The DEFACTO Field Trial: Methodology and Data Sets

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Loughborough University

Contents

1 Introduction

The DEFACTO Field Trial was undertaken as part of a 6-year EPSRC-funded research project (grant EP/K00249X/1) from 1 November 2012 to 31 October 2018, aimed at measuring the energy saving capability of so-called 'smart' heating controls when used with gas-fired, low-pressure hot water central heating systems. This report describes the conduct of the field trial, the methodology adopted for its execution, the data that were collected and the cleaning of those data. Materials used in the field trial are presented in Appendix A (Pilot Study) and Appendix B (Main Study) to this report and are also available at https://doi.org/10.17028/rd.lboro.7837940. Mallaband *et al.* (2014 and 2016), Morton (2014) and Morton *et al.* (2016) present further information about the pilot study in particular.

Data sets for the pilot study (n=12) include:

- Baseline room temperature, at 30-minute intervals, for up to six weeks
- Electricity demand, at ten-minute intervals, for up to ten months
- Gas demand, at five-minute intervals, for up to ten months
- Interview transcriptions, covering use of heating, usability and installation of new heating controls
- New heating control use including room temperature, demanded set-points, system modes and interactions with the controller.

Data sets from the main study (n=400[1]) include:

- Recruitment information, including brief occupant and property details (n=393)
- Gas demand, at 30-minute intervals, over three years (n=249)
- Electricity demand, at two-minute intervals, over three years (n=188)
- Room temperature, at five-minute intervals, over three years (n=188)
- Home energy survey, including a domestic energy assessment, additional heating system details and a property floor plan (n=174)
- Questionnaire 1, covering use of the heating system and technology more generally, and more detailed household demographic and occupancy information (n=167)
- Questionnaire 2, covering use of the heating system, summer and winter heating, changes to the property since the start of the trial (n=122)
- Zonal control pre-installation questionnaire (for those participants receiving new controls), covering the use of current heating controls (n=33)
- Zonal heating control use (for those participants receiving new controls), including set-point temperatures, thermostat temperatures, system modes and interactions with the controller (n=49).

Detailed descriptions and the associated data are held by Loughborough University. Access may be limited as they contain information that could potentially identify individual participants.

[1] An initial sample of 400 households was recruited but this reduced through the study to 155 participants at the end of May 2018.

2 Overview of the DEFACTO Field Trial

The DEFACTO Field Trial ran over a period of nearly five years (February 2014 – November 2018) with additional time ahead of the trial for development of the research methods and materials (Figure 1 and Table 1).

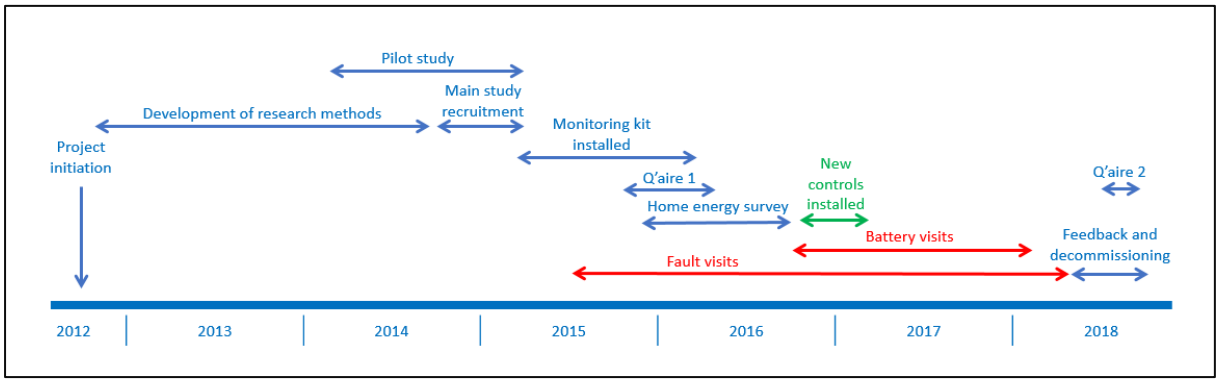

Figure 1: Timeline of the DEFACTO Field Trial stages

Table 1: Dates for each of the Field Trial stages

Phase	Start date	End date
Development of research methods	October 2012	October 2014
Pilot study	February 2014	March 2015
Recruitment of main sample	November 2014	March 2015
Installation of monitoring equipment	March 2015	Feb 2016
Home energy survey	December 2015	October 2016
Questionnaire 1	November 2015	May 2016
Installation of zonal heating controls	November 2016	March 2017
Questionnaire 2	August 2018	October 2018
Feedback and decommissioning	June 2018	November 2018

Following initial planning and development of the research methods, the study received Loughborough University ethical approval for both the pilot study and main study, with updates approved, when there were significant changes to the study protocol that affected participants. Risk Assessments were also completed for visits to participants' properties. Data were collected and stored in accordance with the Data Protection Act (1998) and the Project Data Management Plan. Electronic data were stored on secure servers hosted by Loughborough University, with access only by the project team. Project partners were only provided with personal information where necessary (e.g. names and addresses for visits to install equipment) and confidentiality agreements were signed between partners and the University.

The DEFACTO field trial was given a public-facing name of 'Go Digital' to reduce the emphasis on energy demand research. Participants in both the pilot study and main field trial knew the study only as Go Digital and the branding, study material, communication etc all used this identity.

A number of organisations were involved at different stages of the Field Trial (see Table 2).

Table 2. External organisations involved in the Field Trial

Key stage	Partners
Recruitment	Accent
Gas demand monitoring	SMS (Smart Metering Systems) plc
Electricity / room temperature monitoring	Equipment: Secure Meters (UK) Ltd. Installation: Mark Group Ltd. / John Unwin Electrical Contractors Ltd. Data flow: Seluxit
Home energy survey	Evolve Partnership Ltd.
Questionnaire 1	Developed in-house using Survey Monkey
Questionnaire 2	Developed in-house using BOS
Heating controls installed	Equipment: Honeywell Installation: Mere End Consultants Ltd.
Decommissioning	John Unwin Electrical Contractors Ltd.

2.1 Participant withdrawal

An initial sample of 400 households was recruited to the main study, but this reduced through the duration of the trial for a variety of reasons, including:

- Participant changed their mind about participation (n=73)
- Contact could not be made with the participant (n=45)
- Monitoring equipment could not be installed for technical reasons (n=39)
- Participant moved out of the property (n=17)
- Solar panels or smart meters installed, so no longer met inclusion criteria (n=6)
- Other, stated reasons (n=9)
- Unknown (n=57)

The majority of withdrawals occurred when gas or electricity/temperature monitoring equipment was installed (spring 2015 and spring 2016, respectively), with a small but steady number of participants withdrawing throughout the rest of the trial (Figure 2).

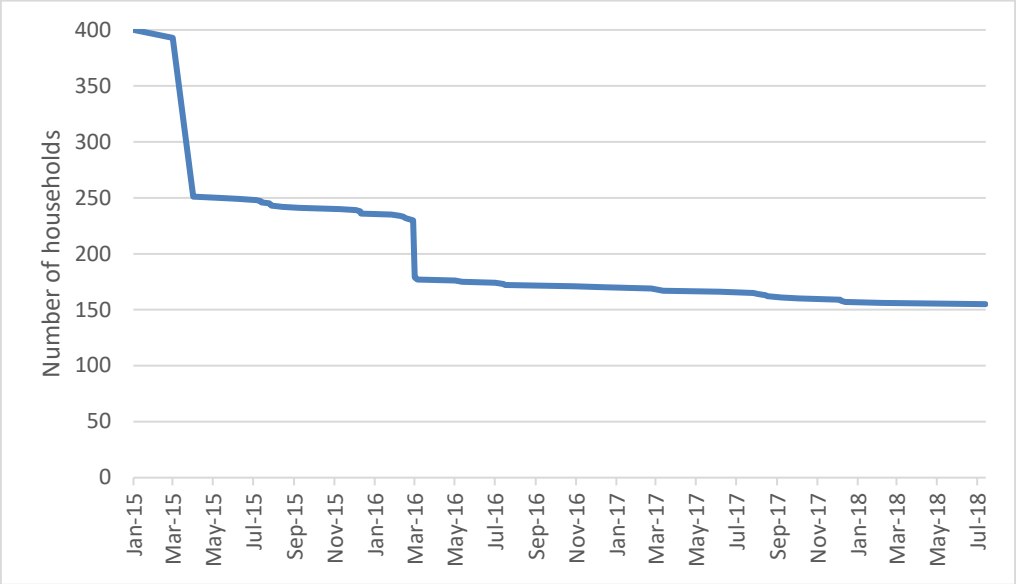

Figure 2. Main study sample size showing withdrawal rate

3 Pilot study

The pilot study ran from February 2014 to March 2015 and involved twelve occupied homes in the East Midlands region of the UK. It was intended to trial the full set of procedures to be used in the main study. Participants were recruited from employees of a partner organisation, as they were not directly involved in the research, but would be sympathetic to the requirements of the pilot study. Homes were recruited during February 2014. An information pack was provided to interested people who then contacted Loughborough University if they wished to take part in the study. Inclusion criteria were:

- Owner-occupied home
- Broadband connected
- Combination or conventional (with hot water tank) gas fired boiler for space heating and hot water.

If suitable, participants were asked to consent to take part in the study and completed an initial questionnaire which included questions about occupants within the home and ownership/use of appliances. Recruitment and consent material can be found in Appendix A to this report. A total of 12 suitable households were recruited to the pilot study and new heating controls were installed in each property, replacing their existing controls. Each home was visited by an installer representative to undertake a technical survey to determine suitability for gas/electricity metering and installation of new heating controls plus temperature sensors and gas/electricity devices.

The technical survey included the following:

- Ensuring the gas meter had suitable pulse output (RJ11/12 socket) or the householder was willing for the meter to be exchanged for one with appropriate output
- Identifying a suitable location for the secondary electricity meter, in agreement with the householder
- Ensuring the existing boiler was suitable for the new heating control system.

Once the technical survey confirmed the suitability of the property, the following items were installed:

- One standard iQe Halo device comprising:
    - Gateway
    - Halo in-home display (IHD) and docking unit
    - Thermostat (temperature feedback sensor)
    - Boiler relay
- Additional Z-wave temperature sensors (Freq 868.42MHz, Euro, Temperature Range 0°C To 30°C, Battery (2xAAA)), one in each room. Temperature data were collected at 30-minute intervals.
- One secondary electricity meter to provide feedback to the Halo IHD, installed between the supply company meter and the consumer unit (either NorthQ Z-wave meter or Aeon CT device. The NorthQ devices were installed in five properties but found to be less reliable and so all were replaced with the Aeon CT device). Electricity data were collected at 10-minute intervals.
- One gas meter pulse transmitter (Zmart Link) to provide feedback to the Halo IHD, attached to the pulse output of the gas meter. If there was no pulse output, then the gas meter was exchanged – this was the case for 8 of the 12 homes. Gas data were collected at 5-minute intervals.

Figure 3 and Figure 4 show the equipment that was installed in the pilot homes.

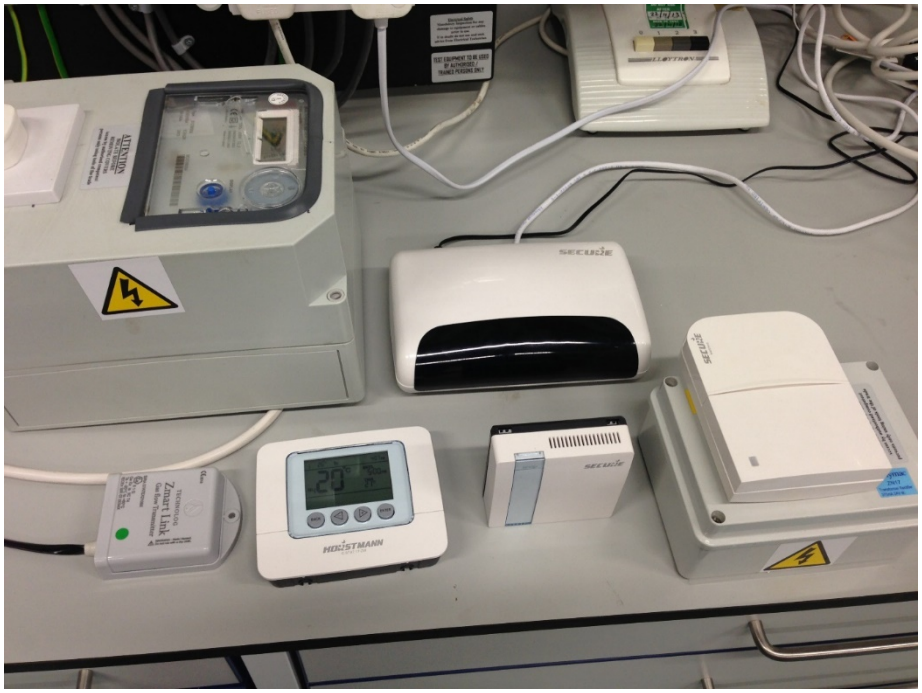

Figure 3. Equipment installed in DEFACTO pilot study homes (from left to right) gas meter transmitter, Halo in-home display, gateway, temperature sensor and boiler relay

Figure 4. Electricity monitoring equipment NorthQ (left) and Aeon CT (right)

The various Z-wave devices (Halo system, gas pulse transmitted and electricity meter, plus temperature sensors) were then paired with the gateway to enable the flow of data to the Loughborough University server. Installers were provided with clear instructions as to their task, including photos where necessary. Data relating to the use of the heating system via the in-home display were also sent to the server via the gateway and included demanded set-point, thermostat temperature, manual interactions and use of various settings, at five-minute intervals.

Installations took place between 19th March 2014 and 9th May 2014 (Table 3). Installation was typically carried out by one engineer (although the first two were undertaken by two engineers) and took between 1h 40 mins and 5 person-hours to complete (average of 3 hours). In some cases, the systems had to be reconfigured as sensors failed or lost connection with the gateway, and three systems required reconfiguring in May 2014.

Table 3. Pilot study installation information

	Installation Date	Installation time (hrs)	No. of installers	Boiler type	Gas meter	Electricity meter	No. of temp sensors
P01	21/03/2014	3	2	Combination	pulse output	Digital	7
P02	25/03/2014	3	1	Combination	Via SMS	Digital	11
P03	19/03/2014	5	2	Combination	pulse output	Mechanical	11
P04	28/03/2014	4	1	Conventional	Via SMS	Digital	11
P05	06/05/2014	3	1	Combination	None	Mechanical	11
P06	02/05/2014	2	1	Combination	Via SMS	Digital	9
P07	03/04/2014	2.5	1	Conventional	Via SMS	Digital	11
P08	04/04/2014	2.5	1	Combination	Via SMS	Digital	9
P09	10/04/2014	2	1	Conventional	Via SMS	Digital	9
P10	09/05/2014	3.5	1	Conventional	pulse output	Digital	13
P11	11/04/2014	1.7	1	Combination	pulse output	Digital	9
P12	30/04/2014	2.2	1	Combination	pulse output	Digital	7

In advance of the installations, participants were sent a confirmation letter of their installation appointment and a pack of 10 Hobo pendant temperature loggers for self-installation in their home (Figure 5). This allowed for a collection of temperature data (over a period of between two and six weeks) before the pre-existing heating controls were removed. Temperature data using the Hobo temperature loggers continued to be collected through spring 2014, alongside the installed temperature sensors to provide comparison between the two. Hobos pendant temperature loggers were posted back to the researchers in a provided envelope during June 2014.

Figure 5. Example of a Hobo pendant temperature logger, labelled for pilot study

In addition to the initial questionnaire (Pilot Questionnaire), participants were also invited to take part in two face-to-face interviews (Pilot Interview 1 and Interview 2) during their period of involvement with the pilot study. These comprised a series of semi-structured questions and activities, carried out in the participants' homes. Interview 1 took place during February-April 2014, before the new heating controls were installed and Interview 2 took place between August and December 2014, after installation. Exact dates are shown in Table 4 and the interview scripts in Appendix A.

Table 4. Pilot study interview dates in relation to installation of equipment

	Interview 1 date	Period from Interview 1 to installation	Installation date	Period from installation to Interview 2	Interview 2 date[2]
P01	25/02/2014	24 days	21/03/2014	4.8 months	12/08/2014
P02	26/02/2014	27 days	25/03/2014	4.7 months	12/08/2014
P03	26/02/2014	21 days	19/03/2014	n/a	No interview
P04	4/03/2014	24 days	28/03/2014	5.2 months	01/09/2014
P05	16/04/2014	20 days	06/05/2014	5.5 months	17/10/2014
P06	27/03/2014	36 days	02/05/2014	3.7 months	20/08/2014
P07	28/03/2014	6 days	03/04/2014	4.4 months	13/08/2014
P08	28/03/2014	7 days	04/04/2014	8.6 months	18/12/2014
P09	1/04/2014	9 days	10/04/2014	4.2 months	13/08/2014
P10	30/04/2014	9 days	09/05/2014	3.2 months	14/08/2014
P11	8/04/2014	3 days	11/04/2014	n/a	No interview
P12	11/04/2014	19 days	30/04/2014	n/a	No interview

Interview 1 enquired about the use of the participants' existing heating system, including their understanding of the role of the various components as well as asking about actions that would be taken in response to various scenarios, e.g. returning to a cold house. Participants were asked to carry out a series of tasks e.g. adjusting the heating to 22°C. These tasks were videoed to enable a simple analysis of the usability of the existing heating controls. Meter readings and photographs of utility bills were also taken at this stage. Interview 2 enquired about the installation process and set-up, and how the new controls were being used (for heating and/or hot water, as appropriate). Questions about the understanding of particular words, e.g. set-point, advance and boost, were included and the usability tasks were repeated, but this time with the new controls. Interviews were conducted by two researchers, one who led the discussion, the other who kept notes. Interviews were also audio-recorded for later transcription.

An audit of sensors was taken on 30 March 2015 to determine how many were still providing data (Table 5).

[2] Some participants withdrew from the pilot study before the second interview could take place, hence there was no second interview.

Table 5. Audit of sensors in pilot study homes on 30 March 2015

	Electricity metering	Gas metering	Temperature sensors present	Temp. sensors working	% temp. sensors working
P01	Working	Working	7	5	71%
P02	Working	Working	11	6	55%
P03	Not working	Not working	11	1	9%
P04	Not working	Working	11	1	9%
P05	Not working	Not working	11	0	0%
P06	Working	Working	9	6	67%
P07	Working	Working	11	6	55%
P08	Not working	Not working	9	7	78%
P09	Not working	Working	9	0	0%
P10	Working	Working	13	6	46%
P11	Not working	Working intermittently	9	3	33%
P12	Not working	Working	7	0	0%

Meters and sensors failed for various reasons: batteries ran down or were removed and not replaced, the gateway was unplugged or needed resetting, or sensors lost connection to the gateway and were not re-paired. To minimise the loss of data, participants were encouraged to reactivate sensors and were supplied with information on how to replace the batteries in the NorthQ electricity meter and how to reactivate the temperature sensors, as well as being supported through restarting the gateway. Batteries were supplied by the project team. Figure 6 shows examples of packs sent out to participants and example materials are included in Appendix A. Where remote support did not resolve the issue, visits were made to the properties, especially where a system reconfiguration was necessary.

Figure 6. Participant information packs

In addition to receiving new heating controls, which the households were able to keep after the end of the study, vouchers for £25 were given to each household for their participation. Vouchers were also given for participation in interviews (£25 per interview). Where additional visits were required, for example for fault visits, an additional £20 voucher was given as a token of appreciation.

4 Main study

The main study took place between November 2014 and November 2018. Six distinct data sets were collected during the DEFACTO Field Trial:

1. Recruitment Interview
2. Monitoring of gas and electricity demand, and room air temperatures
3. Home energy survey
4. Questionnaire 1
5. Monitoring of zonal heating controls
6. Questionnaire 2

As a result of the pilot study and external factors, a number of a changes were made ahead of the main study. A full description of the conduct of the main study, including details of these datasets, are presented in the following sections. Supporting materials are presented in Appendix B.

4.1 Recruitment

The sample of households for the main study were recruited based on the following criteria:

1. Owner-occupier
2. Semi-detached house[3]
3. Gas central heating, with a boiler less than 10 years old
4. Broadband internet connection
5. Located in the Midlands of England, UK

The households were recruited by a professional survey company which employed experienced staff to call on households chosen from a randomly, pre-selected set of 1000 addresses. Using Super Output Areas (Mid Layer) from the 2011 population census (Office for National Statistics, 2016), target areas were randomly selected in nine regions of the English Midlands. Data from the 2011 census on the incidence of owner-occupied, semi-detached properties with central heating were used as a guide to the number of properties needed in each target area. There were additional quotas based on property size to ensure a reasonably representative range (again, based on 2011 census data) within the sample:

- 2 or fewer bedrooms: minimum 30, maximum 49
- 3 bedrooms: minimum 273, maximum 310
- 4 or more bedrooms: minimum 40, maximum 78.

Additionally, it was confirmed that at least 50 households had traditional Thermostatic Radiator Valves (TRVs) on their radiators to enable later system upgrade without significant disruption to the households. Properties were excluded if they had solar panels.

Following development of the recruitment materials and training, recruitment ran from the start of November 2014 to the end of March 2015. Six homes (five in Birmingham, one in Leicester) were recruited during November 2014 as a pilot, and 394 recruited subsequently, totalling 400 households. Participants were recruited via a doorstep interview and initially given information about the study and asked to provide their consent to participate. An example study information sheet and initial consent form are included in Appendix B. They then answered questions from the recruiter who used a Computer-Assisted Personal Interviewing (CAPI) tool loaded to a tablet computer (see Appendix B for the recruitment interview script). The budget allocation included funds for the questionnaire to be translated

[3] It was only realised some significant time into the study (and after installation of the Honeywell evohome system) that one home in the sample was a detached house - ID 087. As so much data had been collected for this property and the participants were actively involved in the study, they remained in the sample.

into two South Asian and one Eastern European language (and for a speaker of the relevant language to conduct the interview). However, these arrangements were not needed and all of the recruitment interviews were conducted in English. Brief information was collected from the households including contact details, number of bedrooms in the property, job title of the main wage earner, respondent age band, gender and ethnic group. The Meter Point Reference Number (MPRN) was also collected, to allow for gas metering equipment to be installed.

Seven households contacted the recruitment company within a few days of recruitment to withdraw and so 393 addresses and associated information were forwarded to the Loughborough research team in batches; all were received before the end of March 2015. These households were sent a welcome email from Loughborough University and their details were added to a participant database held securely on a Loughborough University server (password protected file on a secure server that was only accessibly by a limited number of the project team).

It was not possible to recruit sufficient participants that met all the criteria within the original quotas, so targets were adjusted to enable a sufficiently large sample. In practice, slightly more larger homes were recruited than the target (n=85) and slightly fewer smaller homes (n=22), with 285 three-bedroom homes in the original sample of 400.

The locations of the 393 households, clustered in nine areas of the English Midlands, are shown in Figure 7.

Figure 7: Location of homes in the DEFACTO study showing (red) numbers recruited and with recruitment interview data forwarded to Loughborough University (total 393)

To provide information on the external temperature at the study locations, MIDAS hourly weather data were downloaded from the Centre for Environmental Data Analysis website[4]. Homes in the Leicester and Oakham areas were grouped together for analysis purposes and data for seven weather stations run by the UK Meteorologist Office were accessed (Table 6).

Table 6. Nearest weather stations to the study locations

County	Station name	src-id	Latitude	Longitude	Postcode	Wind speed data available	Solar radiation data available
Leicestershire	Market Bosworth: Bosworth Park	30529	52.6228	-1.394	CV13 0	Yes	No
Nottinghamshire	Nottingham: Watnall	556	53.0053	-1.24969	NG16 1	Yes	Yes
Nottinghamshire	East Midlands	18919	52.8829	-1.2777	NG10 3	Yes	No
Northamptonshire	Northampton: Moulton Park	578	52.2732	-0.87937	NN2 7	No	No
West Midlands	Coventry: Coundon	24102	52.4241	-1.53498	CV1	Yes	Yes
Staffordshire	Keele	622	52.9986	-2.2688	ST5 5	No	No
Warwickshire	Coleshill	19187	52.4798	-1.68925	B46 3	Yes	Yes

4.2 Monitoring gas demand, electricity demand and room air temperatures

4.2.1 Gas demand monitoring

Gas demand was recorded by replacing the household's gas meter with meters supplied and fitted by a utility monitoring company. Contact details of properties were sent securely to the utility monitoring company in batches between February and May 2015. They then contacted the householder to make an appointment to visit their property and exchange the gas meter for one that could be monitored. The first gas monitoring equipment was installed on 17 March 2015 and the final set installed on 6 November 2015, with the majority installed during March – June 2015 (Figure 8).

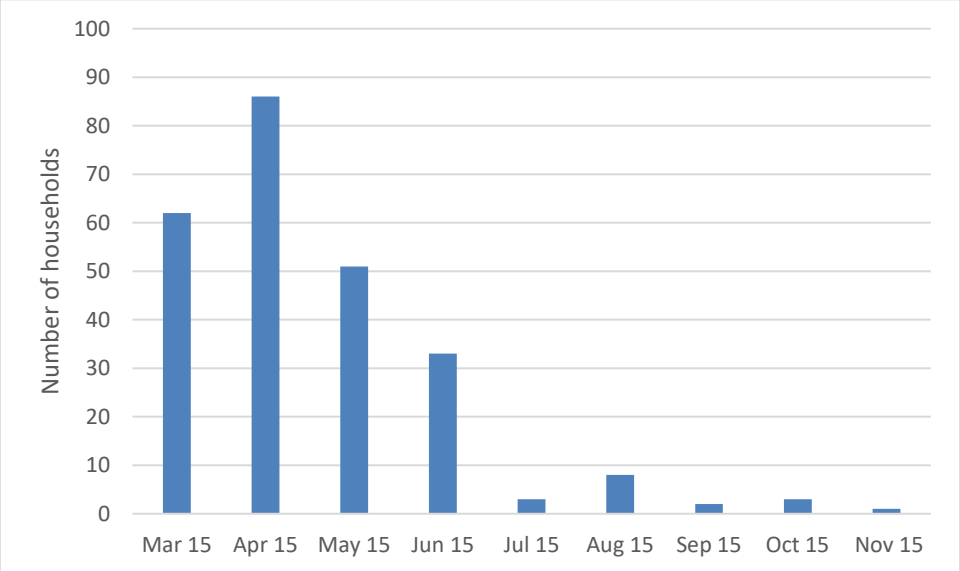

Figure 8. Timing of gas monitoring equipment installation

[4] http://data.ceda.ac.uk/badc/ukmo-midas/data/WH/

Each new meter provided gas consumption (in cubic metres) every half-hour (MID 2004/22/EC gas meters accuracy class 1.5). A GSM-based telemetry system conveyed the data via the digital cellular network to the server. These data were then sent to the researchers' secure server as daily .csv files with unique identifiers.

Figure 9. Gas demand monitoring equipment (left) and as installed (right)

Gas monitoring equipment could not be installed in 144 properties. There were multiple reasons for this, including:

- Participant changed their mind about being involved in the study (n=44)
- Contact with the participant was not possible despite repeated attempts (n=37)
- Equipment installation was not possible for technical or access reasons (n=26)
- Solar panels or smart meter were to be installed so households would no longer be eligible for the study (n=3)
- Participant moving out of the house (n=3)
- Other stated reason (n=5)
- Unknown reasons (n=26).

Although gas demand monitoring was intended as a condition for householders' participation in the trial, two properties which did not have gas demand monitoring equipment installed continued in the trial because they provided valuable additional data, and both remained active to the end of the study.

The gas data collected from all 249 properties were reasonably robust with few extended breaks in the half hourly data delivery. Data were cleaned and reformatted using Matlab to per-dwelling, per-half-hour values (see Figure 10 for an example). Cleaning involved removal of missing data and data for any households that withdrew part way through the study, to ensure recorded data did not extend beyond their withdrawal date. 'Zero' readings were retained as it was not known whether they represented gaps in the data delivery or periods when the householder did not use any gas. As a result, more than 9.5 million datapoints were recorded in the raw data set, and no erroneous datapoints were removed in the cleaning process.

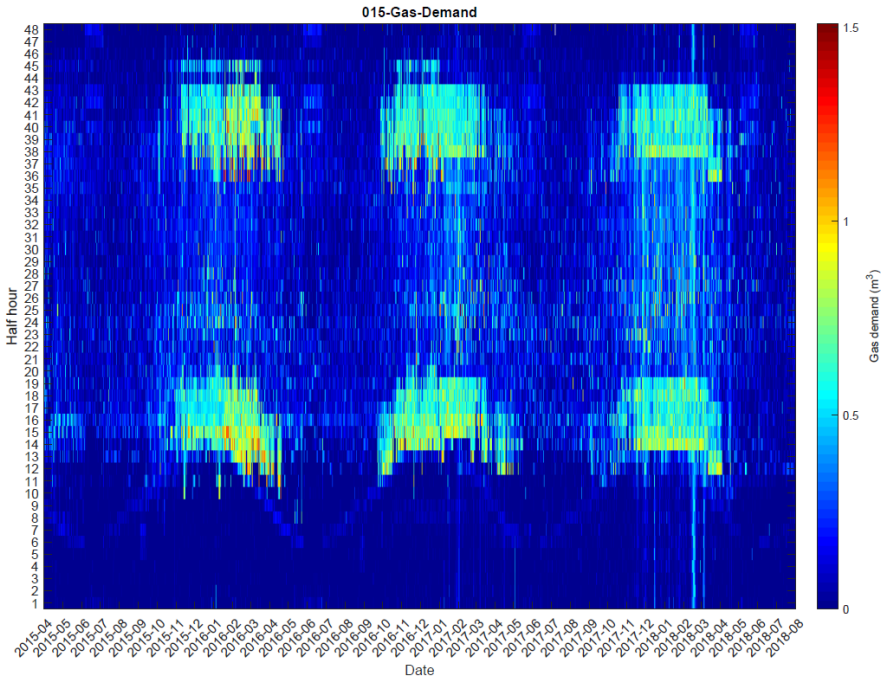

Figure 10. Half-hourly gas demand for one home from 1 April 2015 to 31 August 2018

4.2.2 Electricity demand and room temperature monitoring

In order to collect electricity demand and room temperature data, each home that had had gas monitoring equipment installed was subsequently equipped with a Gateway (Skyline 370B), electricity demand monitoring equipment and temperature sensors (Figure 11).

Figure 11. Installed monitoring equipment showing (from left to right) range extender, electricity demand equipment, gateway and room temperature sensor

4.2.2.1 Electricity demand monitoring

Whole-house electricity demand was obtained using an Aeon Labs Aeotec device, installed by a qualified electrician at the property's electricity meter (see Figure 12). Via current transformer (CT) clamps, the Aeotec monitor recorded electricity demand which was sent to the gateway. Data were integrated over two-minute intervals to provide values for cumulative electricity consumption in kWh to an accuracy of ± 1%. In this way, should the gateway or router lose power, upon restart the total electricity consumed during the 'off' period would be known. The electricity monitor and temperature sensors communicated wirelessly, using the Z-wave protocol, with the gateway, which was connected into each household's broadband router. Where necessary, a Z-wave range extender was installed to improve the reliability of the wireless network.

Figure 12. Example of installation of electricity monitoring equipment

The data from the electricity demand monitor and the room temperature sensors from each home were collected and stored on a cloud-based server. Data were downloaded each day into a MySQL database located on a secure server at Loughborough University. Four backup processes were automatically run each day on this University server and the last 12 iterations kept; the server itself was independently backed up on a three-month rolling basis. Each home had a unique ID and no personal identifiers were stored or linked to the primary data.

Contact details of properties were sent securely in batches to the installer between March 2015 and November 2015 and the installer contacted the householder to make an appointment to visit their property and install the monitoring equipment. The first electricity and temperature monitoring equipment was installed on 13 April 2015 and the final set installed on 24 February 2016, with the majority installed during April–August 2015 (Figure 13).

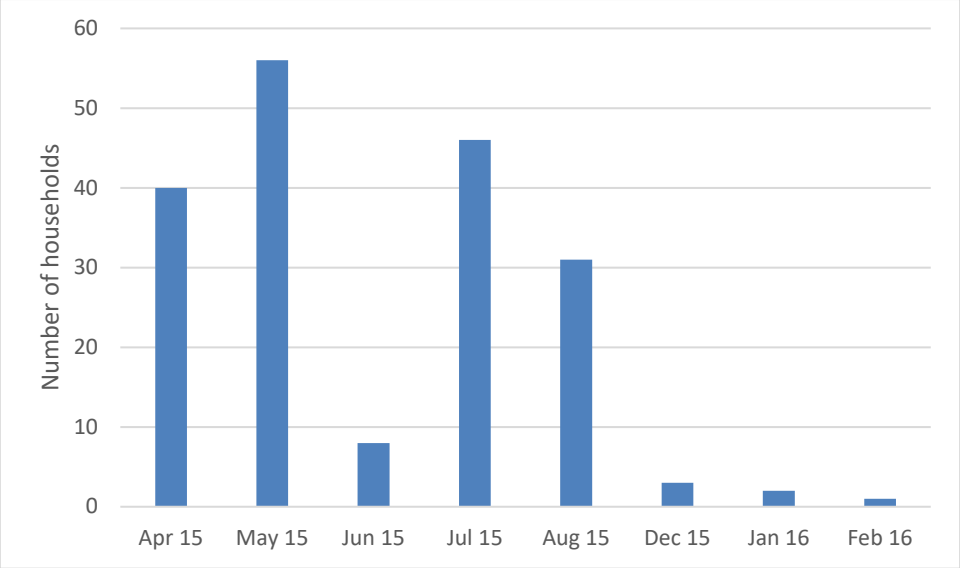

Figure 13. Timing of electricity and temperature monitoring equipment installation

It was not possible to install the equipment in 63 of the active[5] properties. There were multiple reasons for this, including:

- Installation was not possible for technical or access reasons (n=13)
- Participant changed their mind about being involved in the study (n=10)
- Contact was not possible with the participant despite repeated attempts (n=7)
- Solar panels or smart meter being installed so no longer eligible for the study (n=2)
- Other stated reason (n=3)
- Unknown reasons (n=28).

By the end of February 2016, 188 homes had been equipped with a gateway, temperature sensors and the electricity demand monitoring equipment. In two homes, electricity and temperature monitoring equipment was installed even though gas monitoring equipment was not. Whilst this limited the value of the participants' data, it was decided to keep these two participants in the main study. This resulted in 186 fully monitored homes by February 2016.

The raw two-minutely electricity data set was found to contain erroneous values, so the data were cleaned through a phased process:

- "Manual" removal of data from five households identified as erroneous through inspection, for example as a result of faulty monitor readings, with current in excess of 100A. Where monitors were changed, the previous erroneous data were removed.
- All negative readings were considered erroneous, as cumulative electricity consumption must be non-negative in the absence of electricity generation. Negative readings were replaced with a NaN (Not a Number) value in the dataset.
- In five dwellings, electricity monitors were initially set to log the average electrical load (in Watts) since the previous record. These readings were converted to cumulative energy consumption (kWh) and the monitors replaced or reconfigured as soon as possible.
- For 22 dwellings, the raw electricity data were found to contain duplicate values, such that additional data were reported for a monitoring interval covered earlier in the data. Inspection of these data revealed that one set of readings usually consisted solely of

[5] 'Active' refers to participants who had not withdrawn from the study at a particular stage. However, levels of engagement in the various components on the trial varied and so some active participants did not complete every component. As withdrawals occurred throughout the trial, the number of active participants declined gradually.

values lower than the total electrical energy consumed prior to the interval. It was therefore decided to retain the data set where the mean was higher than the prior total consumption, while removing the data set where the mean was lower.

- Time series plots revealed positive and negative spikes, which were usually isolated and followed by 'normal' values (see Figure 14). Each potential outlier was compared with expected values derived from a linear regression using the preceding 30 reading not marked as potential outliers. Identified positive and negative outliers were then replaces with NaN in the data set.

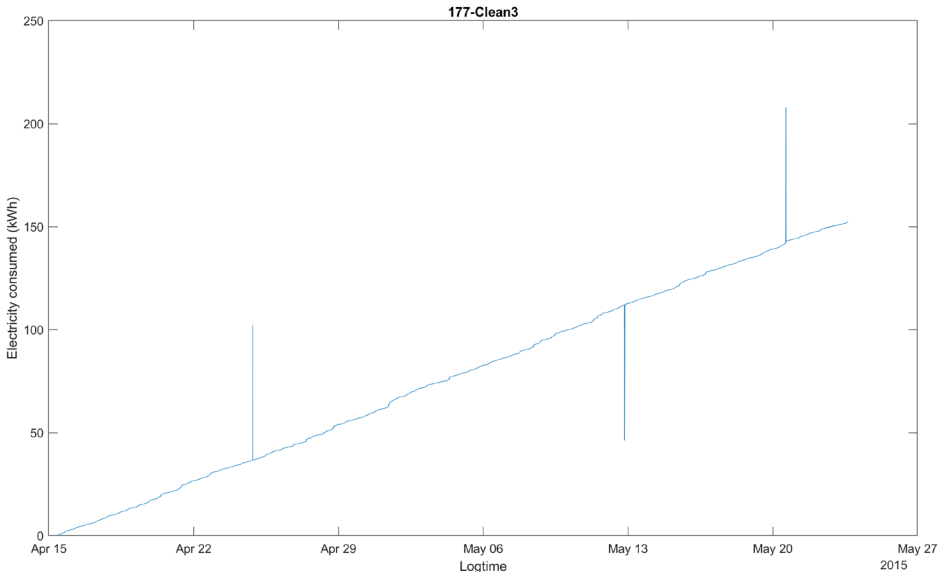

Figure 14. Cumulative electricity consumption data (kWh) for one dwelling showing positive and negative spikes in the data

The raw data included approximately 107 million datapoints at the end of August 2018, and cleaning removed just over 200,000, 0.2% of the sample.

After cleaning, the data were resampled to produce half-hourly, per-dwelling plots, an example of which is shown in Figure 15. Gaps were found in some data sets (indicated by the white in the false colour plot in Figure 15). These gaps were likely to be due to the gateway losing power (accidentally or intentionally unplugged).

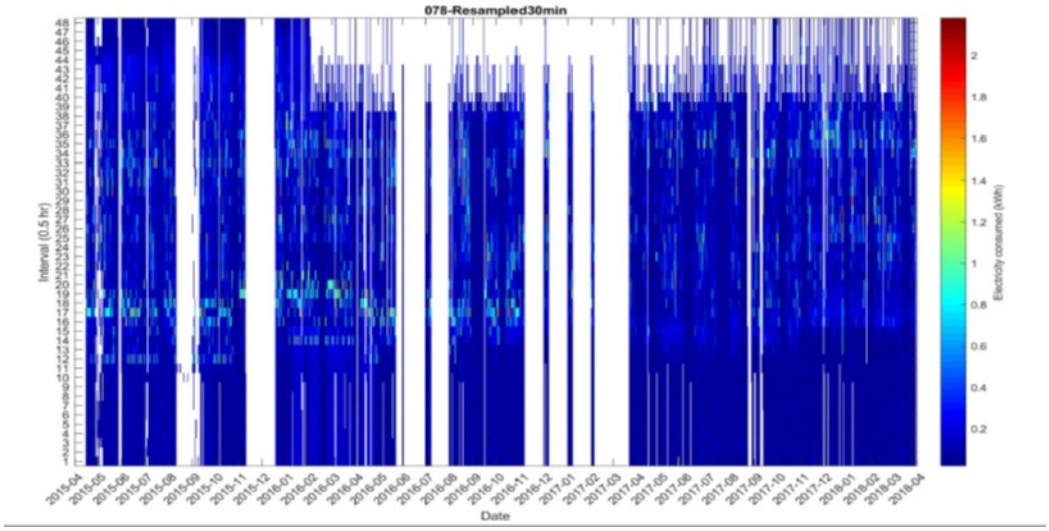

Figure 15. Half-hourly electricity demand for one home from 1 September 2015 to 31 August 2017, with white gaps illustrating the missing electricity demand data

For some homes, there were few gaps in the data stream, for others there were more. Figure 16 shows the distribution of expected hour-hourly electricity demand values found in the cleaned data to 31 October 2017. Overall, to 31 August 2018, 89% of the expected half-hourly readings were found.

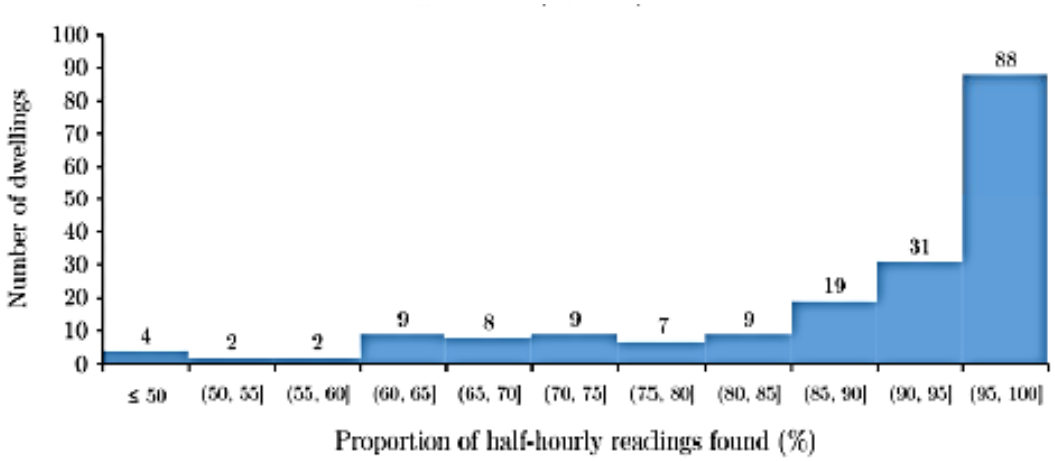

Figure 16. Distribution of proportion of expected half-hourly electricity readings found to 31 October 2017 (n=188)

4.2.2.2 Room temperature monitoring

Temperatures were recorded in every room[6] of every dwelling where possible (including using Secure Controls SES301 sensors, accuracy +/- 0.5°C, which were battery powered by two AA-batteries (see Figure 17). Sensors were placed at mid-room height wherever possible, and away from direct sources of heat or sunlight. The installer recorded the serial number of each sensor and its intended room location, and individually paired the sensors to the gateway (see Figure 18). In all, 188 homes had temperature sensors installed, with between 5 and 11 in each home, an average of 8.6 sensors per home. The sensors were set to record the temperatures at 5 minutes intervals.

Figure 17. Example of a temperature sensor as installed

[6] Rooms included living room, kitchen, dining room, office/study, conservatory, utility room, hall/landing, main bedroom, other bedrooms, bathroom, toilet and other.

Figure 18. Pairing temperature sensors with the gateway

Temperature monitoring was not without difficulties. Firstly, some of the sensors began to indicate that the battery power was low within a few months of installation, so a programme of house visits to replace batteries was begun in May 2016 and continued until December 2017. Batteries were changed in a total of 96 homes and in nine of these, batteries were changed a second time during the study. The shortest interval between installation and battery replacement was 6 months, the longest was 30 months, with an average of 19 months. During the latter stages of the study, it was decided not to replace further batteries in order to minimise disruption to participants. Secondly, because the sensors were not fixed to walls (to minimise damage to participants' properties), there was the risk that sensors may have been moved, removed or otherwise displaced by the occupants themselves. The protocol for the battery replacement visits therefore included checking the location of the temperature sensors. Finally, the sheer volume of temperature data made it difficult to fully check the credibility of the recorded values on an on-going basis and so erroneous and missing temperature data only were highlighted periodically. When these data were identified, visits were made to homes to replace or repair sensors or replace batteries. Data from a total of 1762 sensors was received from the 188 homes, although as a result of a number of replacements, the number of active sensors in the 188 homes totalled 1610.

The raw five-minutely temperature data set was found to contain erroneous values, so were cleaned through a phased process:

- Removal of extreme data points where temperatures were below absolute zero (affecting 123 sensors) or over 80°C (affecting 312 sensors).
- Removal of data for repeated monitoring intervals, as described in the electricity data cleaning process (affecting 86 sensors).
- Removal of spikes where isolated readings were abnormally high or low. Local extremes were identified as spikes and removed whenever the gradients both before and after the reading had a magnitude greater than 1°C per minute. This affected 584 sensors; among these 584 sensors, the mean number of spikes removed was 13 while the median was 1.

An example of a resampled temperature plot for one sensor in one dwelling is shown in Figure 19. The temperature data were also subject to unplugging of the gateway and so included gaps, for example around July 2016 for this sensor.

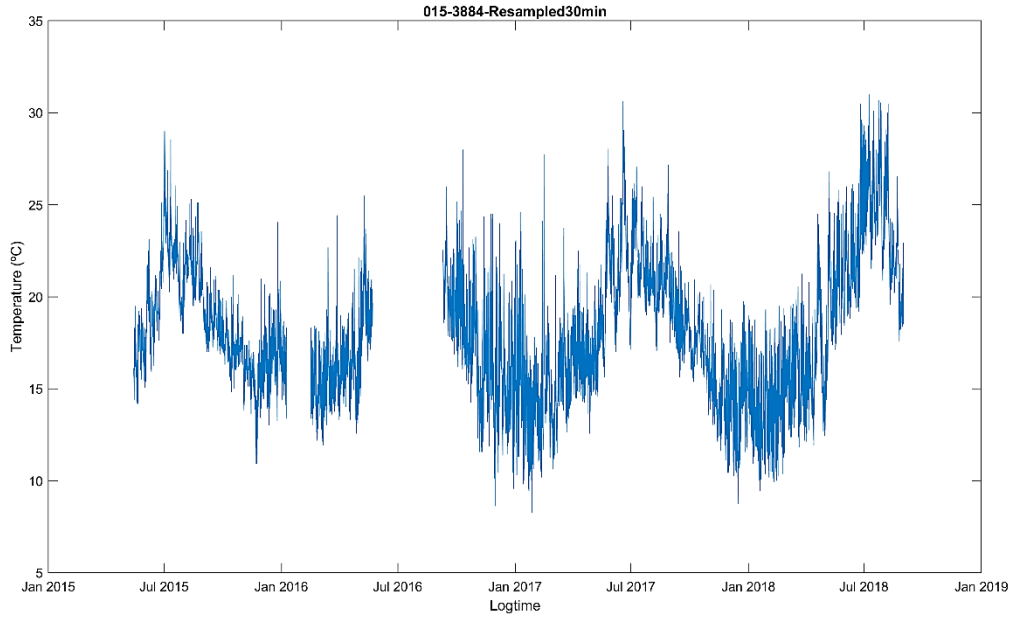

Figure 19. Half-hourly temperature data for one sensor in one home from 14 May 2015 to 1 September 2018, illustrating the intermittent data received

4.3 Home energy survey

Starting in December 2015, trained and certified domestic energy assessors visited homes to gather the data needed to produce Energy Performance Certificates. In addition to providing all EPC data in XML format, the assessors were asked to provide additional information (see summary sheet in Appendix B), thus creating a home energy survey including:

- a scan of the surveyor's site notes
- floor plans (showing room names, dimensions and radiator locations noting the presence of thermostatic radiator valves (TRVs)
- an indication of any open plan staircases
- the direction of north
- a photograph of the front of the house
- the make and model of the boiler and heating controls (with photographs)
- a list of secondary heating devices
- the location of any extractor fans (from cooker hoods, WCs and bathrooms, etc).

The assessors were securely provided with the addresses of the 188 homes remaining in the study. They produced the so-called 'EPC+' information from 174 homes, with 86% of these completed by the end of January 2016 and the remainder by October 2016 (see Figure 20). Home energy surveys were not completed for 14 of the active properties.

The data provided for every property were carefully checked within a week of receipt, to identify inconsistencies, for example between floor plans, photographs and the EPC XML data. Of the 174 surveys undertaken, 21 (11%) were found to contain errors, some with more than one error. These included: incorrect house type chosen (n=3 properties); solid walls not cavity walls indicated (n=2); loft insulation omitted (n=3); missing cavity wall

insulation (n=1); electric, not gas, hot water heating chosen (n=11); and missing low energy lights (n=2). In six additional surveys, the wrong wall type was suspected of being indicated (comparing the XML data with the photographs) and the assessor was asked to provide additional evidence, alternatively, the dwelling was checked during a later visit to replace sensor batteries. In one case, a survey was undertaken for the wrong house. Ultimately, all identified errors were corrected and although most changes had little effect on the EPC rating, in a small number of cases (14 of the 174 homes, 8%) a difference of up to 18 rating points was made.

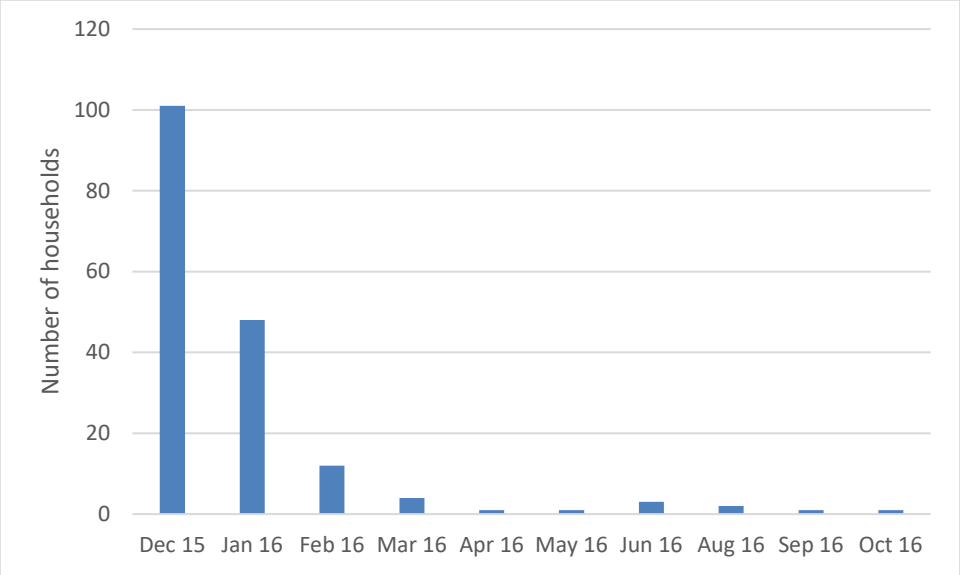

Figure 20. Timing of home energy surveys

4.4 Questionnaire 1

Questionnaire 1 was sent out on 19 November 2015. It was distributed as an on-line questionnaire using Survey Monkey (https://www.surveymonkey.com/) and as a paper version for those who requested that option. A total of 167 active participants completed this questionnaire, which included questions about the following:

- Use and control of heating in winter
- Secondary heating
- Summertime heating
- Use of technology
- Household demographics and occupancy
- Changes in the home since starting the study.

Full details of the questions asked are given in Appendix B. Responses were received between 19 November 2015 and 18 May 2016 (Figure 21). Up to three reminders were sent out to non-responding participants to encourage them to complete the questionnaire. 34% of responses were received within seven days of issuing the questionnaire on 19 November 2015, with an increase in response following reminders in January and April 2016. The questionnaire was not completed by 21 of the active participants; a response rate of 89%.

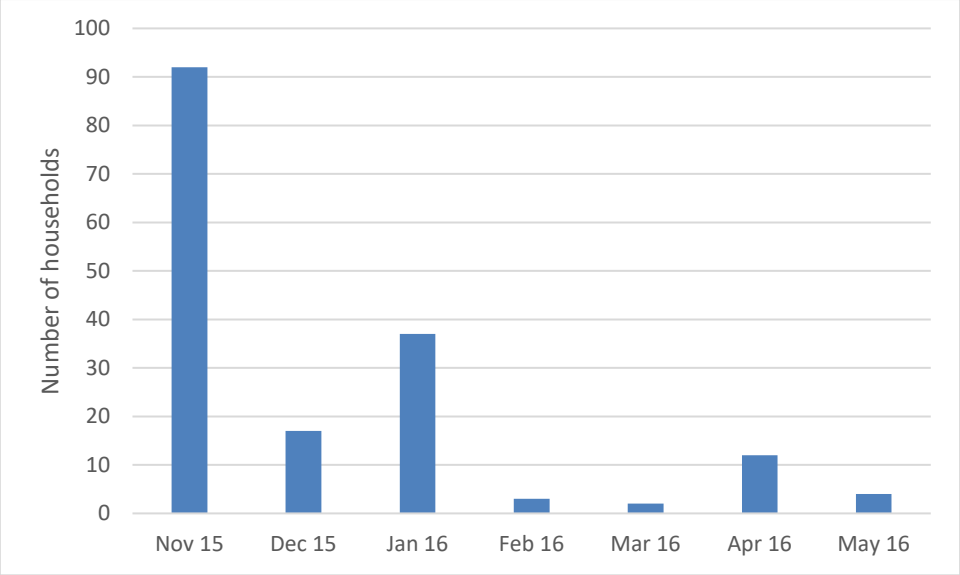

Figure 21. Timing of Questionnaire 1 responses

At this stage in the trial, a total of 163 participants had a full set of monitoring equipment installed, a completed home energy survey and questionnaire 1.

4.5 Installation of the zonal heating controls

After a complete winter of data (October 2015 to March 2016) had been collected for the active homes, a sub-sample of homes was identified for installation of zonal heating controls. In order to select homes for this installation, data already collected were scrutinised to determine whether the households met the following criteria:

1. Participants still active in the study
2. Home energy survey was available at 1 July 2016
3. Heating systems did not have existing zonal or smart (remote access) controls such as 'Nest' or 'Hive'
4. Questionnaire 1 was completed
5. Central heating system did not include underfloor heating
6. Gas demand data available from October 2015 to March 2016 inclusive and still receiving gas data at 18 September 2016
7. More than 50% of room temperature and electricity demand data available between October 2015 and March 2016 inclusive.

Table 7 shows the breakdown of existing heating controls for the sub-sample of 100 homes which met all seven criteria.

Table 7. Existing heating controls in the 100 homes sub-sample

Existing heating controls	Number of homes
Programmer only	6
Programmer and room thermostat	10
Programmer, TRVs and bypass	16
Programmer, room thermostat and TRVs	66
TRVs and bypass	2

Half of the homes with each existing controls type (Table 8) were randomly selected and assigned to one of two groups: 'Zonal control' group or 'No change' group. This resulted in a total of 50 homes in each group. Participants were then invited to receive new zonal heating

controls. In some cases a participant did not want to change their heating controls, in other cases the home was not suitable for a controls change (as determined at the initial visit from the installation engineer – see below). In either of these cases, a participant from the 'No change' group with the same existing controls was randomly selected and invited to have zonal controls installed. Where the heating controls could not be changed, this participant was then moved to the 'No change' group and they kept their existing heating control system. In total, 67 households were contacted and offered the new heating controls; five declined the offer, there was no reply from seven households (despite three attempts) and 55 households accepted the original invitation. However, six of these acceptances were cancelled before installation for the following reasons: two participants moved house and so withdrew from the study, the system was deemed too technical for two of the users (after discussion with them), one heating system was not suitable for the zonal control system (requiring replacement of more of the system than possible within the trial) and one user reported that they did not use their central heating system, relying instead on secondary heating.

This resulted in cohorts of 49 in the 'Zonal control' group and 51 in the matched 'No change' group (including the two participants who were soon to move to a new home, and so would withdraw from the study).

The Honeywell 'evohome' system[7] was selected as the zonal control system for the study and was installed in all 49 homes by an approved installer of Honeywell heating systems. Contact details of the relevant participants were sent securely to installer who then arranged suitable appointments. After an initial visit of about 30 minutes duration to ensure that the home was suitable for the new heating controls and to explain the installation process, an appointment for installation was made. During installation, households were provided with temporary electrical heaters to maintain comfort during the process. Each evohome system comprised a controller and stand or wall bracket, and a set of radiator controllers (HR92) (Figure 22).

Figure 22. Honeywell evohome controller on its stand, and HR92 radiator controller

[7] https://heatingcontrols.honeywellhome.com/products/Connected-Smart-Products/evohome-connected-thermostat/evohome-Main/

Where properties had thermostatic radiator valves already, the heating system did not need to be drained as part of the installation and the radiator valves could simply be replaced. In some cases, the heating system needed to be drained to enable installation. The system was then set up to suit the occupants.

The first Honeywell evohome system was installed on 1 November 2016 and the last one on 7 March 2017, with 55% installed by the end of December 2016 and 82% by the end of January 2017. Once installed, participants were asked to consent to Honeywell sending Loughborough University data from the use of their system (which included set-point temperatures, thermostat temperatures, system modes and interactions with the controller) which required participants to agree to a set of terms and conditions by logging into their Honeywell account and ticking a box. Some participants completed the consent process the same day as installation but for others this process took a little while. The longest interval between installation and consent for data flow was 135 days (mean for the 49 homes of 20 days). Data started flowing to the Loughborough University servers from 4 November 2016; with the last home completing the consent process on 10 May 2017 (Figure 23). A total of 26 of the 49 homes (53%) were sending data within one week of installation and 82% within one month of installation.

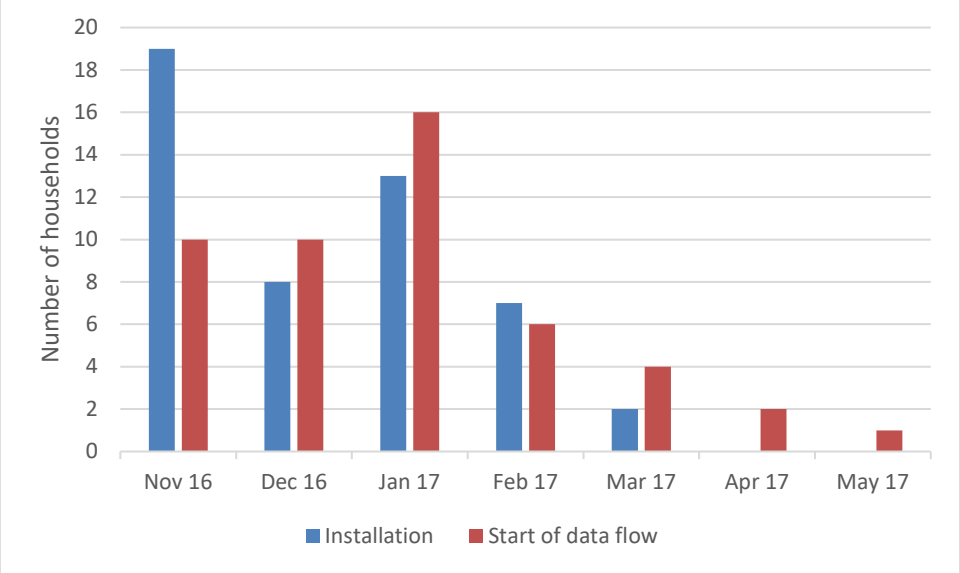

Figure 23. Timing of Honeywell evohome installations, and start of data flows

Faults that occurred during the study were fixed by the installer, either under the warranty agreement or as an additional job funded by the project, to ensure the continued flow of data. Each system was provided with a two-year warranty and participants were able to keep the Honeywell evohome controls in their property at the end of the study.

A short questionnaire was developed to capture more information regarding how participants were using their existing heating system and controls before the evohome system was installed, a copy of which is included in Appendix B. A total of 33 households completed this pre-intervention questionnaire.

4.6 Questionnaire 2

Questionnaire 2 was sent out on 30 August 2018. It was distributed as an on-line questionnaire using the Bristol Online Survey (BOS) tool[8], licensed for use by Loughborough University, with paper versions sent to those participants requesting this format. Two versions of the questionnaire were distributed, one for participants that had a Honeywell evohome system and one for other participants. Reminders were sent to participants who did not respond and in some cases the questionnaire was completed as a telephone interview, for participants who preferred this method of completion. A total of 122 active participants (41 evohome participants, 81 non-evohome) completed Questionnaire 2, which included questions on the following:

- Use of the heating system
- Ease of use and access to heating controls
- Summer and winter heating
- Changes to the property or household since the start of the project
- Use of the Honeywell evohome app (evohome participants only).

Full details of the questions asked are included in Appendix B. Responses were received between 30 August 2018 and 25 October 2018 (Figure 24). 61% of responses were received within seven days of issuing the questionnaire on 30 August 2018, with 80% completed within two weeks. Questionnaire 2 was not completed by 32 active participants; a response rate of 79%.

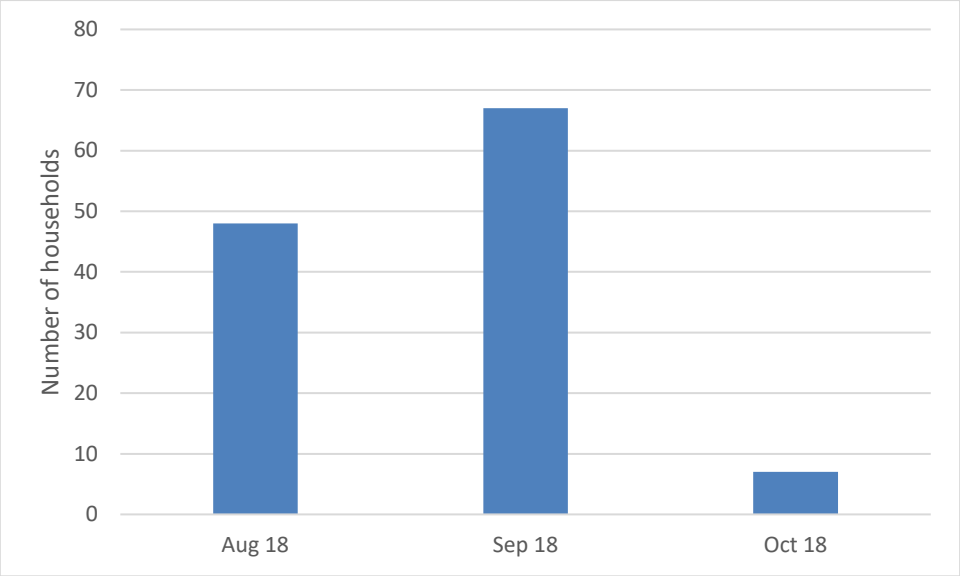

Figure 24. Timing of Questionnaire 2 responses

At this stage in the trial, a total of 115 participants had a full set of monitoring equipment installed and had a completed home energy survey and Questionnaires 1 and 2.

4.7 Data checking, trouble shooting and fault visits

With such a large dataset and complexity of data collection, a number of different approaches were taken to checking data and resolving problems. A weekly monitoring report was produced to identify the number of temperature sensors and electricity monitors sending data. Where significant losses of data were seen, checks were made to determine the appropriate course of action. Where temperature data from high priority rooms (living room

[8] https://www.onlinesurveys.ac.uk/

and main bedroom) were missing, participants were contacted via email, telephone and/or post, to check that their gateway was still connected and working. Where faults could not be resolved remotely, visits were arranged. Fault visits normally involved replacing batteries in sensors or restarting the gateway. The location of sensors was usually checked at these visits too, to ensure they were still in the expected room. Unresolved discrepancies in the home energy surveys were also investigated. Fault visits took place, as required, throughout the main study period.

The flow of data from the various sources was also checked periodically. This involved comparing the data stored in the Loughborough database with the data directly downloaded from the servers. Sample checks were also made of the expected number of datapoints in the database compared with the actual number held.

4.8 Maintaining the cohort

Although there were changes in the research team members over the duration of the study, a consistent branding and visual identity was used throughout. This included the study name itself, 'Go Digital', the bespoke logo and a standard email footer on all electronic communication. Partners and sub-contractors also used the Go Digital study name, for consistency and equipment in homes carried the Go Digital logo.

Participants could contact the research project team at any time using a single email address, godigital@lboro.ac.uk. There was also a study phone number for telephone contact, where participants could leave a message out of office hours and a member of the research project team would call back. Season's greetings cards to all active participants from the research project team were sent each December. These often included a tailored message, for example to remind participants to not disconnect the gateway for any reason during the festive season (an example is included in Appendix B).

4.9 Incentives

Participants were sent vouchers as a token of appreciation for their involvement at various stages of the study. This included:

- £5 at initial recruitment
- £30 once gas, electricity and temperature monitoring equipment was installed
- £30 once Questionnaire 1 and the home energy survey were completed
- £10 when a fault visit was required
- £30 once Questionnaire 2 and decommissioning were completed.

An additional £5 voucher was sent to all participants in November 2015 as an apology for unexpected delays at that stage of the study.

In the early stages of the project, Love2Shop vouchers were sent by post to participants, but in the later stages, they were sent as Amazon e-Vouchers, although vouchers continued to be sent by post for the small number of participants that preferred this delivery method. Of the 188 active participants after the equipment installation, 44 opted for vouchers by post, with 148 preferring e-vouchers.

4.10 Feedback

Feedback was provided to participants at the end of the study, in October 2018. Data from 114 homes from September 2015 to August 2016 were analysed in detail and used to provide property-specific feedback. Generic feedback was sent to all other active participants and to those that had only recently withdrawn. In total, 154 feedback booklets

were sent out (103[9] with specific feedback and 51 generic) and an example of each is shown in Appendix B.

4.11 Decommissioning

A total of 155 households remained active in the study at May 2018. At this point, homes were decommissioned, to safely remove any monitoring equipment. Homes that had withdrawn before this date were also decommissioned by removal or disposal of equipment on a case-by-case basis. In some cases, contact was made with the new occupants of a property, when a participant had moved house before full decommissioning. A total of 171 formal decommissions were completed. The remaining 17 of the 188 homes that had gas and/or electricity and temperature monitoring equipment could not be contacted, despite repeated attempts. For these homes, a final letter was sent by recorded delivery which confirmed the completion of the study and passed responsibility for the removal and disposal of any equipment to the participants. Satisfactory communication of the final decommissioning process to participants was approved by Loughborough University and its insurers.

Decommissioning involved a visit from a qualified electrician to remove the electricity monitor and collect the other monitoring equipment (temperature sensors, gateway, Z-wave signal booster and gas monitoring device). A certificate of minor works was completed to confirm the safe removal of the equipment, together with a checklist of removed items, which were sent to the participant. At the end of the trial, a final letter of thanks was sent from the Project Principal Investigator, by recorded delivery. Participants who had evohome heating controls fitted as part of the study were able to keep these in their home and these were not removed during the decommissioning process. Decommissioning of the 155 active homes started on 19th June 2018 and the final home was decommissioned on 13th November 2018 (Figure 25).

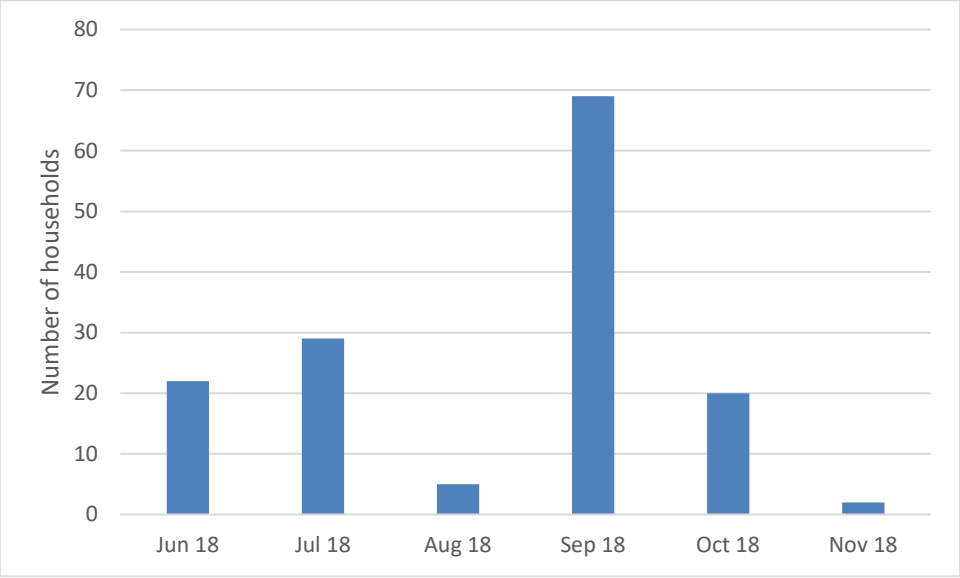

Figure 25. Timing of decommissioning of active homes from May 2018

Examples of the decommissioning letters are included in Appendix B.

[9] At this stage in the trial, 11 of the 114 participants had withdrawn so only 103 households received property-specific feedback.

5 References

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Appendix A: Pilot Study Materials

Pilot Initial Interest Letter
Pilot Information Sheet
Pilot Consent Form
Pilot Questionnaire
Pilot Temperature Sensor Letter
Pilot Interview 1 Script
Pilot Interview 2 Script
Pilot Battery Replacement Letter
Pilot Battery Replacement Instructions
Pilot Temperature Sensor Reactivation Instructions

Appendix B: Main Study Materials

Information Sheet
Initial Consent Form
Recruitment Interview Script
Home Energy Survey Details
Questionnaire 1
Pre-Intervention Questionnaire
Questionnaire 2
Generic Feedback Example
Property-Specific Feedback Example
Final Letter Example
Final Letter (Participants who withdrew early or moved) Example
Season's Greetings – Gateway Reminder