure 34: CO_2 emissions of the households on various tariffs, showing the case with no battery and no solar against simulated scenarios. Agile 2019 data/tariffs from have been excluded as the CO_2 intensity data is based on the simulated 2021 period.

The results, shown in Figure 34, show that by adding the battery to a PV-only system, between 20% and 38% more CO_2 is emitted, depending on tariff. This is due to the energy standby requirements and energy lost in the batteries, which have an efficiency of around 70%. This means that the overall daily net import necessarily increases when the battery is added, from 1.58kWh average without a battery to 2.3kWh-3.5kWh, depending on tariff. It should be noted that 1.58kWh is a low net import – the presence of the PV panels already reduces net import from 7.2kWh (the average daily consumption), reducing average CO_2 emissions by 69% in the process.

The effect of the battery's inefficiency is unfortunately greater than the effect of shifting the energy consumption to times of lower carbon intensity. This is because the profile of average carbon intensity is currently quite flat, with natural gas still a significant part of the energy mix, even at night. It is expected that the CO_2 average intensity profile will become less flat over time (as the grid shifts to higher shares of variable renewables), which will increase the potential for carbon savings through usage shifting.

Fundamentally, it is important to note that it is unlikely that the electricity grid could decarbonise its generation without some form of energy storage, and no form of energy storage is devoid of losses.

Furthermore, it should be noted that the battery controllers are optimising for cost, on all tariffs, not carbon emissions. While the correlation between Agile import price and carbon intensity is quite strong (r=0.6 for the 6 months of simulation data), it is not perfect, and it is likely that carbon savings would be made if this were the variable targeted to be minimised.

4.2.2 Extent of demand-shifting

The tariff simulation that was described in section 2.3.2 is also useful for analysing the extent to which demand would be shifted through the adoption of these batteries. From the perspective of the DNO/DSO, the primary consideration is to reduce the peak load, which usually occurs in the early evening on weekdays. A secondary consideration is the reduction in excess generation, which can cause issues of reverse power flow on sunny summer days.

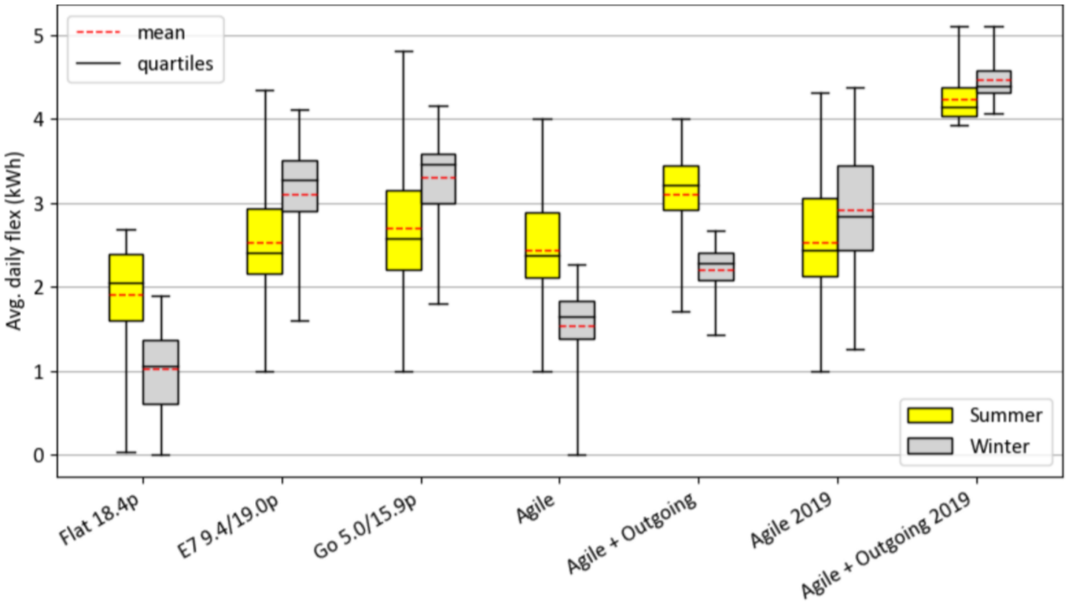

Figure 35: The amount of 'flexibility', i.e. the average gross battery output per day, segmented by summer and winter, on various tariffs. The batteries all have a capacity of 4.8kWh.

The amount of battery 'flexibility' (in terms of gross battery energy output) provided by the batteries when optimised for various tariffs is shown in Figure 35. This varies from 0kWh/day (for the flat tariff and for devices with low production, the battery is barely used) to over 5kWh/day (for ToU export tariffs the 4.8kWh battery frequently does more than one full charge-discharge cycle in a day).

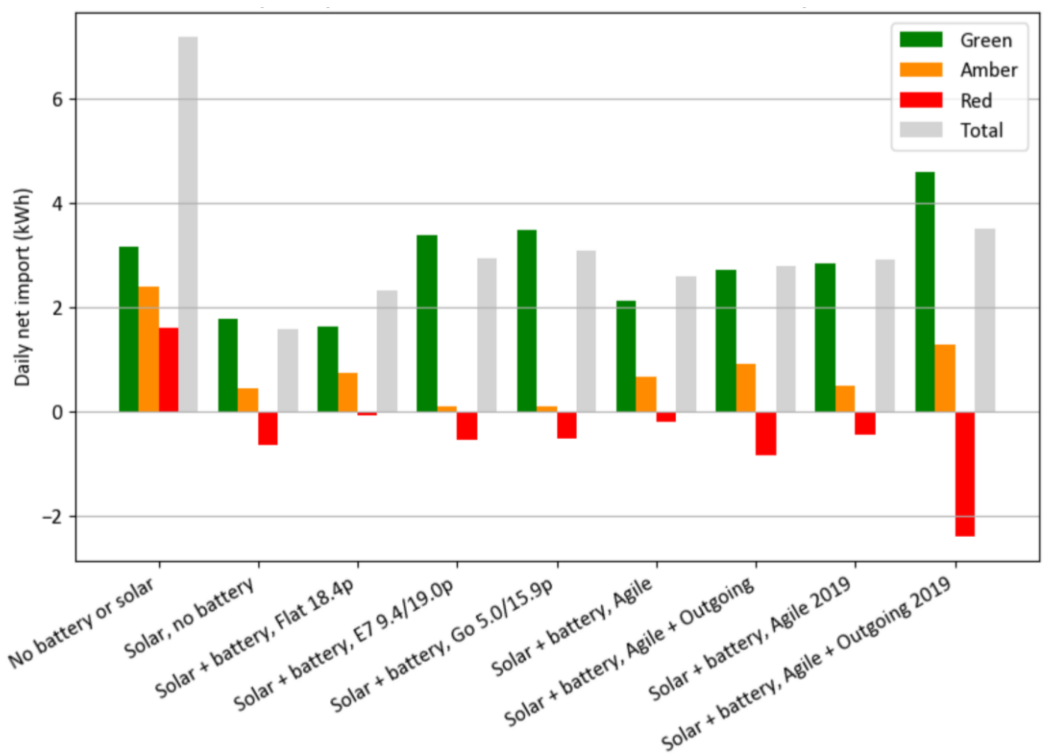

Figure 36: Net import by Time Band (based on UKPN's London Power Network banding), 6 months simulated battery behaviour on various tariffs

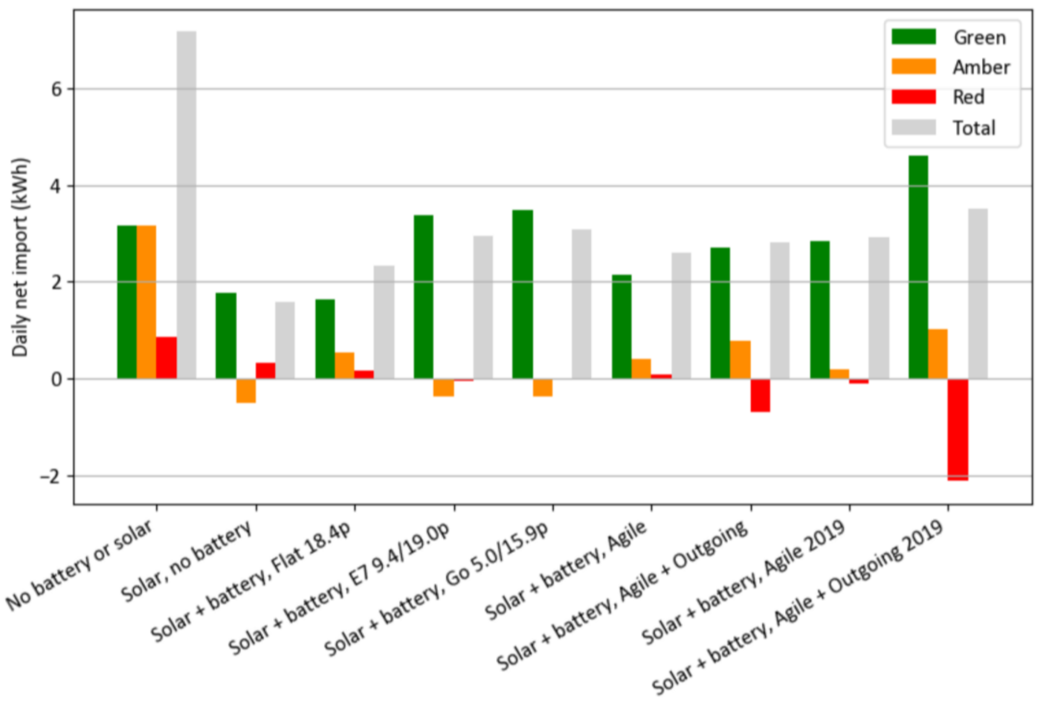

Figure 37: Net import by Time Band (based on UKPN's Eastern Power Network banding; similar to the rest of the UK), 6 months simulated battery behaviour on various tariffs

UKPN divides time into three Time Bands according to the typical demand volume at that time, in order to apply their Distribution Use-of-System (DUoS) charges. For the London (LPN) region, the 'red' Time Band is 11:00-14:00 and 16:00-19:00 on weekdays, the green Time Band is all weekends and 23:00-07:00 weekdays, and the remaining time is amber. Figure 36 shows the effect of the battery and chosen tariff on the average net import for each time band. It was assumed that, for the DNO/DSO, an export at a certain time is equivalent to a reduction in import. On the figure, negative net imports indicate a net export from the household.

The high extent of urbanisation and commercial operations in London mean that the demand profile in London is not representative of the UK. For this reason, the Time Bands for the Eastern (EPN) region, which considers 11:00-14:00 weekdays as 'amber' rather than 'red', have been used in Figure 37 and the red time banding in this graph should be considered indicative of the general UK peak time.

Using the London Time Bands, the addition of the solar panels has a large positive effect in reducing peak 'red' band import, from 1.6kWh/day to -0.7kWh/day, the latter figure probably being negative due to PV export in the 11:00-14:00 weekdays period. The addition of the battery optimised for a flat tariff does not further reduce the 'red' band import, likely because any solar that would have been exported between 11:00-14:00 is used to charge the battery. However, a reduction is seen when optimised for the dynamic ToU export tariffs, down to -2.4kWh/day on the Agile + Outgoing 2019 tariff. This is 1.5 times greater in magnitude than the 'red' import without PV or battery – it could be said that a household with PV and a battery on a dynamic ToU tariff will offset 1.5 'regular' households at the peak hours of the day.

Using the EPN Time Bands, the omission of the 11:00-14:00 period in the 'red' band means that solar panels alone are no longer sufficient to create a net export in this band. The impact of a battery on a flat tariff has only a small effect. However, a battery optimised for the Agile + Outgoing 2019 tariff reduces the 'red' import to -2.13kWh/day, demonstrating that most of the price-driven battery export is in the evening peak rather than in the morning. This is equivalent to offsetting 2.5 'regular' households.

As previously discussed, the total (all time bands) net import inevitably increases compared to the no battery case due to inefficiencies in the battery.

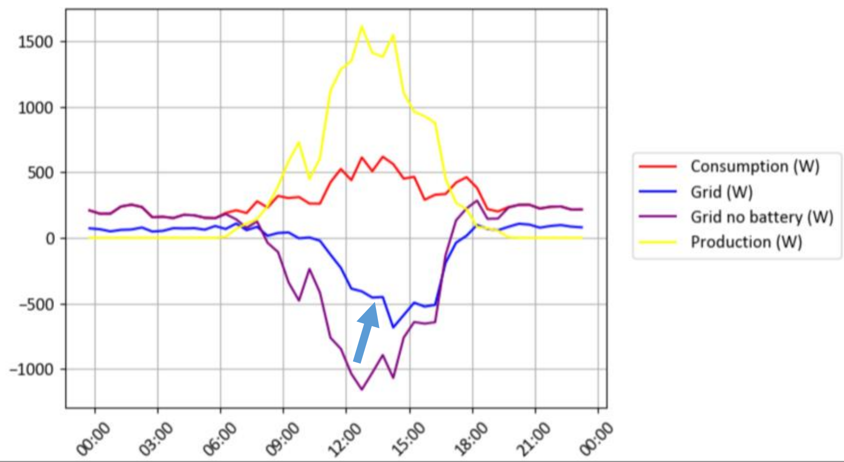

Figure 38: Real battery behaviour on a single day (16/08/2021) with high PV production and low daytime prices, averaged over all devices, showing the reduction in grid export at times of solar peak for the battery case. Almost all batteries are optimised for a flat tariff.

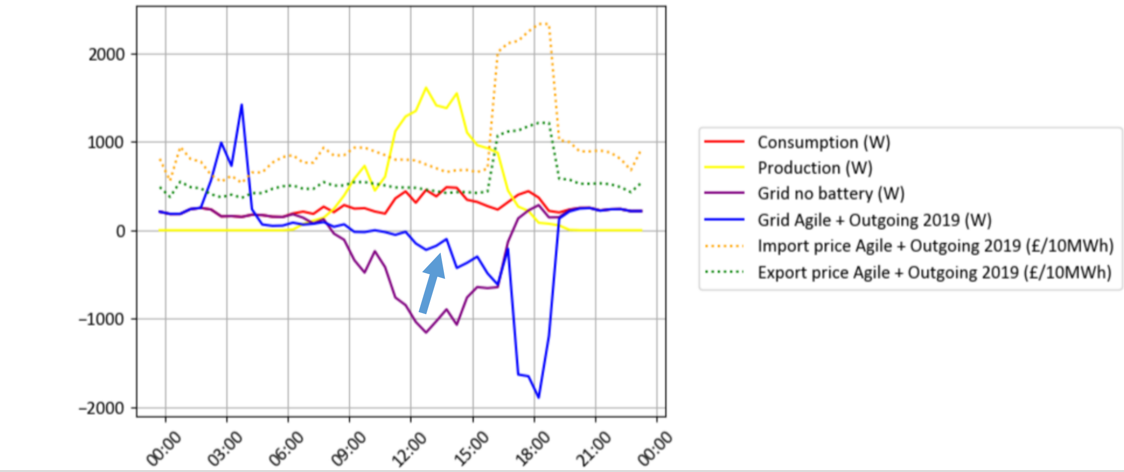

Figure 39: Simulated behaviour on Agile Outgoing 2019 tariff on the same day (16/08/2021) with high PV production and low daytime prices, averaged over all devices, showing the reduction in grid export at times of solar peak for the battery case.

Figure 38 and Figure 39 how the potential benefit of the battery systems for the purpose of avoiding reverse power flow on days of high PV production and low consumption. The real (not simulated) Home Response data in Figure 38 shows that batteries optimised for a flat tariff (which aim to reduce total export irrespective of time) reduce export at the solar peak.

A better performance can be achieved with a dynamic ToU export tariff. It is assumed that on days where reverse power flow is a risk, the dynamic ToU tariff price will be low, as occurred on 16/08/2021 and illustrated in Figure 39. The batteries respond to the low price by charging at solar noon and discharging during the evening peak. This approach has the additional benefit that the export reduction will only occur if incentivised by the low price.

4.2.3 Flexibility service provision

This subsection covers the simulated flexibility service provision testing performed to understand the costs and revenues that could be had from these services.

As described in section 2.3.4, the potential availability for delivering a specific grid service program and resulting expected costs and were estimated from simulations conducted in Moixa's GridShare platform. These involved looking at the expected service windows for each flexibility service, as described in Table 5, and then creating simulated dispatch requests for the Home Response fleet during these windows, triggered at the expected time the service would be requested in live operation. The platform would then aim to return the requested amount of power to be delivered and the lost behind-the-meter optimisation value (i.e. considered an opportunity cost). This was done for steadily increasing power requests such that the correlation in behind-the-meter cost increases as a function of the proportion of total theoretical power could be understood.

Service delivery ability

As different services have different gating periods (i.e. notice durations prior to dispatch requests) to which they must adhere, this work also investigated a fleet's ability to deliver on the required service at varied levels of required power.

The below figure, Figure 40, shows how the average proportion of power delivered relative to the total power requested (for a total simulated fleet size of 26.4kW) for a UK Power Networks Secure service which was gated 24 hours before the 17:00 - 19:00 dispatch window, averaged across all service days. As can be seen, there is a notable drop off in delivery ability above ~60% capacity (i.e. at 15kW relative to the total 26.4kW fleet size). This is a trend that has been seen in previous work, particularly for early testing conducted with a new fleet. However, Moixa typically can deliver services with 95%+ availability for a 24-hour ahead gating. As such, this should not be an inhibitor or contribute to a potential derating factor for the fleet for this type of service; rather, aggregators should aim to test their fleets prior to live flexibility service provision in order to overcome any potential obstacles to delivery.

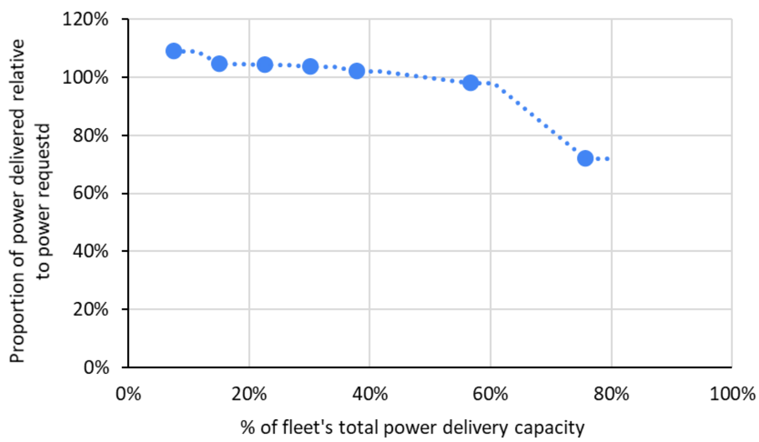

Figure 40. Average proportion of power delivered relative to the total power requested (for a total fleet size of 26.4 kW) for UK Power Networks Secure service, gated 24 hours before the 17:00 - 19:00 dispatch window

Similar simulations and results were calculated for all services, and in this way a map of the service delivery ability for using this fleet of batteries was established. The key correlation derived from this additional analysis is that as the gating time decreases (e.g. to 60 minutes ahead or 30 minutes ahead, instead of 24 hours ahead) and dispatch duration increases, the proportion of the total fleet power capacity that can deliver the requested service decreases. For example, when testing UK Power Network's Dynamic service, more than half the tested simulations see service provision drops even before reaching 50% of the fleet's theoretical maximum delivery power for a service that is requested at a 60-minute gating for a 60-minute dispatch duration. This is explained further as required in the below discussion on Costs & Revenues.

Costs & Revenues

The costs for all services were simulated using various tests across different parameters for gating, dispatch length, and other service requirements. In this way, a detailed view of the opportunity costs and gross revenues for using this fleet of batteries was established. These were then built into the potential returns (as detailed in section 4.2.5) by accounting for the net revenues (considering the costs that offset some of the revenues) in the appropriate revenue stack.

UK Power Network distribution services

The below figure, Figure 41, Shows how the average cost per kWh increases with increasing relative size of power delivery (relative to a total simulated fleet size of 26.4kW) for a UK Power Networks Secure service which was gated 24 hours before the 17:00 - 19:00 dispatch window, averaged across all service days. When considering the below trend (and also a potential linearly increasing trend), the costs for these events, for a fleet's total delivery capacity, can be inferred to be approximately between £0.22 - £0.28 per kWh. It should be noted that these costs are associated with battery discharge events, where there is a need to charge additional energy, or hold back energy instead of covering consumption. Based on Moixa's historical participation in this service, using a 20% utilisation rate, a 60-day season (three months), and other technical assumptions (including observed discharge lengths, average power level, average energy use, etc.), it can be determined that ~£0.15 per kWh could be recovered based on non-dispatched events that later use the charged energy to cover load outside the service window. This would imply that for 80% of events, the costs would fall by £0.15 per kWh, resulting in a weighted average range cost over the period between £0.10 - £0.16 per kWh, or £6 - £10 per kW over the 60-day season.

In contrast, for battery charge events, the cost is much lower as it is only dealing with the round-trip efficiency losses of the system. These were shown to be typically less than £0.04 per kWh across all windows; this is further discussed below under 'Balancing Mechanism'.

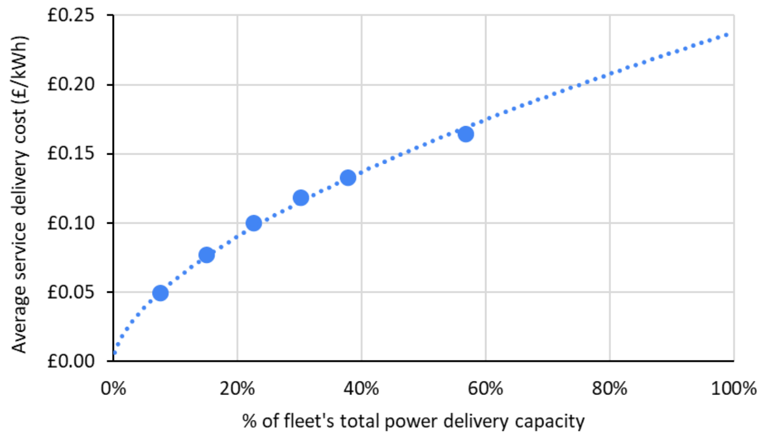

Figure 41. Average cost (£/kWh) for increasing relative size of power delivery (for a total fleet size of 26.4kW) for UK Power Networks Secure service, gated 24 hours before the 17:00 - 19:00 dispatch window

Similar simulations and results were calculated for UK Power Network's Dynamic service which has a gating of one hour. As such, this service only gives the battery system one hour ahead to plan for a 30- or 60-minute dispatch. For the 30-minute dispatch, providing the whole fleet capacity would cost the consumer ~£0.35 per kWh (notably higher than Secure/Sustain which have longer notice periods). For the 60-minute dispatch, even only with the provision of 50% of the fleet, the cost to the consumer is likely to be more than £0.60 per kWh. As such, it is recommended that a derating factor of 33% is used for the fleet to allow a margin whereby the system would be able to provide the service at a reasonable cost. This cost, assuming this 33% derating factor and 25% utilisation rate would be ~£2.61 per kw per year. Combined with marginal revenues, this suggests that participation in this service is unlikely to be lucrative for participants and so this service is not discussed further nor accounted for in the optimised revenue stack in section 4.2.5.

The key correlation derived from further analysis is that as the gating time decreases (e.g. to 60 minutes ahead or 30 minutes ahead, instead of 24 hours ahead) for a consistent dispatch duration (e.g. 60 minutes), the costs become considerably higher. For example, the below lists some example costs for different scenarios:

- £0.25/kWh for a 15kW (57% of total fleet power capacity) provision, 60-minute gating, and 30-minute dispatch duration.
- £0.35/kWh for a 25kW (95% of total fleet power capacity) provision, 60-minute gating, and 30-minute dispatch duration.
- £0.68/kWh for a 15kW (57% of total fleet power capacity) provision, 60-minute gating, and 60-minute dispatch duration.
- Unable to provide a 25kW (95% of total fleet power capacity) provision, 60-minute gating, and 60-minute dispatch duration.

Regarding potential revenues, average figures were calculated for these services based on the published document from UK Power Networks on expected revenues ranges. In the case of Secure and Sustain, this is made up of an Availability and Utilisation fee, and the costs incurred for prepping for the service were recouped in the cases of non-Utilisation as the battery would have a full charge that can be used to cover evening load. For the Secure service, the average revenue is estimated to be between £45 - £60 per kW per year. This, combined with the costs for this service presented above, gives a net revenue range of £35 - £54 per kW per year for participation in this service.

<u>Balancing Mechanism</u>

As the Balancing Mechanism is a 24-hour service, no specific window(s) had been targeted in the simulation. Instead, an average cost for dispatching across the day was utilised. When estimating the potential costs and revenues, the number of events in a calendar year was reviewed. These consist of Offers (battery discharge events) or Bids (battery charge events). Through analysis of published data on Balancing Mechanism events relevant for the use case, a total number of potential events was established. The criteria for relevance are described below:

- fall within “flexible window” for the system (which is all day for a battery),
- have a revenue higher than established cost from simulated analysis for Offers, and
- have a revenue higher than £0.04 for Bids.

This gave a number of remaining events that were applicable and an assumed percentage in which devices took part of 10-20%, allowing for final costs and revenues to be determined.

The Balancing Mechanism was modelled to have a 90-minute gating (pre-planning time) for a 30-minute dispatch. Simulation results showed that the provision of this service at 95%+ of total fleet capacity was consistently possible. For this provision, the average Offer (discharge) costs to the consumer was approximately £0.18 per kWh. Assuming a low and high case of 25 or 50 events per season respectively, this would translate to between £4.5 - £9 per kW per season. As alluded to previously, Bid (charge) costs are significantly lower with a range of £0.02 - £0.04 per kWh. Translating to the full season, assuming a low and high case of 70 or 192 successful events per year respectively, costs are likely to be between £2.8 to £3.8. The resulting revenue range for the Offers is £8.5 - £17 while the Bids come out as £7.7 - £17.3. This gives a net revenue range of £4 - £8 per kW per year for participation in Offers and £4.9 - £13.5 per kW per year for participation in Bids.

Frequency Services

The frequency service figures are based on prior internal evaluation by Moixa based on their expert knowledge and experience participating in these markets. An estimated range of £35 - £70 per kW per year is suggested. However, it should be noted that hardware readiness and qualification represent a barrier to entry into this flexibility service.

4.2.4 Cost of acquisition & installation

To better understand the costs required to run an energy trial like Home Response, the set of different cost types were considered, from engaging a potential participant, through the installation process, to the ongoing monitoring.

Table 6 below summarises the different types of costs incurred and their potential value across three different scenarios. The Low scenario portrays an optimistic view where costs are lower than current-day costs – i.e. potential future costs or costs that could be realised with increased efficiency or economies of scale. The High scenario presents the case in some ways similar to the costs incurred during this study; they account for participants requiring more significant remedial works and higher costs for engagement, kit, installation, and monitoring. This is included to reflect the uncertainty in the other direction, in contrast to the Low scenario. Lastly, the Average scenario aims at a middle ground of what could be realistic present-day costs for a well-deployed trial or set of installs.

All costs in the Table 6 are given on a per-install or per-customer basis, split into the relevant capital expenditures (capex) and operational expenditures (opex).

Table 6. Cost breakdown, across three scenarios (Low, High, and Average) for the battery case across acquisition & recruitment, the physical kit, installation, and monitoring and dispatch

Category	Cost description	Cost type (per unit)	Low-Cost Scenario	High-Cost Scenario	Average-Cost Scenario
Acquisition & recruitment	Client Participation Agreement drafting	Capex, fixed (£)	£ 0.3	£ 5	£ 2
	Landlord sign up	Capex, fixed (£)	£ 3	£ 40	£ 16
	Initial tenant engagement	Capex, fixed (£)	£ 2	£ 4	£ 3
	Tenant sign up	Capex, fixed (£)	£ 50	£ 108	£ 79
	Additional contact for remedial work	Capex, fixed (£)	£ 39	£ 75	£ 57
Physical kit	Kit + auxiliary components	Capex, fixed (£)	£ 3,014	£ 4,333	£ 3,768
Installation	Site visit & survey	Capex, fixed (£)	£ 40	£ 58	£ 50
	Installation	Capex, fixed (£)	£ 360	£ 518	£ 450
	Remedial works	Capex, fixed (£)	£ 120	£ 173	£ 150
Monitoring & dispatch	Cloud compute costs	Opex, yearly (£/year)	£ 9	£ 12	£ 11
	Monitoring costs	Opex, yearly (£/year)	£ 18	£ 60	£ 39
Total costs	**Total Capex**	**Capex, fixed (£)**	**£ 3,628**	**£ 5,314**	**£ 4,575**
	Total Opex	**Opex, yearly (£/year)**	**£ 27**	**£ 72**	**£ 50**

From the above set of costs, a net present cost (NPC) can be determined. Using the standard UK Greenbook discount rate of 3.5% and a varied potential lifetime of the battery, the below table (Table 7) can be generated which outlines the range of potential NPCs for an assumed battery lifetime between 10 and 20 years across the different cost scenarios. As can be seen by contrasting the above and below tables, much of the present cost is based on the capex required for the physical kit (i.e. the actual battery system and its components) with the other costs (acquisition, installation, monitoring) making up the remainder.

Table 7. Net Present Cost (NPC) of the smart battery system for a range of potential lifetimes across the Low, High, and Average cost scenarios

Lifetime (years)	Low Scenario NPC	High Scenario NPC	Average Scenario NPC
10	£ 3,852	£ 5,912	£ 4,987
15	£ 3,939	£ 6,143	£ 5,145
20	£ 4,012	£ 6,337	£ 5,279

4.2.5 Optimised revenue stack

For the battery case, the key revenue streams relevant to installations in London are:

- battery & tariff arbitrage,
- UKPN Secure or Sustain,
- Balancing Mechanism (BM) Offer (discharge),
- Balancing Mechanism (BM) Bid (charge), and
- Frequency Services.

The first item relates to the first two options for value creation as outlined in section 2.1.1, which discusses how the battery behaviour could be optimised to minimise grid import, maximise grid export (in cases where an export tariff is available) and take advantage of price arbitrage throughout the day (in cases where a dynamic ToU tariff is available). The remaining items relate directly to the provision of flexibility services to the DNO/DSO (i.e. UKPN Secure or Sustain) and to NG ESO (BM Offer, BM Bid, and Frequency Services).

Based on (i) the potential savings determined via the tariff switching simulation, as presented in section 4.2.1, and (ii) the flexibility service provision and assumptions, as noted in section 4.2.3, the below table outlines the current-day potential revenue values for the applicable revenue streams across Low, High, and Average revenue scenarios. UKPN's Dynamic service is excluded from the list due to its likely low value coupled with the potential difficulty in delivering full service provision.

Table 8. Applicable revenue streams and potential revenues for a domestic smart battery system, with values shown relative to a 2.4kW system (based the same battery capacity in this study) across Low, High, and Average revenue scenarios.

Revenue Stream	Unit	Low Revenue Scenario	High Revenue Scenario	Average Revenue Scenario
Battery & tariff arbitrage	£ / year / 2.4kW battery system	117	310	237
UKPN Secure or Sustain		85	130	107
BM Offer (discharge)		12	32	22
BM Bid (charge)		10	19	14
Frequency Services		84	168	126

The set of revenue values attributed to the flexibility service provision all already consider the potential cost to the consumer for participation – i.e. the difference between optimising for the user's own residential consumption or arbitrage and needing to prepare to participate in the service. As such, these can be considered net revenue values. Regarding the "Battery & tariff arbitrage", the Low, High, and Average scenarios correspond to the following cases relative to a 'Baseline' case where the resident does not have a battery and is on a flat tariff (for further information, please review section 4.2.1).

Considering the Average case as the most relevant, Figure 42 illustrates what a potential optimised revenue stack could look like for a domestic battery system, reaching just over £500/year for the 2.4kW system.

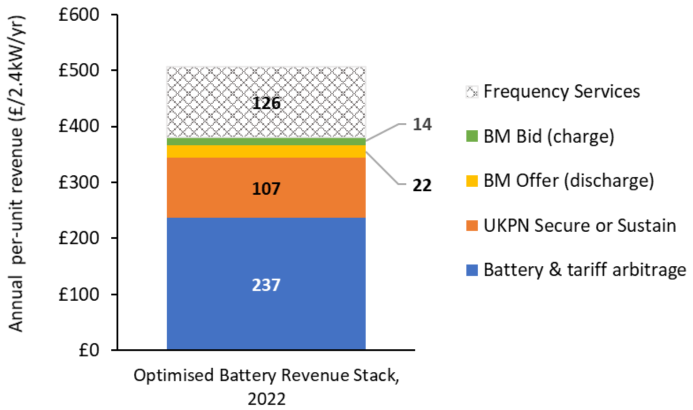

Figure 42. Optimised revenue stack (£ / year / 2.4kW battery system) via the installation of a battery, tariff switching, and flexibility service provision

From the above revenue stack, a net present value (NPV) of revenue is able to be determined. Again, using the standard UK Greenbook discount rate of 3.5% and a varied potential lifetime of the battery, the below table (Table 9) can be generated which outlines the range of potential revenue NPVs for an assumed battery lifetime between 10 and 20 years across the different revenue scenarios.

Table 9. Net Present Value (NPV) of revenues for the smart battery system for a range of potential lifetimes across the Low, High, and Average revenue scenarios

Lifetime (yrs)	Low Revenue Scenario NPV	High Revenue Scenario NPV	Average Revenue Scenario NPV
10	£ 2,903	£ 7,152	£ 5,033
15	£ 4,213	£ 10,963	£ 7,454
20	£ 5,429	£ 14,765	£ 9,771

The above table also accounts for two key assumptions in how the revenues are may change going forward into the future. First, aligned to typical inflation rates, it is assumed that there is a 2% year-on-year increase in revenues made from flexibility services. Second, based on the likely correlation between volatility and battery savings against the baseline case (as noted previously in this report), it is assumed that the battery and tariff arbitrage revenue stream increases in relation to increasing volatility. This year-on-year modelled increase is scaled differently between the Low (~2.5%), High (~10%), and Average (~5%) scenarios but is derived from a linear trend of the intra-day wholesale price spread over the last five years of available half-hourly data (i.e. difference in p/kWh between the highest cost during the day and the lowest cost during the day, and the resulting trend over time). Based on these assumptions (which could be seen as an optimistic case), the projected potential undiscounted future revenue stack in 2030 and 2040 increase to £655 and £852 respectively.

4.2.6 CBA results: net present value (NPV)

Considering the cost of acquisition and installation (covered in section 4.2.4) coupled with the optimised revenue stack (covered in section 4.2.5), the overall net present value (NPV) of the system over its lifetime can be determined. To cover the portray the range of uncertainty, the following three scenarios are combined with the spread of potential lifetimes (as previously shown): (i) Low Cost, High Revenue Scenario, (ii) High Cost, Low Revenue Scenario, and (iii) Average Cost, Average Revenue Scenario. The final outputs of this cost-benefit analysis (CBA) are shown in Table 10 below. For clarity, positive NPVs are shown in green and negative NPVs are shown in red.

Table 10. Summary results of the cost-benefit (CBA) analysis net present values (NPVs) for the battery use case for three different scenarios and a range of potential lifetimes

Lifetime (yrs)	Low Cost, High Revenue Scenario NPV	High Cost, Low Revenue Scenario NPV	Average Cost, Average Revenue Scenario NPV
10	£ 3,300	-£ 3,009	£ 46
15	£ 7,024	-£ 1,930	£ 2,309
20	£ 10,754	-£ 907	£ 4,492

As can be evidenced from the above table, there is a range of possible outcomes which are quite sensitive to the incurred costs and achievable revenue. In the average case, the typical payback period for the battery is on the order of ~10 years; of course, if the battery were to last longer (i.e. to 15 or 20 years), there would be significantly more benefit to reap from continuing to use the system. For the low cost, high revenue case, as can be expected, there is a positive NPV for all potential lifetimes. In contrast, for the high cost, low revenue case, the NPV is negative including accounting for up to 20 years of potential usage. This range in NPVs is a result of the financial uncertainty these domestic flexible assets may face. This risk could be mitigated in a number of ways, including via public funding to decrease the burden of capital cost upfront, ensuring a streamlined and efficient acquisition and installation process to lower upfront spend, continuing development of battery systems to lower the capex requirement, and development of more mature flexibility markets and regulation to ensure some type of confidence in the availability of future revenue streams.

4.3 Hot water

4.3.1 Non-DSR benefits

As noted in section 2.1.2, 'fixing incorrectly configured tanks' was realised as a potential non-DSR benefit of this trial. Several different value streams became apparent; a sample, looking ones that relate directly to the hot water use case, are outlined below.

- Failed off-peak immersion element whereby a user could only consume at peak rates: considering the average daily off-peak hot water demand (6kWh), there is significant value to be had by switching from peak-use to off-peak use.
- E7 optimisation: based on the hot water optimisation trial conducted as part of this larger study, 0.7kWh of daily energy demand could be reduced from off-peak times by shifting a user's charging time to later in the night an optimising for consumption requirements.
- E10 optimisation: for households with high afternoon/evening hot water demand, value of shifting the peak demand (while on an E7 tariff – average of 1.2kWh) to an off-peak time on an E10 tariff.
- Reducing callouts: by having remote monitoring/trouble shooting, there is value to be had in reducing the number of physical callouts (e.g. thermostat replacement, immersion replacement, tank replacement).

Table 11, below, summarises the above set of potential benefits, assuming a peak tariff of 19p/kWh and off-peak of 9.4p/kWh, aligned to the E7 prices used elsewhere in this work (as presented in Table 3 in section 2.3.2). The table outlines the key fault or intervention and the yearly value per unit.

Table 11. Overview of potential non-DSR benefits pertaining to the HR trial and an estimation of their potential value over the course of one year

Category	Fault / intervention	Estimated yearly cost / benefit to participant or landlord
Hot water usage	Failed off-peak immersion element	£210
	E7 optimisation	£24
	E10 optimisation	£41
Landlord maintenance cost	Reduced callouts	£80

These types of issues could potentially pose quite large problems (and financial benefit when resolved) particularly when considering the number of flats that could be problematic or optimised. As an example, if 10% of a tower block of 50 flats were to have the above issues, this would result in an estimated value of just under £1800.

4.3.2 Demand-shifting opportunities

Time-shifting to improve comfort

It has been reported by Connected Response and in the residents' survey that it is not uncommon for the hot water to run insufficiently hot in the evening, due to a combination of usage (cold mains water flows into the tank upon water usage) and heat loss through the tank. If this occurs frequently early in the day, this may be due to an undersized tank, such as the example in Figure 19. However, in other cases, it is the large time interval between heating and usage which is allowing heat to escape through the tank and energy to be wasted.

As discussed in 0, the interval between the median heating time and median water usage time was measured for all devices, and the average interval was 9.25 hours (min: 2.5h, max: 14h). In section 3.2.8 it was determined that a typical tank will cool halfway to its minimum temperature in 11.9 hours with no water usage. This suggests that heat loss from the tank is indeed a significant factor in the cool water that some tenants experience in the evenings.

As heating the tank only takes 0.5-3.1 hours, a relatively simple modification to improve comfort and reduce heat loss would therefore be to shift the heating period to the end of the E7 overnight period, for example from 04:00-07:00. This is the modification that was performed by Connected Response to positive effect in Figure 13.

A further improvement could be achieved through heating outside the rigid E7 off-peak hours. With increasing amounts of solar generation, wholesale prices during the early afternoon are now often as cheap as during the night, especially in summer, which is not reflected in the E7 peak price. Newer E10-style tariffs offer an improvement to this, often allowing some hours of peak heating in the afternoon in addition to overnight. A similar (non-commercial) tariff is used in the supplemental data in section 3.3. An additional heating period in the afternoon should reduce the risk of the water running cold without significantly increasing costs.

Time-shifting to a dynamic ToU tariff

As explained in section 2.3.3, a simple heating regime was devised: for each day (midnight to midnight), the total consumption (measured and inferred) was taken and shifted into the cheapest half-hour Agile periods of the day, maintaining the constraint of the maximum heating power, thereby keeping the consumption magnitude constant.

An example day is shown in Figure 43.

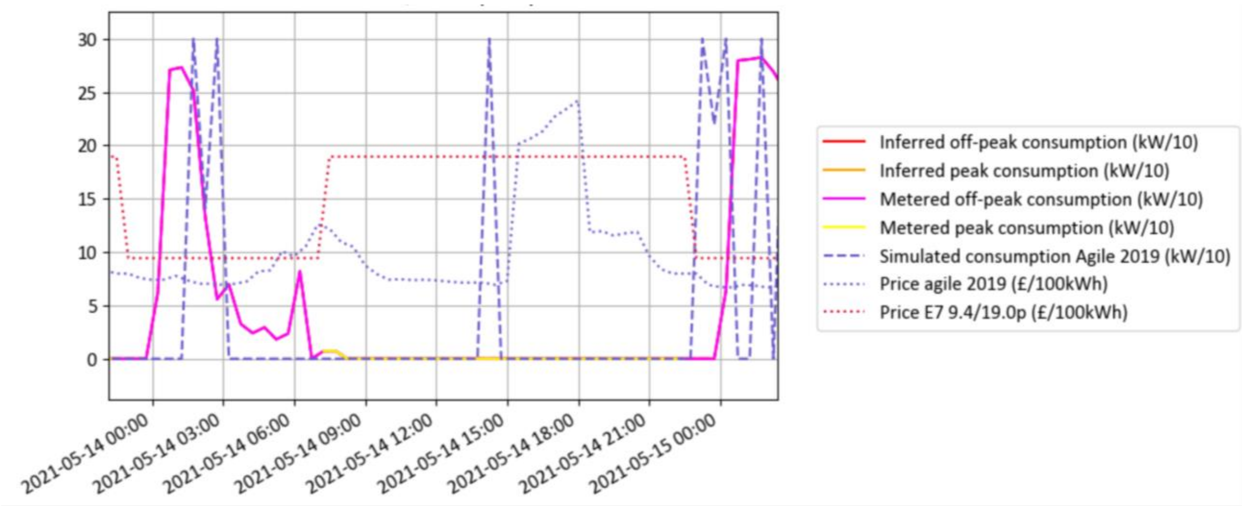

Figure 43: An example summer day for a hot water device showing the actual consumption (pink) compared to the simulated consumption (dashed purple) at the cheapest Agile times. E7 and Agile prices are also shown (dotted).

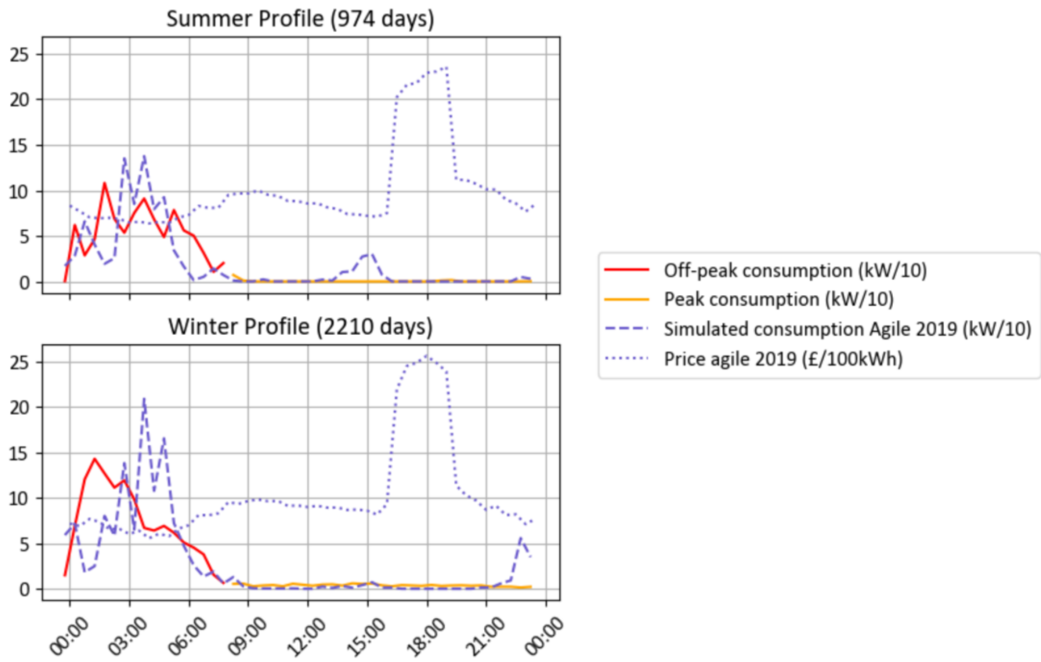

Figure 44: Average consumption times for the PV + battery devices, segmented by season, comparing the status quo to the simulated Agile heating times.

The average consumption profile for the simulated heating regime is shown in Figure 44, comparing to the status quo. It is broadly similar, but heating is shifted to later during the night, and in summer there are periods of mid-afternoon charging. If every day followed the profile of an average day, this would likely lead to greater comfort for the customer, as the heating would be closer to the time of use. However, it should be noted that the cheapest hours of the day are not regular and there are some days when heating is entirely afternoon or overnight. Considering the long interval between heating and water usage in the status quo regime, the simulated regime is unlikely to offer inferior comfort, but further simulations of water temperature under the simulated regime should be carried out to confirm this. Note that the simulated regime follows a very basic rule ('heat at cheapest Agile times') which offers large potential for improvement – continuous water usage analysis with machine learning methods could optimise for some combination of comfort and price, to determine the best heating time.

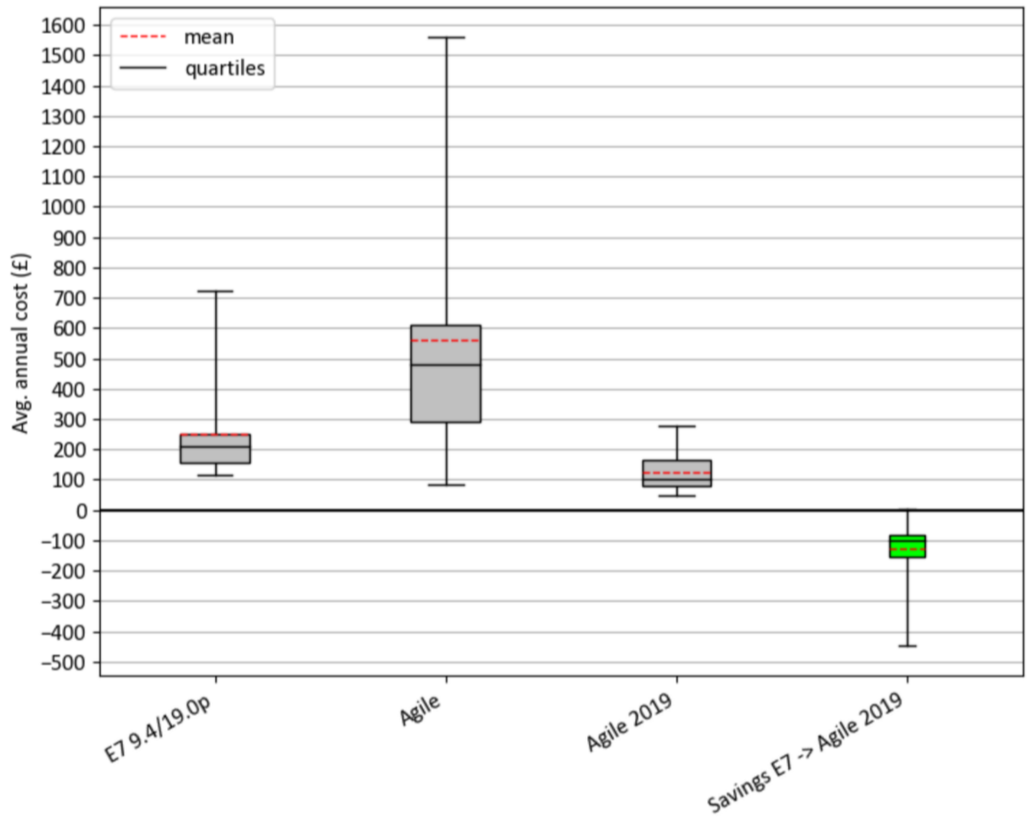

Figure 45: Annual cost for the hot water devices on E7 (status quo) and Agile tariffs, with the heating for Agile shifted to the cheapest Agile time of each day. Savings are presented as a difference so are negative.

The annual cost under the simulated regime is shown in Figure 45. The tariffs are as for the battery case in section 2.3.2; however, the true E7 rates paid by the tenants in the trial are not known. Following the new regime using Agile 2019 prices, we see an average 50% saving (from an annual cost of £252 to £126) compared to E7. This is due to the price at the cheapest time of day being frequently <£0.05/kWh, undercutting even the 'cheap' E7 off-peak price. The largest savings (up to £447) were seen in the few devices that have significant peak-time 'boost' consumption, because this peak consumption was also included in this shift, bringing large savings per kWh, even though in practicality it is likely that tenants may continue using the boost at peak times if this is immediately before their shower or bath. However, the median device does not use the 'boost' and still makes a saving.

The energy crisis of 2021 led to the Agile price hitting its £0.35/kWh cap for much of the time, which leads to the inflated costs seen on this tariff compared to E7. It should also be noted that the cost under this regime (relative to a less dynamic offering) is likely to decrease if the daily volatility of the Agile price increases over time.

In summary, this proposed charging scheme would offer significantly reduced costs (under pre-2021 market conditions) which may decrease with increasing price volatility, likely equal or improved comfort (although additional tests or simulation would be worthwhile to confirm this) and is a more future-proof and flexible regime than any fixed ToU tariff such as E10. However, in practicality, many of the households in the Home Response trial require price security as a priority, which may exclude switching to dynamic tariffs as an option unless offered as part of a managed service with the provider taking on the risk rather than the resident.

4.3.3 Flexibility service provision

As seen in Figure 11, there is an average of at least 1.2kW per device used between 00:30 and 03:00, which gradually tails off to 0.5kW until 7:00. At 01:15, 25% of devices are consuming at least 2.8kW. If the ~600,000 hot water immersion heaters in London had smart switches and agreed to participate in potential turn-down or shifting services, this would imply an available capacity of 720 MW between 00:30-03:00 or a 300 MW capacity between 00:30-07:00. There is minimal opportunity for turn-down services outside of this time window.

Based on initial analysis, aligned to trajectories for fuel switching seen in the CCC's 6CB analysis for residential decarbonisation, this 720 MW potential could rise to >750 MW by 2030 and >1.1 GW by 2050. However, it should be noted that it is also possible that (due to fuel switching) this could drop to ~700 MW by 2030 and ~500 MW by 2050.

Balancing Mechanism

Considering the uncertainty and variation from the average data, and for ease of simulation, the following assumptions were considered for flexibility testing within the E7 off-peak period for potential applicability into the Balancing Mechanism:

- All requests between 00:00 and 06:30 were considered, assuming that were sufficient systems online a bidding strategy could be adopted in shaping a charge profile of the fleet in order to establish a baseline.
- Moving charge from 00:00 to 02:00 has no negative impact on the customer.
- Turn down (Offers) options (power/coil on average):
  - 1kW available from 00:00-03:00
  - 0.5kW available from 03:00-06:00
- Turn up (Bids) options (power/coil on average; assuming tanks can be 'overcharged' for a half hour):
  - 2kW available from 00:00-03:00
  - 2.5kW available from 03:00-06:00

Based on the above coupled with assumptions regarding the Balancing Mechanism (i.e. applicability of events, number of events, etc.), it is likely that the range of possible revenues for a single smartly controlled hot water tank with electrical immersion heater amounts to between £4-£9 per system per year for Bids and £0.5-£1 per system per year for Offers.

Hypothetical demand turn-up service

In the future, there could also be the potential that National Grid ESO would require a demand turn-up service to support the system. Currently, they offer a demand turn-up service with assets of 100kW and up; however, this exercise proposes that this service could be considered if this were dropped to smaller required capacity to allow hot water tank immersion heaters to participate.

This service is likely to be related to wind power, and therefore have overnight service windows where additional demand on the system would be beneficial in some cases. As such, a service window from 23:30-08:30 was proposed, and would be relevant for hot water tanks. Based on the availability and the larger set of assumptions noted in this section, a revenue of ~£6 per system per year could be realistic.

A DSO-level demand turn-up service as also considered. However, it is likely that this type of service would be related more to local PV on the low voltage network and have peak PV associated service windows (e.g. between 11:00 and 15:00). As this period falls outside the current shiftable load for the Home Response hot water case, this was not accounted for in the larger revenue stack.

4.3.1 Cost of acquisition & installation

Similar to the battery use case, to better understand the costs required to run an energy trial like Home Response, the set of different cost types were considered, from engaging a potential participant, through the installation process, to the ongoing monitoring. Table 12 below summarises the different types of costs incurred and their potential value across three different scenarios. The Low scenario portrays an optimistic view where costs are lower than current-day costs – i.e. potential future costs or costs that could be realised with increased efficiency or economies of scale. The High scenario presents the case in some ways similar to the costs incurred during this study; they account for participants requiring more significant remedial works and higher costs for engagement, kit, installation, and monitoring. This is included to reflect the uncertainty in the other direction, in contrast to the Low scenario. Lastly, the Average scenario aims at a middle ground of what could be realistic present-day costs for a well-deployed trial or set of installs.

All costs in the below table are given on a per-install or per-customer basis, split into the relevant capital expenditures (capex) and operational expenditures (opex).

Table 12. Cost breakdown, across three scenarios (Low, High, and Average) for the hot water case across acquisition & recruitment, the physical kit, installation, and monitoring and dispatch

Category	Cost description	Cost type (per unit)	Low-Cost Scenario	High-Cost Scenario	Average-Cost Scenario
Acquisition & recruitment	Client Participation Agreement drafting	Capex, fixed (£)	£ 0.3	£ 5	£ 2
	Landlord sign up	Capex, fixed (£)	£ 3	£ 40	£ 16
	Initial tenant engagement	Capex, fixed (£)	£ 2	£ 4	£ 3
	Tenant sign up	Capex, fixed (£)	£ 50	£ 108	£ 79
	Additional contact for remedial work	Capex, fixed (£)	£ 39	£ 75	£ 57
Physical kit	Kit + auxiliary components	Capex, fixed (£)	£ 315	£ 500	£ 450
Installation	Site visit & survey	Capex, fixed (£)	£ 40	£ 58	£ 50
	Installation	Capex, fixed (£)	£ 150	£ 450	£ 225
	Remedial works	Capex, fixed (£)	£ 120	£ 173	£ 150
Monitoring & dispatch	Cloud compute costs	Opex, yearly (£/year)	£ £9	£ 12	£ 11
	Monitoring costs	Opex, yearly (£/year)	£ 31	£ 33	£ 31
Total costs	**Total Capex**	**Capex, fixed (£)**	**£ 719**	**£ 1,413**	**£ 1,032**
	Total Opex	**Opex, yearly (£/year)**	**£ 40**	**£ 45**	**£ 42**

For this use case in particular, it should be noted that in typical high density installs, the equipment in each flat can form a building wide network and the cost of the gateway in the building is shared amongst each flat.

From the above set of costs, a net present cost (NPC) can be determined. Using the standard UK Greenbook discount rate of 3.5% and a varied potential lifetime of smart controls, the below table (Table 13) can be generated which outlines the range of potential NPCs for an assumed lifetime between 10 and 20 years across the different cost scenarios. As can be seen by reviewing the above and below tables, much of the present cost is based on the acquisition, recruitment, and installation (in contrast to the battery case where the physical kit dominated the costs). As such, these are key areas to ensure costs are driven down to further benefit the economics of smart controls.

Table 13. Net Present Cost (NPC) of the smart controls for the hot water use case for a range of potential lifetimes across the Low, High, and Average cost scenarios

Lifetime (yrs)	Low Scenario NPC	High Scenario NPC	Average Scenario NPC
10	£ 1,051	£ 1,787	£ 1,377
15	£ 1,179	£ 1,931	£ 1,510
20	£ 1,287	£ 2,052	£ 1,622

4.3.2 Optimised revenue stack

For the hot water case, the key revenue streams relevant to installations in London are:

- the smart switch & dynamic ToU optimisation,
- Balancing Mechanism (BM) Offer (discharge),
- Balancing Mechanism (BM) Bid (charge), and
- a hypothetical demand turn-up service.

The first item relates to the second option for value creation as outlined in section 2.1.2, which discusses how the hot water behaviour could be optimised to minimise cost by switching to a dynamic ToU tariff and only charging at the lowest-priced times. The remaining items relate directly to the provision of flexibility services to NG ESO (BM Offer, BM Bid, and a hypothetical demand turn-up service). The hypothetical demand turn-up service is included here as potential service that may be required in the future; however, as will be seen in the below analysis, the potential for revenue from this stream is not significant and so it is not discussed much further.

Based on (i) the potential savings determined via time-shifting to a dynamic ToU tariff, as presented in section 4.3.1, and (ii) the flexibility service provision and assumptions, as noted in section 4.3.3, the below table outlines the current-day potential revenue values for the applicable revenue streams across Low, High, and Average revenue scenarios. DNO/DSO flexibility services are excluded from the list due to lack of technical suitability regarding this use case.

Table 14. Applicable revenue streams and potential revenues for a domestic hot water tank smart control system, with values shown relative to a 3kW immersion coil (based the same capacity in this study) across Low, High, and Average revenue scenarios.

Revenue Stream	Unit	Low Revenue Scenario	High Revenue Scenario	Average Revenue Scenario
Smart switch & dynamic ToU optimisation	£ / year / 3kW electric coil	-2	268	113
BM Offer (discharge)		0.6	1	1
BM Bid (charge)		4	9	6
Hypothetical demand turn-up service		4	8	6

Regarding the "Smart switch & dynamic ToU optimisation", the Low, High, and Average scenarios correspond to the following cases relative to a 'Baseline' case where the resident does not have a smart control system and is on an E7 tariff (at 9.4p/kWh off-peak and 19p/kWh peak):

- Low: resident installs smart control system and switches to Agile (based on 2019 prices) but is unsuited to the switch.
- High: resident installs smart control system and switches to Agile (based on 2019 prices) and is suitable to the switch.
- Average: resident installs smart control system and switches to Agile (based on 2019 prices) and is very suitable to the switch.

Considering the Average case as the most relevant, Figure 46 illustrates what a potential optimised revenue stack could look like for a domestic hot water tank with a 3kW electric immersion coil and smart control system, reaching just over £125/year.

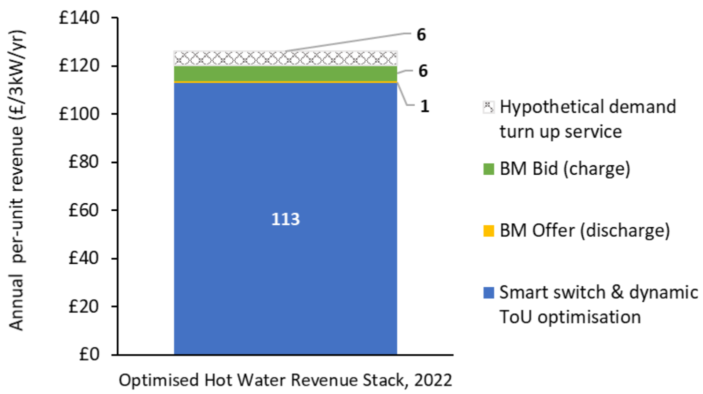

Figure 46. Optimised revenue stack (£ / year / 3kW electric coil) via the installation of a smart switch, tariff switching, and flexibility service provision

From the above revenue stack, a net present value (NPV) of revenue is able to be determined. Again, using the standard UK Greenbook discount rate of 3.5% and a varied potential lifetime of the system, the below table (Table 15) can be generated which outlines the range of potential revenue NPVs for an assumed system lifetime between 10 and 20 years across the different revenue scenarios.

Table 15. Net Present Value (NPV) of revenues for the hot water tank with smart control system for a range of potential lifetimes across the Low, High, and Average revenue scenarios

Lifetime (yrs)	Low Revenue Scenario NPV	High Revenue Scenario NPV	Average Revenue Scenario NPV
10	£ 63	£ 3,517	£ 1,317
15	£ 91	£ 5,617	£ 1,987
20	£ 118	£ 7,794	£ 2,640

Similar to the battery revenue stream assumptions, the above table also accounts for two key assumptions in how the revenues are may change going forward into the future. First, aligned to typical inflation rates, it is assumed that there is a 2% year-on-year increase in revenues made from flexibility services. Second, based on the likely correlation between volatility and smart control system savings against the baseline case (as noted previously in this report), it is assumed that the smart switch & dynamic ToU optimisation revenue stream increases in relation to increasing volatility. This year-on-year modelled increase is scaled differently between the Low (~2.5%), High (~10%), and Average (~5%) scenarios but is derived from a linear trend of the intra-day wholesale price spread over the last five years of available half-hourly data (i.e. difference in p/kWh between the highest cost during the day and the lowest cost during the day, and the resulting trend over time). Based on these assumptions (which could be seen as an optimistic case), the projected potential future undiscounted revenue stack in 2030 and 2040 increase to £177 and £241 respectively.

4.3.3 CBA results: net present value (NPV)

Considering the cost of acquisition and installation (covered in section 4.3.1) coupled with the optimised revenue stack (covered in section 4.3.2), the overall net present value (NPV) of the system over its lifetime can be determined. To cover the portray the range of uncertainty, the following three scenarios are combined with the spread of potential lifetimes (as previously shown): (i) Low Cost, High Revenue Scenario, (ii) High Cost, Low Revenue Scenario, and (iii) Average Cost, Average Revenue Scenario. The final outputs of this cost-benefit analysis (CBA) are shown in Table 16 below. For clarity, positive NPVs are shown in green and negative NPVs are shown in red.

Table 16. Summary results of the cost-benefit (CBA) analysis net present values (NPVs) for the hot water use case for three different scenarios and a range of potential lifetimes

Lifetime (yrs)	Low Cost, High Revenue Scenario NPV	High Cost, Low Revenue Scenario NPV	Average Cost, Average Revenue Scenario NPV
10	£ 2,466	-£ 1,723	-£ 60
15	£ 4,438	-£ 1,839	£ 476
20	£ 6,507	-£ 1,934	£ 1,018

Similar to the battery use case, the NPV of the system is quite sensitive to the incurred costs and achievable revenue. In the average case, the typical payback period for the system >10 years. Considering that in some cases, the savings from switching to a dynamic ToU tariff is negative (i.e. costs more than the baseline E7 case), it can be expected, there is a negative NPV for all high cost, low revenue scenarios, across all potential lifetimes. In contrast, for the cases where the E7 tariff is not suitable and a dynamic ToU tariff would be (i.e. low cost, high revenue case), the NPV is positive for all shown lifetimes. A significant range of NPVs is reflective of the large uncertainty around the financial feasibility for this use case, based on the risk of switching to a dynamic tariff. As previously noted, providing hot water as a managed service (for a cost that is no more than a resident's standard E7 tariff bill) while leveraging the electric coils for flexibility (via demand shifting on a dynamic ToU tariff), could be a solution to de-risking this use case from the resident perspective. Some of the same other risk mitigation measures mentioned for the battery use case also apply: ensuring a streamlined and efficient acquisition and installation process to lower upfront spend and development of more mature flexibility markets and regulation to ensure some type of confidence in the availability of future revenue streams.

5 Barriers to domestic demand side response (DSR)

As alluded to throughout this report, there are several different barriers to domestic DSR. This section aims to organise a subset of key considerations into lists that fall under larger categories below. However, it should be noted that many of the barriers noted could have potential derivations (or solutions) from items flagged in another category.

5.1 Value

One of the barriers discussed the most regarding flexibility is the value – value to the customer, value to the supplier, value to the network, etc. This category covers a number of different aspects that relate to the sufficiency of value, its certainty, and how it could be split across the members of the value chain. The list below highlights some of these barriers:

- The capital cost of technology acquisition can be one of the largest barriers for a domestic customer.
- Certainty of future revenue is important as currently all aspects of a revenue stack are constantly changing (e.g. wholesale price fluctuation, market reform, flexibility service prices); additionally, these types of supplementary revenue stacks (i.e. apart from self-use) are typically required to meet reasonable financial payback periods.
- The value of flexibility being paid (i.e. flexibility revenues being given) are often considerably lower than those seen elsewhere (e.g. the US has examples that can be up to ten times higher); as such, domestic DSR is not being incentivised but expected to complete at market rates.
- Regarding council procurement, this is often driven by cost which sometimes leads to the least-cost technology being taken up, rather than the smart (potentially more flexible / useful) technology; frameworks need to be put in place to support councils in purchasing future proofed systems.
- More generally, barriers to adoption include low incentives for suppliers and low rewards for customers.

5.2 Markets & Regulation

As referenced in the previous subsection on value, the energy markets and their regulation play a critical role in giving confidence to the flexibility markets and the potential feasibility for participants. Considering the flexibility market is still in its nascent stages, there is significant opportunity to formalise this area. The list below highlights some aspects to consider:

- There are currently no centralised energy market structures agreed amongst all relevant parties; in order to realise an optimum revenue stacks for flexibility participants, aggregators need to maintain many integrations (and contracts) with energy system actors, of whom each has different standards and rules.
- There is also a lack of standardisation around communication protocols; this is currently being discussed and has been progressed by trials such as this one.
- Charging reform is undergoing significant changes which poses a threat to the certainty of future potential revenue streams; for example charges within a customer's (i.e. whole cost, DUoS, TNUoS, etc.) are being reworked. Ideally, these charges would match grid requirements to further incentivise customers in regional constraint zones to be flexible.
- Other barriers in regulation such as the lack of green home allowance for domestic batteries or VAT considerations also need to be considered to enable uptake.

5.3 Customer engagement and trust

One of the key barriers to the adoption of any new technology or service is customer engagement and trust – domestic DSR is not an exception to this. The below list details some of related barriers in this category:

- Sometimes residents are likely to be less inclined to install new technologies due to hesitation based on limited space in their household, the disruption of the installation, the unfamiliarity of the technology, and the uncertainty of its service or financial payback.
- Though seemingly a small point, it has been noted that many smart tariffs are not on price comparison websites which causes low awareness of smart products/services.
- For more technical innovations, such as many concepts included within DSR, there is a risk of 'information overload' or 'choice overload'.
- It has also been noted that some may feel that these novel technologies and installers are potentially unfamiliar and untested; it may be that some form of publicly available database of assessments of real-world performance of previous installations would be helpful as an aid for future participants' reference.
- The logistics of tariff switching, and half hourly settlement enablement can be quite slow and difficult to do considering the detailed and bureaucratic requirements throughout the process for the end customer.
- Lastly, providing a quality and functioning equipment installation is a key enabler to ensure customers are happy and that the following word-of-mouth feedback to others is positive.

5.4 Technical hurdles

Finally, technical obstacles and required development are of course key enablers to the successful uptake of domestic DSR. As this study has mostly focused on the non-physical / technological perspectives, only a few examples have been provided below for reference. However, it should be noted that this category is often interlinked with regulation.

- Some flexibility services require almost instantaneous response times (e.g. NG ESO's Fast Frequency Response); the installed smart technology (e.g. smart batteries) would need to be built to this specification to be able to participate in these types of services.
- Flexibility requirements are geography-specific in their need, which makes the potential for DSR uptake, and resulting potential value, heavily reliant on location; for example, two customers in living in two different boroughs have the potential to earn significantly different amounts from grid services.
- Voltage level and minimum size requirements also post a barrier considering that requirements for flexibility services tend to be for the high voltage network with minimum capacity requirements in the level of MW rather than kW; this presents a more difficulty for domestic low voltage DSR compared to HV cases such as in the services or industrial sectors.

6 Exploitation and scale-up

This section is sets out the future exploitation plan for Home Response (HR) learning and the potential follow-on projects or scale-up opportunities that have been identified at social housing locations in London. For more details, please refer to the D30 deliverable available on the GLA's website published alongside this report.

6.1 Opportunities

The key opportunities are to:

- Improve flexibility of electricity consumption and customer outcomes for electric hot water and heating through the wider adoption of smart controls alongside novel electricity tariffs (such as E10 tariffs) that offer the opportunity to charge hot water and heating in multiple windows across the day.
- Install correctly sized and optimised smart batteries in homes with PV panels. Well performing PV with the right smart battery can offer peak demand shifting and flexibility service provision while also lowering consumer bills.

The scale of the opportunity identified in July 2021 was reviewed in detail with project partners and key stakeholders. The specific opportunities identified in July 2021 were reviewed for ongoing relevance and progress with project partners involved in their development. There remains confidence that 1MW of flexibility potential can be developed in the near future from the immediate prospects listed below.

- **L&Q** are discussing the opportunity to further install Home Response controls including heating in one of their housing blocks identified in July where fabric refurbishment works are planned. This interest is based on the HR learning but funding for the energy upgrades has still to be confirmed. L&Q have agreed to retain the controls for a further 12 months to explore the benefits. This is considered a positive development from the position in July 2021.
- **Lewisham** are still progressing the upgrade works on the energy infrastructure at electrical heated blocks and continue to express intention to install smart controls.
- **Westminster** do not have a systematic programme but are continuing to upgrade controls in the blocks identified as the opportunity arises.

Wider opportunities to install HR-like solutions were explored in two workshops:

- Potential opportunities through the five key GLA programmes, particularly Warmer Homes, Retrofit Accelerator-Homes and Local Energy Accelerator (LEA) and Solar Together, were identified and will be further explored:
    - Solar Together includes a battery offer but this may need to be developed to ensure that there is an offer that can support flexibility services.
    - Warmer Homes funding opportunities will be explored to identify where smarter controls could be included, possibly from GLA funding which is less restricted to fabric upgrades.
    - LEA has potential interest in solar installations in social housing, which if progressed could include batteries and smarter controls.
- Wider Housing Association and Local Authority programmes were explored in a second workshop.
    - The opportunities for smart controls will be progressed through ongoing engagement with the London Councils practitioners' group.
    - Waltham Forest have 1000 properties with solar panels and have expressed interest in the findings.

6.2 Key Exploitation Challenges

6.2.1 Funding

Most current funding programme are specifically designed to support fabric upgrades to improve energy efficiency and so do not support improvements to electric hot water and heating systems at the same time. Funding support favours larger programmes, which may make smaller programmes to install smart control more difficult to establish.

The familiar problem of split incentives – improved energy controls can produce better outcomes for tenants but no direct returns to landlords making the business case more challenging.

6.2.2 Energy tariffs and markets

Atypical energy market conditions that persisted at the time of writing had resulted in electricity suppliers no longer offering tariffs to support customer switching to suitable tariffs. This appears set to persist for some time.

Home Response has clarified the need for tariffs that offer more opportunities to optimise demand across the day (for example three off-peak period E10 tariffs) and for half-hourly settled tariffs to support battery optimisation and use in national grid support markets.

6.3 Recommendations

The below three points represent the key recommendations for near-term exploitation and scale-up:

- Pursue the three main opportunities with L&Q, Lewisham and Westminster.
- Consider the installation of smart controls for electric heating for inclusion in wider retrofit programmes including Warmer Homes and Solar Together.
- Raise the awareness of the importance of suitable tariffs so that benefits of smart controls can be realised.

7 Conclusions

The Home Response project set out to install domestic DSR technologies in several London homes to investigate the value they produce for customers, for the DNO/DSO, and for the wider world through the reduction of carbon emissions. Two use cases were investigated, and both were found to offer flexibility opportunities to the grid and revenue opportunities for the customer.

This report commenced by outlining the objectives and key performance indicators (KPIs). The trial design was explained for both the battery and the hot water use cases, including a list of potential value creation strategies. A comprehensive analysis of the data was then presented, showing the key findings in relation to the objectives, the performance of the equipment, and several interesting, unexpected findings. In section 4 Business modelling, the tariff simulations were presented, including an assessment of the financial savings, the grid flexibility provided, the CO_2 impact associated with the DSR technologies on various tariffs. For the hot water use case, certain non-DSR benefits were also outlined. The CBA was then presented, demonstrating the financial viability of both use cases if certain conditions are met. Finally, sections 5 and 6 offered insights to businesses, community organisations and innovators of the opportunities and challenges of exploitation and scale-up of this technology.

Progress towards all objectives has been achieved. A total of 23 battery systems and 35 hot water smart controls were installed, despite the challenge of carrying out site visits during the pandemic. This is a credit to the innovative engagement methods used, although there were further lessons to be learnt in this area.

The holistic view for both technology use cases is positive. The CBA showed that the battery may be able to repay its considerable capital cost in a period of approximately 10 years if the technology, markets, and regulation are developed to allow the batteries to participate in DNO/DSO and NG ESO flexibility services that have committed financial offerings. Furthermore, a household with PV and a battery on a dynamic ToU export tariff can export as much during peak times as 2.5 'regular' households. For the hot water use case, the trial has revealed the potential for optimising for a dynamic ToU tariff, which could reduce costs by 50% while offering a greater degree of flexibility to the grid than the relatively rigid E7 window. Installing smart controls and monitoring equipment has the additional benefit that it allows for identification of existing faults or incorrect configurations, which were found to be surprisingly prevalent.

The principal Key Performance Indicators (KPIs) were the reduction in energy cost for the customer through shifting or reduction of consumption, the increase in energy system flexibility as measured by the installed capacity (in power and energy terms) and utilisation rate, and the reduction in CO_2 emissions associated with the shift in usage to times of lower grid carbon intensity. The use cases have been assessed against the KPIs throughout the report and a summary is available in section 7.3.

Further work is recommended before these technologies can be fully exploited. These are set out in full in section 7.5, and include notably for the hot water case an investigation into more optimal strategies for responding to a dynamic price signal, and the impact this would have on hot water outcomes. It is suggested that an additional use case, space heating, should be investigated alongside hot water, as this is closely related, and controls could be installed for both at the same time. The changing energy market furthers the necessity to keep the CBA up to date. Lastly, further consumer behavioural analysis is recommended to ensure adoption of the technology on the scale that is required for decarbonisation within the next 30 years.7.3

7.1 Battery

The battery use case has shown it can reliably produce a revenue for customers on a range of tariffs and for a range of household and PV installation sizes (except for low PV-producing households on a flat tariff). The viability assessment for participation in DNO/DSO and NG ESO grid services suggests that this development in domestic DSR may soon offer a significant revenue stream for domestic customers with battery assets. In practical terms, the installation and monitoring of the battery systems was carried out with relative ease during this project, requiring minimal remediation work.

The primary obstacle to the business case for the battery is as expected: the capital cost of the equipment. Despite this, it is shown that the battery can be economical over a period of approximately 10 years under an 'average' optimism scenario, assuming participation in grid flexibility services, determined based on a discounted cash flow analysis. Further, it is important to note that the balance of cost vs. benefit is currently shifting in favour of the battery: the price of batteries is diminishing while the price of energy (and its volatility) is rising.

Key Takeaway

- ✓ Adding a smart battery to a household with existing solar PV could be a financially viable method of adding flexibility to the grid if the technology, markets, and regulation are developed to allow the batteries to participate in DNO/DSO and NG ESO flexibility services that have committed financial offerings.

Findings

1. A battery optimised for a flat tariff that does not participate in grid services does generate revenue, but it is unlikely to repay the initial capital cost.
    - In this case, savings are strongly dependent on PV production; households with low PV production which cannot switch tariff should not buy a battery.
    - The average household will save £117/year compared to ~£5000 cost (total net present value of all capex and opex considered over a 10-year lifetime).
2. A dynamic Time-of-Use export tariff will provide the greatest revenue for a PV + battery system.
    - Savings on ToU tariffs are dependent on the daily volatility of the import price.
    - A household switching from a flat tariff to a dynamic ToU export tariff could save £310/year or 87% of their baseline cost (i.e. with solar PV, but without the battery).
    - A household with PV and a battery on a dynamic ToU export tariff exports sufficient energy during peak times to offset the consumption of 2.5 'regular' households.
3. Estimations indicate that participation in grid flexibility services could earn significant revenue.
    - Further development in this nascent market would be beneficial to allow some confidence in future revenue potential and enable this further.

7.2 Hot water

The hot water use case has provided a useful insight into the usage patterns of a widespread domestic storage asset. While the focus for new hot water installations turns to heat pumps, the question of how to retrofit improvements to existing installations remains. As electric immersion hot water tanks are a common feature in social and low-income housing, cost is critical and has remained a focus in the analysis.

It was expected that the project would reveal ways to avoid peak-time 'boost' usage by customers seeking to avoid cool water in the evenings. Instead, it was found that the peak-time consumption was smaller than expected, and that the issue of incorrectly configured or malfunctioning tanks is contributing to more peak-time consumption and associated costs for unlucky residents.

Smart controls and monitoring systems can offer landlords or housing associations the opportunity to identify such issues and correct them. Furthermore, the proof of concept has been shown for optimising the system for a dynamic ToU tariff, which would shift the ~6kWh per day per device into the cheapest (and likely least carbon intensive) time of the day, saving residents 50% of their baseline costs in the process. This is a finding which merits further research.

Key Takeaways

- ✓ There is potential for hot water customers to save up to 50% on their costs and provide additional flexibility to the grid by installing smart controls which are optimised for a dynamic ToU tariff; further research is required to ensure negative impacts on comfort and potential rises in baseline costs can be mitigated (e.g. through a managed service).
- ✓ Several 'quick fixes' are available to reduce costs and improve comfort without installing any new equipment.

Findings

1. A simulation of a simple heating regime that responded to prices of a dynamic ToU tariff without changing the total consumption showed that on average, savings of 50% could be achieved.
    - Further tests are required to determine the impact on comfort outcomes with this regime, although a negative impact is considered unlikely.
    - This regime provides greater flexibility to the grid than the relatively rigid E7 tariff.
2. Significant numbers of hot water installations were found to be incorrectly configured or malfunctioning.
    - Smart monitoring equipment could be used to identify and correct these faults, saving owners of these devices approximately 50%.
3. Consumption could be easily shifted within the E7 period to improve comfort outcomes and reduce heat loss.
    - As the tanks take only 0.5-3h to heat up, this could be moved to the end of the E7 period, e.g. 04:00-07:00, rather than after midnight.
    - E10 tariffs are also likely to improve comfort outcomes and prevent 'boost' usage during peak times.
4. Peak 'boost' consumption by the customers was observed but not in the quantities expected.
    - For correctly configured devices, only 9% of the total consumption was observed to occur during peak times.

7.3 Review of KPIs

This review revisits the KPIs presented in section 1.3 and assesses the project outcomes against this.

Table 17: Project performance against KPIs

KPI	Measurable indicators	Outcome
KPI 4: Business relationships	Number of new business relationships and collaborations established	**12 formal relationships were established:** Local Authorities (Royal Borough of Kensington and Chelsea, Camden, Waltham Forest, Westminster, Lewisham), Housing associations (L&Q), Connected Response, Moixa's contracts (Perfect Sense & Carbon3), Energy Unlocked, Apteno Consulting, and the Home Response pop-up/leaflet designer (G. Birchall). **23 additional informal relationships were formed:** Equiwatt, Flexitricity, The Carbon Trust, Sharing Cities DDSR projects, Association of Decentralised Energy, EDF, Smart DCC, SLS, SEIE (Smart Energy Information Exchange), Energy for London, Future Climate, Clarion Housing Group, The Hyde Group, Metropolitan Thames Valley, Network Homes, Notting Hill Genesis, Peabody, Lambeth, Islington, Barking and Dagenham, Newham, Southwark, and London Councils.
KPI 5: Technology advancement	TRL level (and progression) for each technology being used	Different technologies were used as part of the Home Response project, each with their own development pathway and resulting TRL level progress (project start - project end): - Connected Response Zigbee Mesh (5 - 8). - Integration of SMETS2 meters with DCC (3 - 4). - UKPN dispatch for mixed portfolio of assets (6 - 9). - GridShare control of Hot Water Systems (3 - 6). *N.B. GridShare control of batteries is already at least TRL 9*
KPI 6i: Additionality of funding	Potential revenue available for domestic DSR provision	Though it was infeasible to switch participant tariffs and enable real-time participation into flexibility markets to provide domestic DSR, this was simulated in a robust manner. The potential optimised revenue stack for an 'average' optimism scenario for a domestic smart battery system reaches just over £500/year for the 2.4kW system. The potential optimised revenue stack for an 'average' optimism scenario for a domestic hot water tank with a 3kW electric immersion coil and smart control system reaches just over £125/year. The full detail of potential revenues is provided in further detail in section 4.2.5 for the battery use case and 4.3.2 for the hot water use case.
KPI 6ii: Follow-on funding	Number of follow-on projects and amount of funding received	Several boroughs (Westminster, RBKC, Lewisham) have contributed internal resource / investment to add to the project's analysis and research outcomes. Their objectives algin with the Home Response project objectives: to collect data on the usage patterns, consumer incentives and outcomes of DSR - informing business case and scale up learning, and ultimately improving comfort and reducing bills for customers.

KPI 7i: Reduced energy costs	Bill savings and potential future savings to customers	**Battery:** Excluding participation in grid flexibility services, the battery plus tariff switching was found to save the average customer £310/year in an 'average' optimism scenario. Including grid flexibility services, the customer could save £500 in an 'average' optimism scenario. A detailed breakdown of costs on tariffs is available in Figure 25, and an optimised revenue stack including flexibility services in Figure 42. **Hot water:** A simulation showed that an average customer could save 50%, without reducing their total consumption, by switching to a dynamic ToU tariff and following a simple optimised heating regime (4.3.2). The potential participation in flexibility services was not found to offer a significant additional revenue opportunity (4.3.3). The 'quick fix' of rectifying incorrectly configured or malfunctioning tanks (3.2.7) could save these customers up to the difference between their peak and off-peak rate (i.e. 50% for the typical E7 tariff studied).
KPI 7ii: Reduced total energy demand	Potential future savings to customers and reduction/removal of supplementary heating	**Battery**: The addition of a battery necessarily increases the total energy demand of the household as it is not 100% efficient and consumes a standby power. It does not aim to reduce total energy demand, rather shift the demand to a time of lower cost and carbon intensity (Figure 37). **Hot water:** Relatively straightforward opportunities to reduce hot water demand were identified. The average interval between median heating and median hot water usage each day was 9.25h (3.2.4), and the cooling analysis (3.2.8) suggests that significant heat will be lost in this interval. Shifting the heating to later in the E7 window or enrolment on E7 tariffs would bring the heating closer to the time of use and therefore reduce heat loss. Retrofitting additional tank insulation is another obvious improvement that could be made simultaneously to a timer modification. Based on the hot water optimisation trial conducted as part of this larger study, 0.7kWh of daily energy demand could be reduced from off-peak times by shifting a user's charging time to later in the night an optimising for consumption requirements
KPI 7iii: Increased energy system flexibility	Installed capacity and frequency/duration of use of flexible assets	**Battery:** The batteries have a nominal capacity of 4.8kWh and a nominal power of 2.4kW. A total of 23 batteries were installed bringing the fleet capacity to 110.4kWh, with a power capacity of 55.2kW. The tariff simulation revealed that this capacity is utilised to a greater extent on ToU tariffs – some devices undergo more than one full charge-discharge cycle in a day on a dynamic ToU export tariff (Figure 35).

		From the perspective of the grid, the simulation showed that the addition of a battery optimised for a flat tariff does not significantly reduce the peak time (UKPN EPN 'red' Time Band) grid import (Figure 37). However, when the battery is optimised for a dynamic ToU export tariff under normal market conditions, the household exports an average of 2.1kWh/day during this peak period, effectively offsetting the peak-time impact of 2.5 'regular' households (without batteries or solar panels). Furthermore, there is significant potential for batteries to participate in grid flexibility services (4.2.3), particularly the DNO/DSO Secure/Sustain service, which allows some time for the batteries to prepare for the dispatch event. In simulations with a 24h gating, the fleet is likely to be able to deliver 100% of the requested power for requests up to 95%+ of the nominal power of the fleet. **Hot water:** The potential power for turn-up services is simply the element power: 3kW per device. For turn-down services, 1.2kW/device would be available between 00:30-03:00 under current consumption patterns (3.2.3). For the 35 installations, this translates to 105kW power capacity for the installed fleet with 42kW available to turn down on average between 00:30-03:00. It was found that the customers were using the 'boost' functionality to heat during peak times less frequently than expected, as this only made up an average of 0.59kWh of the 6.67kWh total average daily consumption for heating. There may still be scope to reduce this by shifting within the E7 window or switching to an E10 tariff which would provide better temperature outcomes without the boost. Greater flexibility would be available to the grid if smart controls were configured to respond to the price of a dynamic ToU tariff (4.3.2), which would flex 6.67kWh per device per day into the cheapest times of the day.
KPI 8: Steps towards commercialisation	Dissemination statistics and number of products (and potentially services) sold in UK and overseas	Many of the technologies that were used throughout this project underwent technological advancement (i.e. TRL advancement). In the future, the results of the trial demonstration will provide a proof-of-concept for residential DSR and serve as an example for further development. For example, some external stakeholders (such as aggregators) showed interest in developing their commercial offering into the domestic sector after the trial phase of this project.
KPI 9: CO_{2e} emissions reductions	Calculation of potential to accommodate more intermittent renewable generation due to DSR and thereby	**Battery:** A CO_2 impact assessment was performed using grid average intensity data from NG ESO (Figure 34). This found that for all tariffs the effect of energy losses in the battery was greater than the benefit of shifting the usage to off-peak times, so the addition of the battery caused a small increase in grid CO_2 emissions, although well below the emissions of a household without PV. This finding has several caveats: grid average intensity rather than marginal intensity was used; the

	avoid of high carbon generation	intensity profile may become less flat over time; the battery was optimised for cost rather than CO_2; and fundamentally it is unlikely the grid could decarbonise its generation without energy storage solutions such as this. **Hot water:** A CO_2 impact assessment was not performed for the hot water case as 91% of the consumption for correctly configured devices was found to be within the E7 off-peak period (3.2.3), which is a typically a period of low grid carbon intensity. The largest potential CO_2 emissions reduction would likely come from the identification and rectification of incorrectly configured devices. However, it should be noted that in future, greater flexibility (and potential to reduce CO_2) would be available to the grid if smart controls were configured to respond to the price of a dynamic ToU tariff (4.3.2), which would flex 6.67kWh per device per day into the cheapest times of the day (which would ideally then align to the times of lowest CO_2 intensity).

7.4 Lessons Learned

The Home Response project has provided many valuable learnings to all partners involved in the trial, ranging from data quality and revenue potential for demand shifting and flexibility to tenant engagement methods and understanding. These key lessons are detailed in this section.

7.4.1 Project Management

In a long-term trial like Home Response, delays can be caused by a variety of reasons, but clear communication and regular meetings can ensure the project remains focused on the goal it set out to achieve. Lessons learned regarding the project management are listed here.

Clear Communication
Modern tools for communication can be leveraged
Modern communication tools (such as Teams) could potentially make coordination across project partners easier. Weekly virtual governance meetings and emails have proven to be effective; however, sometimes some details or minute information seems to get lost in replies/responses.
Upkeeping lists and logs is essential (e.g. no-install cases)
There were a few cases of "no-install" where an installation of HR equipment did not occur or where an early decommissioning had taken place. Reviewing these repeatedly as part of the main list of installs led to reduced project management effectiveness, as they could have been moved to a separate list.
Rewards/project incentives need to be clearly stated
Rewards for participating could be better communicated/agreed upon with project partners and participants at project commencement. On Home Response, some participants were expecting Love2Shop vouchers, while some expected cash payments into their bank accounts.

Project Management
Novel participant engagement could be required
Due to pandemic impacts, some aspects of the project were unachievable, such as the participant engagement activities. Novel ways of engagement, including digital methods, could benefit these types of situations.
The dissemination strategy should be agreed upfront
Participant success stories could be shared as part of the project's general learnings via the website; actual dissemination strategy best agreed at project start.
Coordination between installation team and participant-recruitment team is vital
It was realised during the latter stages of the project that a potential participant was contacted in 2020 regarding a home survey to determine the suitability of his apartment for Home Response equipment, however there was no follow-up with the resident on whether their property was shortlisted for installation or not.
Sharing data/information sharing between housing association/project partners is imperative
A tracker for coordinating landlord-led remedial visits was launched too late into the project, sharing this early on will allow for sufficient time for the housing association (e.g. L&Q maintenance team) to carry out works.

7.4.2 Installation

Since the start of the project a lot of experience has been gained regarding the installation of both hot water switches/sensors and smart battery systems, particularly related to data communications and installation quality. A variety of issues was resolved throughout the project, and the lessons learned in the process are outlined below.

Hot Water Switch Installation
Physical space for installation can be an issue
Space within the hot water tank cupboard is an important consideration in terms of easy access for remedial works, especially as tank cupboards double as storage for residents.
A higher density of installations reduces costs and prevents communication issues
Gateway installation location affects signal strength: a high-gain antenna could be required, or the gateway could be installed at a more favourable location. Ensuring a high density of installations within a multi-dwelling building would allow only a single shared gateway per building to be installed, reducing both cost and communication issues.
Light remedial works can be carried out by residents
Light remedial works such as temperature logger battery replacement and adjustments to the sensors could be carried out directly by the resident if they are comfortable handling a screwdriver and guided over a video call.
Temperature sensor placement is key to accuracy of data
Some of the temperature sensors were found to be installed on inlet and outlet pipes rather than the tank itself, or installed without lagging, which all greatly diminishes the accuracy of the data feeding back. Clear instructions to the installer should be issued to avoid this.
Landlord-led repairs are more difficult to coordinate
Landlord-led repairs (e.g. off-peak immersion faults, leaky tanks) generally took longer to arrange due to the availability of their internal maintenance teams and the large building stock they are responsible for.
Trained housing association technical teams would be useful
In-house technical teams (of housing associations) would reduce the amount of coordination required to arrange installations and remedial works, as they would be trained in the O&M of the project equipment.
Remedial works could be better coordinated
To further increase data quality from hot water equipment and temperature sensors, remedial visits could be better managed/arranged to reduce downtime of equipment, therefore reducing gaps in collecting/transmitting readings.
Installation of a new hot water tank would have led to better data and outcomes, although is expensive
Approximately 30% of hot water systems had a pre-existing fault, typically a faulty immersion element but also thermostat and water leakage. This required landlord remediation. Although more disruptive and higher cost, installation of a new tank as part of the project would have allowed these issues to be addressed early on and created a more consistent data set. However, this was not possible within the project budget due to the funding criteria on capital costs.

Battery Installation
Installation space can be an issue
Physical space for installation within the property is an important consideration in terms of easy access for remedial works/replacement/maintenance.
Onboarding of participants could be improved
The onboarding process could be improved to enable participants to make better use of the online dashboard and mobile application.

7.4.3 Tenant Engagement

The project encountered significant challenges with tenant engagement, undoubtedly exacerbated by the pandemic. Lack of engagement hindered the installation and remediation of the hot water installations, leading to a much-reduced dataset for analysis compared to the project outline. Some issues and recommendations are detailed here.

Understanding of Tenants
Participants may lack crucial understanding of their own electricity tariff
The project revealed that a considerable number of residents do not realise that using the boost function on their water heating system during peak times may cost them up to twice as much as they pay for off-peak tariffs on E7 and E10. This reveals that the education of residents on electricity pricing is necessary and important.
Installations require PPE in the context of the pandemic
Some participants required engineers to wear PPE during remedial works visits due to Covid-19 pandemic, especially where households had vulnerable residents, so engineers should be prepared for this.

Customer Recruitment
Participants' preferred means of contact varies
Some participants respond better to some methods of engagement over others (e.g. response times via email vs. text or phone calls varied by participant).
Action from external parties is needed to resolve out-of-scope problems
Several issues were identified during the project that were outside of the control of the project partners and the landlord (e.g. participants being on inappropriate tariffs, inappropriate meters, or faults with their time switches). While Repowering London supported participants to address these issues, these are generally responsibilities of licensed energy suppliers. Participation of an energy supplier as project partner could help improve coordination, however this could potentially restrict recruitment if participants were required to be customers of that supplier.

Tenant Engagement
Financial incentives improve project engagement
Residents were generally keener to support the project and have engineers visit when they were reminded of the £50 payment to be issued at the end of the project, proving the effectiveness of financial incentives.
Short-notice remedial visits are possible
Residents were generally agreeable to the remedial visits by engineers, even in cases where the visit was to occur the following day.
Resident survey could be better designed
The participant surveys could be condensed to capture only relevant information where needed, so it is more likely to be completed by participants. Battery participants were asked questions about the temperature of their hot water, and a few participants tagged the survey as "requesting too much sensitive information".
The choice of project name was poor
The project name "Home Response" seemed to ring a bell only if used in the same sentence as "L&Q" or "Moixa solar battery" when contacting participants. The project name alone was sometimes insufficient, and residents struggled to remember the name. Branding could clearly be improved.

7.4.4 Data Analysis

Working with large datasets, particularly in trials, will almost always cause some complications. The importance of having reliable and consistent data streams in place has been highlighted during this trial, as well as the fact that deadlines in a trial should be responsive to trial issues. An overview of the lessons learned related to the data analysis and tariff / flexibility modelling is presented here.

Data quality and availability
Start the data analysis early in case supplemental data is needed
Once the data analysis commenced in earnest, it became apparent that information about the physical properties of the hot water tanks would be useful. If the data analysis could have started earlier, this would have been identified and the information could have been collected during site visits.
Ensure datasets are communicated in a consistent format
Thanks to the lessons learned on a previous project, this advice was followed, and the analysis code could be run on updated datasets with minimal reconfiguration.
Ensure conventions, units, and definitions are clearly communicated
It was discovered relatively late in the data analysis that data for the two use cases used different conventions for metering/time-grouping: the hot water data used a trailing convention, and the battery data used a leading convention. This was also an issue that had to be tackled with differing time zones (e.g. British Summer Time).

Automated Data Analysis
Data cleaning is vital
Depending on the nature of the anomalies, both automated and manual data cleaning may be necessary to ensure the integrity of the data. In this project, manual verification was necessary and was facilitated by plotting the data. A significant amount of time should be allotted for this stage of a project.
Take advantage of repetition
It was identified early-on that the analysis of both uses cases would share similar functions. The decision was taken to unify the code for the analysis of both (using Python inheritance), which allowed the same function to create an average daily profile for the hot water as for the battery use case.
Allow results to be easily recreated
Particularly during a trial, it is important to be able to have insight in the data at multiple times throughout the project. All code which produced the range of total outputs used in the report was kept.

7.5 Further work

There is potential for DSR to have a considerable impact on facilitating the integration of renewables into the national grid whilst minimising the need for additional investment in grid infrastructure. To fully understand and exploit this potential, further investigation should be carried out.

There are significant opportunities for further analysis of the existing data and exploration of the models developed. As a brief set of examples, some areas for further could include:

- Monitoring data over a longer timescale (>1 year) to fully assess the impacts of seasonality and changes in the attributes of the technology over time.
- Making use of trial data in scoping the development of future potential ToU tariffs that are more flexible than the E7 tariff and delivery of potential future DSR services.
- Researching more advanced heating regimes for hot water systems with smart controls which respond to a dynamic ToU tariff price signal. An optimisation based on cost and comfort could be performed using predicted hot water usage times.
- Researching the impact on comfort and hot water outcomes for the case of a hot water system which responds to a dynamic ToU tariff price signal.
- Understanding the impacts of the analysis in conjunction with the potential differences in application between local authority / housing association tenants, heat-with-rent schemes, and private tenants.
- Determining the effect on secondary heating by shifting to a smarter heating method and understanding if ToU tariffs provide incentive to remove secondary heating, as compared to E7.
- Furthering understanding via qualitative and quantitative assessments to answer the following questions:
    - Why do/would consumers engage?
    - Why do/would landlords engage?
    - What is the effect of secondary heating use by incorporation of flexibility?
    - What is the business case for the landlord?
    - How does value get split across the value chain?

8 References

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Appendix A: Detailed modelling methodology

This appendix describes the modelling methodology in greater detail than the main report.

Most of the analysis was performed using the *pandas* package in Python. Some analysis (tariff testing simulation for the batteries and flexibility testing for both use cases) was done using Moixa's internal simulation and optimisation software. The business case analysis was performed using Microsoft Excel.

Battery

For this section, variable names and sign convention are as per section 2.1.1 of Trial design.

Data cleaning

Detailed fully in the main report in section 3.1.2.

Estimation of battery properties

It was noticed that the batteries consumed a certain power when not in use. This standby consumption was measured by taking all periods where SoC was constant and taking the median value of Storage.

'Adjusted Storage' is then calculated by subtracting the battery standby consumption from Storage. This is the power that reaches the battery cell.

The battery efficiency is then calculated by dividing the total energy out of the battery by the total energy in. For 'total efficiency' the battery standby consumption is included; for 'charge/discharge efficiency' it is excluded.

In order to estimate the capacity of the batteries, the 'instantaneous battery capacity' is calculated for each half hour period by dividing the Adjusted Storage by the change in SoC (and unit conversion). Only periods where the change in SoC is greater than 1%/half-hour are considered. The estimated battery capacity in kWh is the median of the instantaneous battery capacities.

Hot water

As discussed in 2.1.2, there is a large variation in the physical properties of the hot water tanks which hindered the analysis. Furthermore, it was discovered too late in the project timeline that more information about the physical installations was needed.

Therefore, the temperature and consumption data from each tank was examined manually to infer some key physical properties: the locations of the primary and secondary (if present) coils and the location of the intake pipes. This was done by examining which temperature sensors rapidly increase or decrease upon a heating or water flow event. The results were then imported into the data analysis code. As it is impossible to infer the location of the outflow pipe in this way, it was assumed that this was always at the top of the tank. It was also assumed that the temperature sensors were located at the bottom and top of the tank except where they appear to be placed on pipes, which often rendered the data unusable.

Data cleaning

Detailed fully in the main report in section 3.2.2.

Estimation of tank properties

In the following calculations, the midpoint temperature of $Temp_{top}$ and $Temp_{Bottom}$ was assumed to represent the average temperature of the boiler ('$Temp_{Avg}$').

The power rating (kW) of the primary (off-peak) heating element was taken as the 98th quartile of the metered consumption (converted from kWh/half-hour into kW).

The tank capacity (L) was estimated from the primary consumption by taking all instances where consumption power was greater than 75% of the maximum, and then dividing the consumption by the change in average temperature. As we expect many values to be erroneously high due to simultaneous water flow, we take the 0.1 quantile of the capacity estimations for each device. This quartile has been found to be roughly accurate for the few devices where Connected Response reported an estimated capacity from their site visits.

Estimation of consumption

The consumption was estimated from meter readings (metered consumption) and from the temperature increases (estimated consumption). It was then split into peak and off-peak.

Firstly, an estimation of the consumption was made based on the increase in temperature. Whenever $Temp_{Avg}$ increased above a threshold (1.0 degrees/half-hour), then the consumption was estimated using the change in $Temp_{Avg}$ and the estimated tank capacity.

The total consumption was then calculated as follows. If no secondary element is present for a particular device, then the metered consumption always takes precedence over the estimated consumption unless the meter is offline (meter readings are NaN). If a secondary element is present, then the metered consumption only takes precedence over the estimated consumption if the metered consumption is positive (it is assumed that only one heating element will be used at once).

The total consumption was then split into peak and off-peak consumption.

Estimation of water usage/flow

Hot water was inferred to be flowing whenever the drop in $Temp_{Bottom}$ (for devices with inlet at bottom) or $Temp_{top}$ (for devices with inlet at top) exceeds a threshold (-0.5 degrees/half-hour) and $Temp_{Avg}$ is also decreasing.

The volume of hot water flow is estimated from the measured temperatures using an energy balance model which assumes that:

- Hot water flows out of the top of the tank at temperature $Temp_{top}$.
- Mains water enters the tank at a temperature which varies according to the fixed monthly profile in [6]
- $Temp_{Avg}$, the midpoint of the top and bottom temperatures, always represents the average temperature of the tank.
- $Temp_{top}$ varies linearly over each the half-hour period of flow.
- The capacity of the tank is as previously estimated.

Although the position of the outlet pipe on the tank varies, this requires no change to the energy balance model.

Estimation of cooling properties

Heat is transferred from the tank hot water to the environment by all three modes: conduction, radiation, and convection (of air). However, as most tanks have some degree of insulation, it is assumed that conduction through the insulation will be the dominant source of thermal resistance (this can be verified by measuring or feeling the temperature on the exterior of the tank – if it is closer to the ambient air temperature than the water temperature then conduction is dominant). This assumption implies that without any water usage, cooling will follow an exponential decay curve, with two key parameters: ambient temperature T_a and exponential decay coefficient *k.*

In order to estimate these coefficients, periods of simple cooling (without water usage) were extracted from the data and analysed. The tank was assumed to be cooling when (i) $Temp_{Avg}$ was decreasing at a rate greater than 0.1 degrees/half-hour, (ii) there was no primary heating element consumption, and (iii) there was no estimated water flow. Only periods of at least 5 hours were extracted.

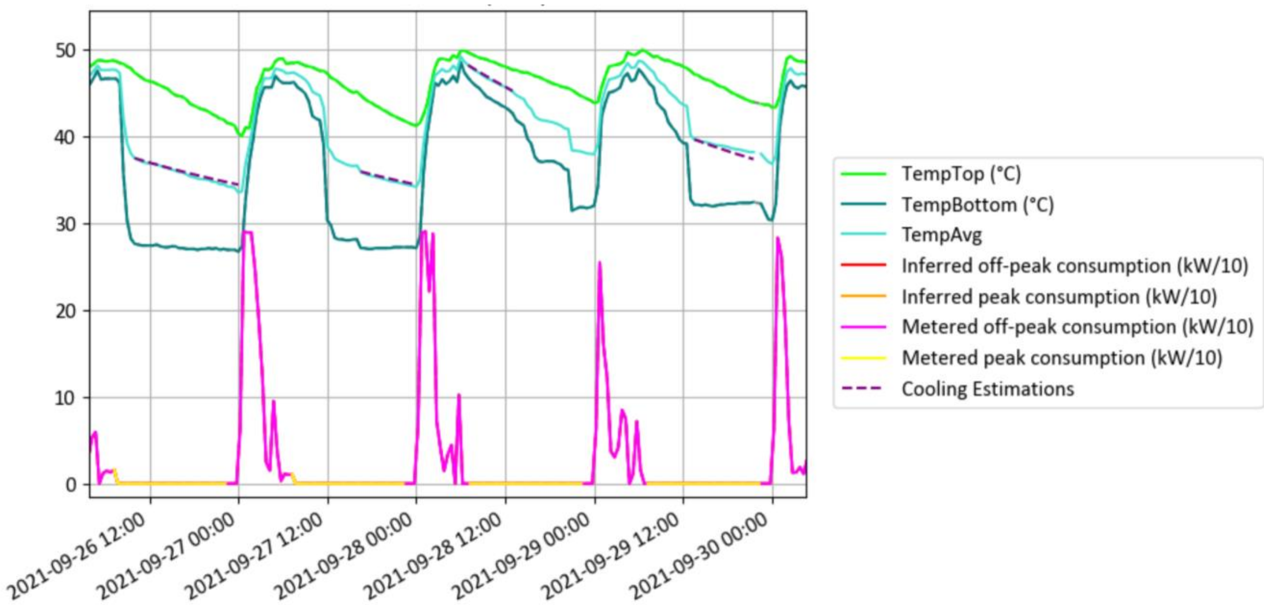

Figure 47: The cooling estimations (dashed purple) superimposed on 4 days of data from a single hot water device. The estimations fit closely to the $Temp_{Avg}$ line (midpoint of $Temp_{top}$ and $Temp_{Bottom}$).

An attempt was then made to fit an exponential decay curve to the $Temp_{Avg}$ (not measured; midpoint of $Temp_{top}$ and $Temp_{Bottom}$) curve for each extracted period using the *scipy.optimise* Python library. This was a two-stage optimisation process:

- First optimisation: T_a and *k* were fit to each period.
- For each device, the 0.15 quantile of the T_a estimations in each cooling period was taken. It was expected that most measured values of T_a would be an overestimate as the air in the tank cupboard may vary to some extent along with the water temperature. This leaded to estimations which fit the data well. The estimations of *k* were discarded.
- Second optimisation: T_a and *k* were fit to each period, fixing the value of T_a to be as calculated above.
- For each device, the median (0.5 quantile) of the *k* estimations in each cooling period was taken. This leaded to estimations which fit the data well.

Each time an optimisation was performed, any results which were not considered sensible ($0<k<0.5$, $15<T_a<45$) were discarded. Figure 47 shows the 'cooling estimations' superimposed on real data. These are estimations of cooling based on an exponential decay curve starting at the temperature at the start of the cooling period and using the cooling parameters T_a and *k* calculated for the device in question.