Utilizing Smart Home data to support the reduction of energy demand from space heating – insights from a UK field study

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Abstract

It is anticipated that the wider deployment of Smart Home systems will give building occupants improved control and automation capabilities over building conditions, services and equipment. These smart technologies will also provide numerous streams of data which could help to identify opportunities to reduce energy demand in homes. This paper explores this topic by focusing on data gathered from Smart Home systems, installed in a sample of five UK homes, which provide occupants with advanced zonal space heating control. Initial results suggest that Smart Home data can generate useful information to assist energy demand reduction; including the identification of excessive heat loss from specific rooms, periods of unoccupied heating, and heating system characteristics that lead to suboptimal heating patterns. Practical issues encountered during the field study highlight important social and contextual factors that can influence the quality of data recorded. These factors could potentially impede the wider adoption of Smart Home technologies with zonal heating functions. This work is continuing and the next steps are to calculate the energy savings which would result after data from Smart Home systems was used to identify inefficient homes, systems or practices.

Introduction

The UK government is committed to achieving a significant reduction in carbon dioxide emissions – an 80% reduction by 2050 in comparison to 1990 carbon dioxide emission levels [1]. It has been estimated that, in 2009, buildings accounted for around 38% of greenhouse gas emissions (by end-use) in the UK [2]. Therefore, measures to reduce energy consumption in buildings are considered as important methods to meet UK carbon reduction commitments [3, 4]. The UK's housing stock is comprised of approximately 27.6 million dwellings which are estimated to be responsible for around 29% of UK energy consumption [5]. Space heating is the largest energy end use in homes, accounting for around 62% of the average UK home's energy use and therefore provides a significant opportunity to achieve energy reductions [5]. At present, efforts to reduce energy demand for space heating in existing dwellings include policy initiatives designed to facilitate retrofits (e.g. the Green Deal), such as thermal upgrades (e.g. loft and wall insulation), more efficient heating systems, and improved heating controls [6]. In regard to the latter, the increased availability of wireless sensors and controls have enabled key elements of the 'Smart Home'[1] concept to be introduced into existing dwellings relatively easily and there is optimism that these technical developments could revolutionize the operation of heating systems; by providing improved efficiently through automation, as well as giving occupants the opportunity to control the use of energy remotely. For instance, recent research suggests that smart zonal heating controls could potentially reduce annual gas demand for space heating by 12% in many UK homes [9]. In addition to smarter controls, the numerous streams of data (e.g. energy and water consumption, environmental conditions, occupancy patterns) from Smart Homes may enable occupants to access more comprehensive and tailored information about daily energy use and information to support retrofit decisions; decisions that offer the long term energy demand reduction through changes made to buildings' built form (e.g. thermal upgrades) [10]. This paper explores this topic by evaluating the type and quality of information that can be derived from Smart Home data to support energy demand reduction in dwellings. More specifically, this paper focuses on technologies that provide advanced zonal space heating control and automation capabilities to investigate household heating patterns and opportunities to reduce space heating energy demand. The work draws on data gathered by the REFIT project (see acknowledgements for project details) from an ongoing 2.5 year field study in 20 UK homes.

[1] The term 'Smart Home' is used broadly to describe dwellings that incorporate a variety of information and communication technologies (ICTs), sensor networks and artificial intelligence to gather and utilize data (e.g. regarding occupants, building equipment, the physical environment) to undertake automated actions that optimize building operations and services [7, 8].

The next sections provide a brief overview of the types of space heating systems that are typically found in existing UK dwellings. The technologies and methods employed are then described. Initial results from the analysis of sensor data from five UK homes are then presented, followed by a description of practical insights that may influence the quality of data recorded. Finally, the results are discussed and preliminary conclusions are drawn.

UK central heating systems

The most common form of domestic space heating in the UK is from gas central heating systems [6]. At a basic level, these heating systems consist of a gas-fired boiler to heat water, which is pumped to wall mounted radiators in the rooms of the homes (see Figure 1). The system is usually controlled by a programmer/timer (often integrated into the boiler) which allows building occupants to automate heating schedules; modern systems will often allow more complex heating schedules to be set-up for different days of the week. However, the controls also enable occupants to override the heating schedules at any time. When a central heating system is in operation it will pump hot water to the radiators until a predefined temperature is reached. The temperature is frequently governed by a room thermostat (often located in a hallway or living room) which can be adjusted by building occupants; therefore, the temperature of heating throughout the dwelling is determined by the temperature in one location. When the set temperature is achieved, the boiler turns off; however, the pump will continue to propel hot water around the heating system, for a period of time, to ensure that hot water does not stagnate at the boiler. The boiler will only turn back on if the temperature falls below the set point temperature on the room thermostat.

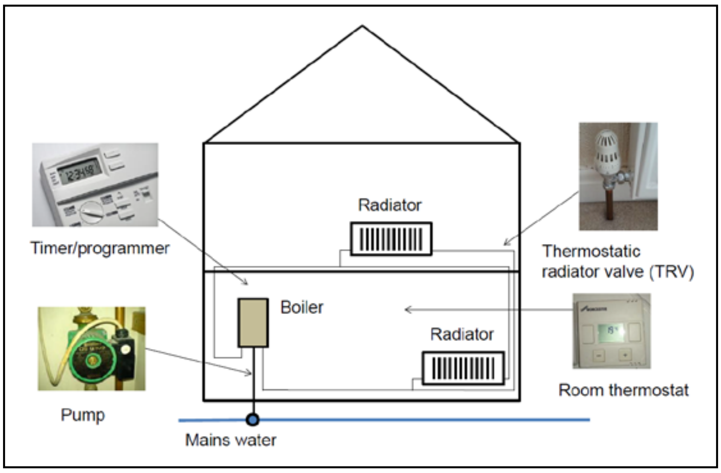

Figure 1: Schematic of a central heating system in a UK home (adapted from [6])

Another common heating control, in many UK homes, are thermostatic radiator valves (TRVs) which control the flow of hot water to individual radiators and thereby control the temperature of individual rooms. TRVs moderate the flow of hot water through the radiator, via a rotating control, by reacting to the local temperature. Although TRVs provide occupants with increased control, the temperature of individual rooms can also be influenced by other factors; such as internal gains (e.g. from appliances), the size of the radiator (i.e. oversized or undersized radiator), heat loss from the physical characteristics of the room (i.e. infiltration rate) and occupant behavior (e.g. window and door opening) [6]. Therefore, individual room temperatures can vary throughout a dwelling and can be very different from the temperature setting of the central heating system's room thermostat. As a result, the collection of Smart Home data about actual temperatures within individual rooms (and the temperature settings made by building occupants) could provide valuable information for energy demand reduction [10].

Methods

Smart Home technologies deployed

A range of Smart Home technologies have been installed in the REFIT project's sample of 20 homes. The procurement process was influenced by key requirements of the project which included: *Functionality* – the project required technologies that would be relatively simple to operate by the householders who have different technical and ICT abilities; *Reliability* – it was essential that the technologies could be relied upon to remain operational (e.g. maintain wireless connection) for the duration of the study. This was not only to ensure the collection of the best quality data possible, but also to minimize house visits to resolve technical difficulties; *Access to data* – remote access to data was important to minimize the number of home visits (a time consuming process to organize and an inconvenience for participants); *Established technologies* – the study sought to utilize existing technologies, widely available for households to purchase. This was partly to avoid technical difficulties with less developed technologies and also to use devices that were representative of those likely to be introduced more widely into UK homes in the short term.

Preliminary testing of a variety of Smart Home technologies was undertaken in test homes prior to the procurement process. However, the testing encountered technical difficulties using a unified system. Therefore, a pragmatic decision was made and two separate systems were installed in each of the study sample homes. These systems provided the homes with real-time feedback information and increased levels of control over the use of electricity, space heating and home security. The first of these systems consisted of Z-Wave Vera3™ controllers [11] connected to Current Cost [12] units which monitor whole house electricity consumption and electrical appliances. Additional Z-Wave smart plugs were installed to enable remote and automated control over connected appliances. The second system, and the focus of this paper, consisted of RWE Smarthome™ devices to control space heating and provide home security features. The details of the RWE system are outlined below.

RWE Smarthome™ system

The RWE Smarthome system provides monitoring and control functions for individual space heating radiators and provides home security capabilities. The system has been developed specifically for the German market by the large German Utility RWE [13]. Key reasons for its use in this study include: its secure and robust wireless propagation (868.3 MHz proprietary protocol); the capability for sensor data to be downloaded remotely from each device; devices can be controlled easily via a computer or laptop with a web browser and /or a smartphone application; and the user interface is comparatively straightforward to use by individuals with relatively limited ICT skills. Figures 2 and 3 show a screenshot of the RWE Smarthome user interface and a range of the sensors installed in the homes, respectively. The 'standard' system procured for each home consisted of the following devices (the number of devices is shown in brackets):

1. Central controller (1): this device communicates with the other RWE devices connected to the system. The device plugs into the back of a broadband router and acts as the gateway for the system's user interface which can be accessed via a computer's web browser and /or a smartphone app).

2. Radiator thermostat (9): the radiator control units allow individual radiators to be controlled remotely or by a rotating control on the device. The device collects data about 'nominal' temperature (i.e. temperature setting nominated by building occupants), 'actual' temperature (temperature measured by the device), and air humidity. When more than one Radiator thermostat is installed in a room (i.e. in rooms with more than one radiator) the devices synchronize so that heating provided by multiple radiators is done in unison.

3. Room thermostats (3): these devices provide an additional physical mechanism to control radiator temperatures in a particular room or zone. Radiator thermostats in a zone automatically synchronize with the Room thermostats.

4. Motion detector (interior) (6): these devices detect movement within a room (detection range of 12 metres). They also have an integrated brightness sensor to detect lighting levels.

5. Motion detector (exterior) (1): this is a weather proofed version of the interior motion detector.

6. Door/window sensor (6): these devices can be attached to a door or window to record opening and closing events.

7. Smoke detector/alarm (1): this device provides basic home security capabilities. The system enables the alarm to be triggered by the motion detectors and/or the contact sensors.

8. Wall-mounted transmitter (2): these wall mounted switches provide participants with physical devices to control the automation profiles set-up on the system. These devices can be fixed to walls and other flat surfaces. Data about their use is not recorded by the system.

9. Remote control (1): similar to the wall-mounted switches, the remote controls provide 8 buttons which can be configured to control the alarm and Radiator thermostats. Data about their use is not recorded by the system.

It should be noted that the RWE system works independently of the boiler and current room thermostat present in the home (it was designed to be 'plug and play' and does not require a qualified installer) and consequently there are times when the two sets of heating controls contradict each other. In addition to this although we have good data about the profiles used for individual radiator thermostats, but we do not have the corresponding data about central room thermostats or timer settings.

Figure 2: Screenshot of RWE Smarthome user interface via computer web browser

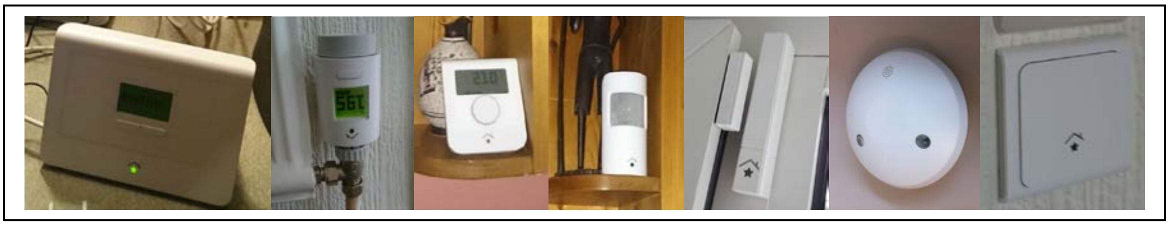

Figure 3: Example of RWE Smarthome devices – (from left to right) Central controller; Radiator thermostat; Room thermostat; Motion detector; Door/window contact sensor; Alarm; Wall mounted transmitter (switch)

The user interface facilitates the remote control of the smart devices and the activation of automation 'profiles' from any location, with Internet access, via a smartphone/tablet app or a computer with a web browser. When accessing the user interface via a computer it is possible to set up three main types of automation 'profiles': (1) *Time profiles:* enable the individual or multiple radiators to be controlled at designated time periods; (2) *Event profiles:* allow the alarm and radiator thermostats in rooms to be controlled by specified events; for example, using motion detectors to trigger the alarm (3) *Rule profiles:* logic-based profiles involving one or more conditions; for example, turning a radiator on or off at certain temperature and humidity levels when a window is open. A key feature of the system is that data are collected, managed and stored on a secure database server. These time-stamped data can be viewed via the user interface and downloaded as csv files. This includes 'actual' room temperature measured by the radiator thermostats and the 'nominal' temperature set by the building occupants. However, only one month's data are available to be downloaded at any one moment in time; data are continually overwritten so it is essential to download these data regularly or they will be lost. Although not a perfect solution (e.g. the householders' were required to learn how to use two different user interfaces, no integration between the two systems sensors), it allowed the field study to progress. This approach has also exposed the study participants to different Smart Home technologies and user interfaces, providing valuable data for social science research conducted by members of the project.

Field study sample and installation process

The REFIT project has recruited 20 homes, in the East Midlands region of the UK, to take part in a field study of Smart Home technologies. Five of these homes were selected for this initial data analysis to provide a subsample with different built forms and household types. Table 1 below provides a brief summary of the main characteristics of the chosen homes.

Table 1: Summary of five homes key socio-demographic characteristics

	H3	H10	H15	H19	H20
Built form	4 bedroom, detached house	3 bedroom, detached house	3 bedroom, semi-detached house	3 bedroom, semi-detached house	4 bedroom, detached house
Household type	Retired married couple	Married couple, dependent children	Lone parent, dependent child	Married couple, dependent children	Married couple, with non-dependent child
Number of occupants	Two adults (1 male, 1 female)	Two adults (1 male, 1 female), 2 children (male)	One adult (female), 1 child (male)	Two adults (1 male, 1 female), 2 children (male)	Three adults (1 male, 2 female)

The installation of the Smart Home equipment consisted of two key phases. In 2012-13, monitoring equipment was installed in the homes to collected baseline data about electricity and gas consumption and thermal temperatures in the homes. At this stage the Vera Z-Wave system was installed (excluding the *TKBHome* smart plugs) but occupants of the study homes were not given access to the system. In summer 2014, the 'standard' RWE Smarthome system acquired by the project (outlined in the previous section) was installed in the homes. The participants were also given access to the Vera Z-Wave system and the smart plugs were installed. Prior to the installation, a face-to-face meeting was conducted with each home to explain the equipment and discuss any concerns. Decisions about the placement of sensors were discussed at this 'pre-installation' meeting with guidance from members of the research team; for example, which radiators (if the homes had more than nine) and windows/doors were to have sensors attached. The participants were given the option to have sensors fixed in specific locations (i.e. motion detectors and smoke detectors/alarms are designed to be fixed to walls with screw fittings included with the sensors). In all the 20 homes, the participants requested that the sensors were not fixed in permanent positions at the installation so that they could be given time to experiment with the system and to avoid unnecessary damage to their home's interior decor. The participants were informed that they could either contact the research team to have them fixed by a contractor or fix the sensors themselves. Only one of the 20 homes contacted the research team to have them fixed in permanent locations and although some occupants fixed sensors themselves, many sensors have remained in 'unfixed' locations (e.g. Figure 2 shows a motion detector placed on a shelf). In most of the 20 homes, the installation was completed by the research team. However, on request, some participants were given the opportunity to install some of the equipment themselves; these were participants with higher than average technical abilities and a generally stronger interest in technology. In some cases (e.g. larger houses) extra devices were installed where deemed necessary for research purposes (e.g. extra Radiator thermostats). At least one member of the household was given a brief tutorial of the RWE and Vera Z-Wave systems, during the installation, and made aware of online guidance and instructions. Additional tuition was offered, however, in order to maintain the ‘real world’ conditions of the field study, the participants were encouraged to attempt to learn how to use the systems themselves.

Data analysis

This paper focuses on data collected during December 2014 from the subsample of five homes and concentrates on four key room types in each home: Kitchen; Lounge (living room); Bathroom; and one Bedroom. All the homes use gas central heating systems as their primary source of space heating. As mentioned previously, the positioning of the sensors was influenced by the number of sensors procured for the project, where the householders wanted the sensors positioned and physical characteristics of the homes (e.g. location of radiators). Table 2 indicates that Houses 3 and 20 did not have radiators in their kitchens. House 20 refrained from having contact sensors installed because they perceived little benefit from the functionality due to having an existing security system. Motion detectors were not installed in any bathrooms or bedrooms. Data were downloaded as csv files from the RWE server (via the web interface) and were processed and analyzed in Microsoft Excel. Data have been manually screened, but a full analysis is yet to be completed.

Table 2: Summary of RWE Smarthome sensors installed in the homes

RWE device	H3	H10	H15	H19	H20
Kitchen thermostat	0	1 radiator, 1 room	1 radiator, 1 room	1 radiator	0
Kitchen motion	1	1	2	1	1
Kitchen contact	1 door	1 door	2 door, 1 window	0	0
Lounge thermostat	1 radiator	2 radiator, 1 room	1 radiator, 1 room	1 radiator, 1 room	1 radiator, 1 room
Lounge motion	1	1	1	1	1
Lounge contact	1 door	1 door, 1 window	2 window	0	0
Bathroom thermostat	1 radiator	1 radiator	1 radiator	2 radiator	1 radiator
Bathroom contact	0	0	0	1 window	0
Bedroom thermostat	1 radiator, 1 room	1 radiator	1 radiator, 1 room	1 radiator	1 radiator, 1 room
Bedroom contact	2 window	0	0	1 window	0

Where ‘heating period’ values are presented (e.g. the average room temperature when a radiator is set to provide heat by an occupant), “cut off” temperatures were used, based on the occupants settings of the room and radiator thermostats, to determine periods of heating. For example, Figure 4 shows temperature data recorded in House 10’s kitchen by the RWE system and shows that two internal room temperature values are recorded: ‘nominal’ – the temperature setting nominated (i.e. set) by occupants; and ‘actual’ – the room temperature measured by the sensor(s). Although the radiator is set at 15°C for the majority of the day, in this case the radiator’s heating period would be considered to occur during the 19°C periods, in the morning and evening, and a “cut off” temperature of 16°C would be used. Figure 4 also illustrates a limitation of the system; it can be seen that the actual temperature dips below the nominal temperature in the morning and that the radiator is not on in the evening heating period. This is because the central heating system’s boiler has been turned off by the programmer or room thermostat which is not controlled by the radiator thermostats. It is also apparent during the midday hours that an additional source of heat (e.g. a heat gain from cooking or solar radiation) and/or heat from another room is resulting in a temperature increase despite the radiator having been turned off. Future work will conduct a detailed analysis of the data for the 20 homes over the full heating season. Internal temperature data are also being recorded in each of the dwellings' rooms with Hobo temperature data loggers to provide comparative data for the future analysis, these temperatures will also enable the RWE temperatures to be assessed for uncertainty, however, this data was not available at the time of publication. Consequently, there is still some uncertainty regarding the validity of the results and their interpretation must be done with caution, that said, much of the discussion of this paper is focused on heating patterns and not relative temperatures and therefore the data is still insightful.

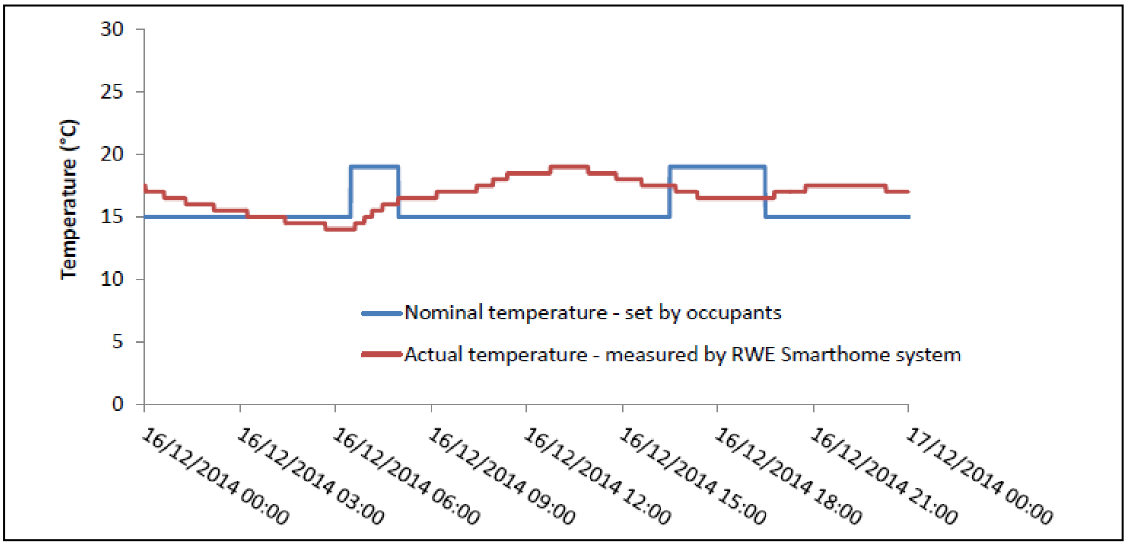

Figure 4 – Example of temperature data from the RWE system at House 10 showing nominal (or nominated) and actual (measured) temperature in a single room on the 16th December 2014

Initial results

This section provides results from the initial analysis of 'real world' data recorded at the five homes, in December 2014, for the kitchen, lounge, bathroom and a main bedroom. The first section provides average values for the heating periods (i.e. room temperature when a radiator is set to provide heat). The second section provides example profiles to illustrate potential opportunities for energy demand reduction that can be derived from Smart Home data.

Average internal room temperatures

Table 3 provides average values for 'nominal' (the setting nominated by occupants) and 'actual' (measured) internal room temperatures. It is apparent that the overall average values for the actual temperatures in the sample's kitchens and bathrooms fall below the nominal temperatures set by the occupants. In two kitchens (House 10 and House 15), the temperature is around 2°C lower than the nominal temperature. It is not possible, at this stage of the analysis, to definitively explain the differences between nominal and actual temperatures in these rooms, however it is of interest as it highlights the disconnect between the settings that occupants use and what actually happens. For example, House 10's kitchen is a large space (connected to a hallway) and this built form may prevent the room's radiator from heating this space effectively, particularly during periods of cold external temperature. In House 15, the nominal temperature of the kitchen radiator thermostat was set continuously at 21°C but the heating system was rarely able to heat the room to this temperature. House 15's bathroom, which particularly influenced the overall average values, had its nominal temperature set continuously at 26°C; this temperature was well above the boiler's room thermostat setting. Consequently, the nominal temperature was never reached and the radiator valve was continuously open. As a result, opportunities to use the RWE system to reduce periods of 'unnecessary' heating in House 15's bathroom were not undertaken by the occupants. The range of nominal and actual temperatures shown in Table 3 also indicates a significant amount of variation which is not clear from the average values alone. In order to gain a deeper insight the following section explores the data in more detail.

Table 3: Average and range of nominal (as set by the user profile) and actual internal room temperatures recorded during heating periods

	H3	H10	H15	H19	H20	Average
Kitchen nominal (°C)	N/A	19.2 (30.0-19.0)	21 (21.0-21.0)	18.0 (21.5-14.5)	N/A	19.4
Kitchen actual (°C)	N/A	17.4 (20.5-12.0)	17.3 (21.5-13.5)	18.5 (24.0-8.0)	N/A	17.7
Difference (%)	N/A	90.6	82.4	102.8	N/A	91.2
Lounge nominal (°C)	19.0 (22.0-19.0)	19.0 (26.0-17.0)	20.4 (26.5-19.0)	17.9 (22.0-12.5)	18.5 (22.0-17.0)	19.0
Lounge actual (°C)	19.4 (22.5-13.0)	19.3 (22.0-15.0)	18.1 (24.0-14.0)	18.3 (26.5-10.5)	19.2 (23.5-16.0)	18.9
Difference (%)	102.1	101.6	88.7	102.2	103.8	99.5
Bathroom nominal (°C)	19.0 (19.0-19.0)	18.0 (20.0-18.0)	26.0 (26.0-26.0)	17.0 (23.5-15.0)	18.5 (22.0-18.0)	19.7
Bathroom actual (°C)	18.0 (21.5-14.5)	18.4 (22.0-13.5)	18.1 (24.0-12.5)	17.6 (23.0-14.5)	18.8 (25.0-14.5)	18.2
Difference (%)	94.7	102.2	69.6	103.5	101.6	92.4
Bedroom nominal (°C)	19.0 (19.0-19.0)	19.1 (30.0-19.0)	17.7 (22.5-16.0)	17.3 (21.5-15.0)	13.7 (30.0-12.0)	17.3
Bedroom actual (°C)	17.6 (20.0-14.5)	19.6 (23.5-13.0)	18.3 (23.5-15.0)	17.3 (23.0-6.5)	16.0 (21.0-6.5)	17.8
Difference (%)	94.2	102.6	103.4	100.0	116.8	102.9

Space heating profiles

The manual screening of the Smart Home data and the production of profiles to explore patterns of space heating led to identification of some potential opportunities to reduce energy demand and improve occupants' thermal comfort. The significance of these potential opportunities to energy reduction in the homes is yet to be fully understood; for example, the initial analysis does not take account of external temperatures, but the examples highlight areas where there is energy saveing potential.

Heating system characteristics – set-point overshoot and heating lag

Figure 5 provides a simple example of a 24 hour heating profile for House 10's bedroom gained with the data from a radiator thermostat; the nominal temperature in this example was automated through the use of the RWE systems' 'Time' profile function. It is clear that the room temperature remains above the minimum 15°C nominal setting for the 24 hours and that the humidity in the room generally decreases as actual room temperature increases. Importantly, the actual temperature in the room is often above the 19°C maximum setting during heating periods; this is when the residual heat within the radiator continues to heat the room despite the radiator valve being turned off. Analysis of other rooms in this dwelling suggests that the morning heating period (set using the timer on the boiler) is around two hours, so some of the additional heat which continues to make the room overheat could also be from other rooms. However, the 'set-point overshoot' in this room suggests that the occupants may also be able to reduce their energy use by altering the nominal time periods to focus the heating when it is required (i.e. account for the heating after the valve is turned off) or by reducing the nominal temperature setting (e.g. from 19°C to 17°C) which may be able to reduce the effects of the set-point overshoot.

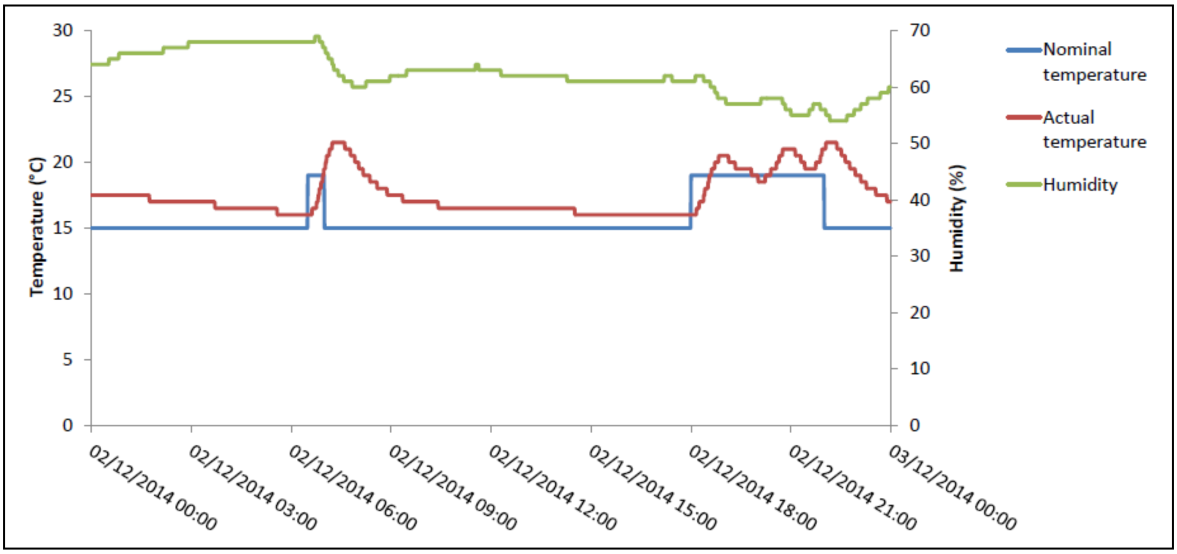

Figure 5: Heating profile recorded by RWE Smarthome system for House 10's bedroom on the 2nd December 2014

It is also apparent that there is a delay, or 'heating lag', between the radiator valve turning on and the room reaching the nominated temperature (i.e. the time taken for the room to increase from the 15°C to 19°C nominal temperature). An optimized start would help this but is not available in the system used here. This is particularly pronounced for the heating period between 0630 and 0700 where it can be seen that the room only reaches 19°C at around 0700 and the temperature continues to rise until it reaches a peak of 22°C (3°C higher than the nominal temperature) an hour after the nominal temperature is set to 15°C. In terms of thermal comfort, the occupants may need to incorporate the heating and cooling lags into their use of the RWE system to ensure their nominal temperature is met for the entire time period. Occupants may already be taking this heating characteristic into account because the time it takes to heat up the room would be similar to the use of conventional heating controls. Data regarding the thermal comfort of the occupants or information about why they turn their heating on at certain times were not collected; consequently, the research team is unaware whether the occupants are incorporating the heating characteristics into the automation. If the occupants are unaware, then this simple feedback could help them to improve their thermal comfort. A less complex solution, from the occupant's perspective, would be to introduce more intelligent control capabilities into the Smart Home system's automation (i.e. control algorithms) so that the system can respond to the heating system characteristics (i.e. set-point overshoot and heating lag) to meet occupants nominal settings automatically. This increased intelligence would save energy and would be more intuitive for the user.

Identifying excessive heat loss

The previous example highlighted that feedback could help occupants understand how their heating system operates in a particular room. Further insight can also be gained by examining the rate at which the actual temperature increases and decreases. For instance, in Figure 5, the relatively rapid rate at which the room heats in the morning may indicate that the heating system is functioning efficiently. In contrast, the rate at which the heat is lost from the room may indicate whether the room is sufficiently insulated. For example, Figure 6 shows a 24 hour heating period for House 19's lounge which uses the RWE system's 'Time' profile function to automate the room's heating. The temperature in this space did not drop significantly during the night and the morning heating period may be unnecessary given that the room appears to retain the heat throughout the day. This slow rate of heat loss (relative to the other dwellings shown here) may indicate that the room is well insulated; assuming that no additional heat source is being used or that these measurements were not taken on a mild day. Interestingly, the actual temperature during the evening heating period does not reach the nominal temperature set by the occupants and there is a slow rate of temperature increase. This is a pattern that often appeared in the month's data for this room. This could suggest that there may be a regular 'temporary' form of heat loss (e.g. an internal door or a window is open) or that the heating system is unable to respond and provide the level of heat required by the occupants – i.e. the radiators are undersized for the space or a radiator is not working correctly (e.g. flow of water is inhibited by residue). A conversation with one of the occupants highlighted that the installer of the radiator had reservations that it was not large enough to heat the space; however, the occupants preferred the slim dimensions of the radiator and progressed with its installation.

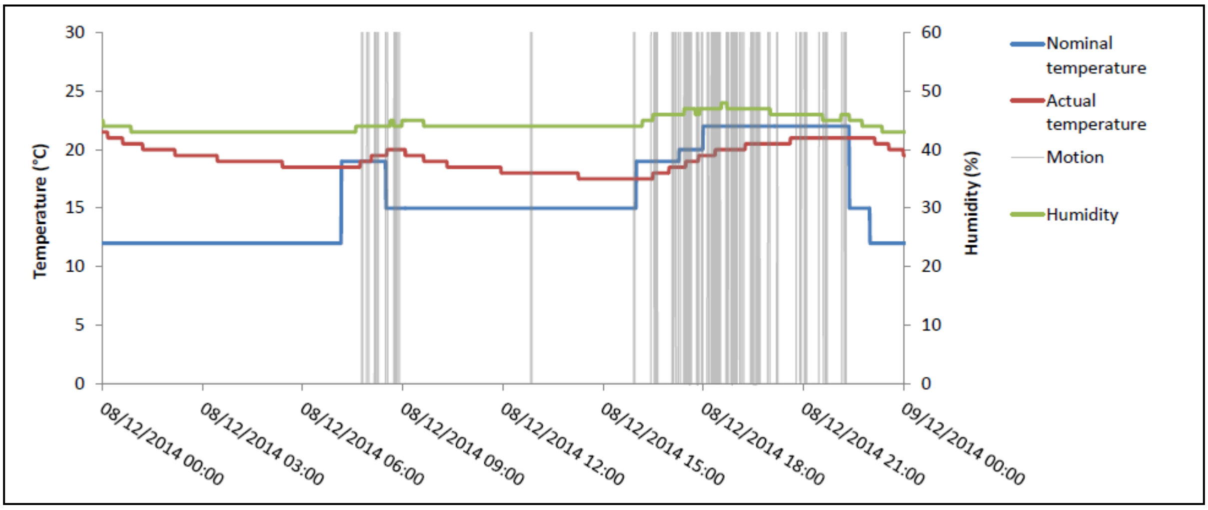

Figure 6: Heating profile recorded by RWE Smarthome system for House 19's lounge on the 19th December 2014

Figure 7 shows a 48 hour heating profile for House 3's lounge; the RWE's 'Time' profile function used to automate the nominal temperature is clearly discernable. Similar to the bedroom at House 10 (see Figure 5), there is a 'set-point overshoot' leading to measured temperatures, during heating periods, being in excess of the temperature nominated by the occupants. A 'heating lag' is also observable which leads to a delay in the room reaching its nominal temperature. The adjustment of the automation (i.e. reduce the nominal temperature and period of heating) could potentially improve occupants comfort and/or reduce the amount of energy used for heating the room. However, in contrast to House 19 (see Figure 6), the faster rate of heating and heat loss may indicate: (1) the heating system is performing efficiently in the room (i.e. reaching the nominal temperature quickly); (2) thermal upgrades (e.g. insulation, draught excluders) or changes in occupant behavior (e.g. closing internal doors) could be an opportunity to reduce the rate of heat loss and retain heat in the room.

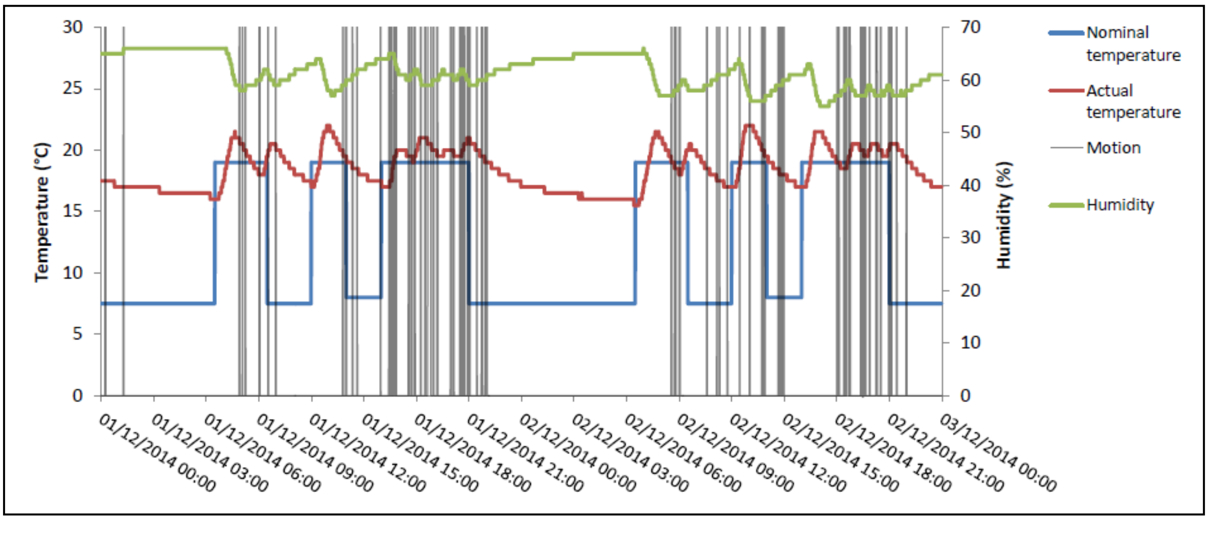

Figure 7: Heating profile recorded by RWE Smarthome system for House 3's lounge on the 1st and 2nd December 2014

These potential opportunities are not clear from the average values shown in Table 3 (nominal and actual values are similar for both House 3 and House 19 and could easily be interpreted to indicate both rooms are performing efficiently). However, as will be discussed later, any interpretation of the information must be done carefully as other contextual issues may be influencing the data recorded.

Unoccupied heating

Figure 6 and 7 also provide information about occupancy patterns gained from motion sensors. The general occupancy recorded in House 19 (Figure 6) fits relatively well with the automation profile. The main unoccupied heating occurs from around 07:10 to 07:50 which may be time factored into the profile due to the delay in the room reaching its nominal temperature. Although not excessive, data from House 3 (Figure 7) provides an example of periods of heating without occupancy in the room – e.g. early afternoon on 01/12/2014 – and potential opportunities to reduce energy use. However, this is a complex issue because it takes time (numerous hours in some cases) to heat a room to the nominal temperature. Therefore, it is not always possible to heat a room only when it is occupied. Nevertheless, it is possible to identify heating periods which are regularly unoccupied and, as above, this data could be used by occupants to change their heating practices and alter automation settings.

Contextual factors and limitations of sensor data

Although the above figures may infer information about the characteristics of heating systems and/or potential opportunities for energy saving, the examples also highlight the need to understand the context in which data is collected. For instance, the built form of House 3 may play an important role for the observed patterns of heating (see Figure 7). In this dwelling the lounge is connected to the dining room by an opening that contains a two sided fireplace; consequently, the temperature in the lounge will be influenced by the flow of air from other parts of the building. Further influences on the lounge's internal temperature relate to the positioning of furniture in the room and other 'energy saving' devices. Figure 8a shows that a sofa next to the radiator which may influence the flow of air from the radiator and that a 'radiator booster' has been installed by the occupants – a battery powered device used to increase the circulation of warm air from the radiator. Another factor reported by householders, was the drying of clothes on radiators (see Figure 8b). These examples highlight that to gain a more complete understanding of the data recorded by Smart Home systems, it is essential to appreciate other contextual factors that may exist in a home. Thus, simple interpretations of data must be viewed with caution.

Figure 8a and 8b: Examples of contextual influences on radiators – (left) House 3's lounge radiator with a sofa in close proximity and a battery powered radiator booster; (right) Radiator covered by large bath towel at a study home

Another limitation to the analysis relates to the number of sensors installed in the homes. For example, Figure 9 shows a heating profile over 24 hours in House 3's main bedroom located on the first floor; it is apparent that the same RWE 'Time' profile applied to the lounge (see Figure 7) is used to automate the heating of the bedroom. The actual measured temperature remains relatively constant throughout the day suggesting that the room retains heat efficiently. However, it is apparent that there is a difference of around 0.5°C between the nominal and actual temperatures; this may be measurement error and will be investigated in future analysis (previous studies have reported sensor uncertainty at approximately 0.5°C [6]). Without occupancy data for this room (a motion detector was not installed in the bedroom) it is not clear how often the room was occupied during the day but the opening and closing of a window indicates some activity. An observable decrease in internal room temperature occurs when the bedroom window was open. Despite installing contact sensors in the majority of the homes, the initial data analysis has experienced difficulties linking door and window opening events directly to temperatures in the building. In addition, the contact sensor shown in

Figure 9 provides no indication of how wide open the window was during this period; important data if attempting to evaluate the thermal characteristics of the room.

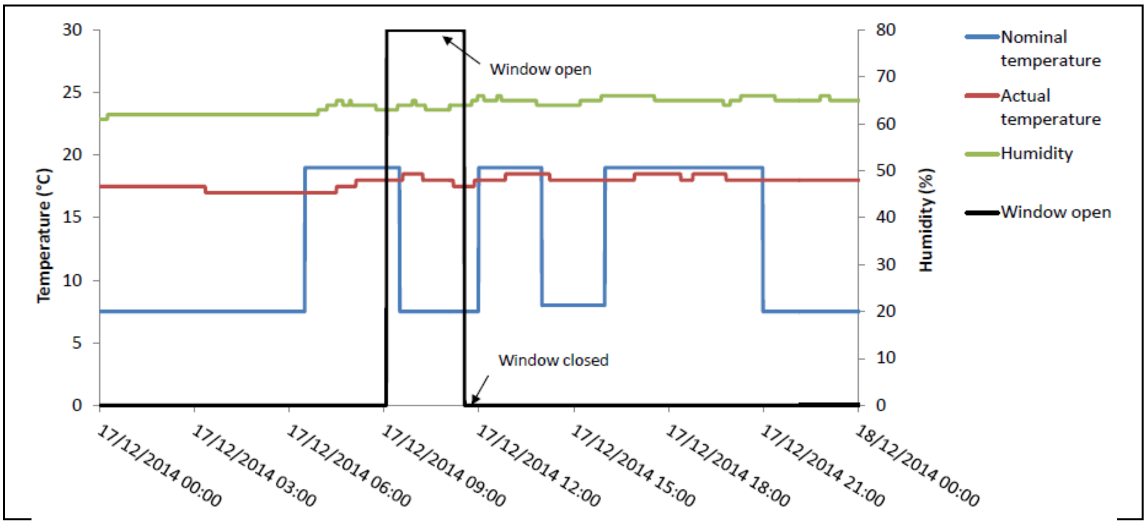

Figure 9: Heating profile recorded by RWE Smarthome system for House 3's main bedroom on the 17th December 2014

The limited number of contact sensors installed in each individual home (n=6) means that it is impossible to know whether other windows and internal doors are open or closed over a given period and thereby influencing the temperature measurements recorded. To gather these data would require all windows and internal and external doors to be monitored. Furthermore, the use of motion detectors in all rooms would enable a more detailed assessment of unoccupied heating in each room. This installation approach was too expensive for this study to undertake and highlights that comprehensive sensor installations would enable a better interpretation of the data to be made.

Practical insights

The previous section has highlighted that contextual issues need to be understood in order to gain a more complete understanding of Smart Home data. The practicalities of conducting the field study reflect this finding and in some cases such issues have significantly influenced the quality of data gained from the Smart Home systems. For instance, a limitation associated to the use of the RWE system in the UK (the system was designed for use in German dwellings) was the lack of data gathered about occupants' control of boilers and associated programmers and room thermostats; these data would provide a much more comprehensive understanding about patterns of heating but as stated above are not available for this analysis. The accuracy and precision of the measurements recorded by the 'off the shelf' equipment is also fundamentally important and still to be assessed; poor accuracy could lead to incorrect interpretations and result in inappropriate (and potentially counterproductive) decisions being made to reduce energy demand. As mentioned previously, the majority of the motion detectors were not positioned in fixed locations which presents the possibility that devices could be moved by participants or obstructed by household objects. Importantly, the maintenance of the RWE system relies on occupants replacing batteries in the sensors, performing software and firmware updates, and managing the occasional loss of wireless communications. The neglect of this type of maintenance has occurred in some of the 20 homes during the study, often due to individuals' limited technical knowledge or lack of engagement with the Smart Home systems. As a result, these issues have led to periods of less that optimal data in some of the homes (e.g. sensors not in operation).

Social and contextual issues could also influence the adoption of the technologies. Using Smart Home systems appears to require much higher levels of engagement from building occupants, in comparison to the use of standard TRVs, and occupants will likely require new technical skills to manage Smart Home systems. Many existing building infrastructures will also likely require infrastructural upgrades. The field study often experienced limited access to Ethernet sockets on routers (and available mains power sockets) due to exiting ICT equipment in the dwellings. Importantly, many of the homes required upgrades to their heating system's radiator valves which were often old and/or defective (e.g. corroded, immovable valve pins) or incompatible with the RWE radiator thermostats (e.g. radiator valves of low manufacturing quality were often incompatible). The replacement of these valves required the services of a plumber at 13 of the 20 homes; on average the cost was around £545 for each of the 13 homes. This additional cost to the purchasing a Smart Home system may present too higher price for many homeowners.

Conclusions

The initial results presented in this paper suggest that data from Smart Home systems have the potential to inform attempts to reduce energy demand from the use of space heating. The examples used in this paper illustrate three potential areas where data from the increased uptake of Smart Home sensors could be used to show where energy can be saved in homes.

(1) *Heating system characteristics – set-point overshoot and heating lag*: these characteristics resulted in rooms being heated to higher temperatures and for longer than the automation set by the occupants. A more accessible and user-friendly form of feedback (e.g. web application) could help occupants to evaluate their heating patterns more easily and optimize their automation profiles accordingly. Alternatively, as Smart Home heating controls become more 'intelligent' the systems will learn to account for these characteristics so that occupant's automation profiles are heated without human intervention; (2) *Identifying excessive heat loss*: the rate of heating and cooling observed from the temperature data could potentially be used to assess heat loss and inform thermal upgrades (e.g. insulation, draught excluders, etc.) or behavior change (e.g. close windows or internal doors). In terms of thermal comfort, these data could also be used to assess the performance of a heating system (e.g. whether radiators are a sufficient size to heat a space or malfunctioning). In the UK, products are now available that use algorithms to estimate a dwellings insulation levels and the performance of its heating systems based on the rate of changes in internal temperature (see [14]). Similar algorithms could be developed to assess the performance of individual rooms within a dwelling. (3) *Unoccupied heating* – although a complex issue, it is possible to identify heating periods which are regularly unoccupied. This information could be used by occupants to change their heating practices or use technologies to automatically reduce heating periods based on occupancy patterns.

The initial results also suggest that without the widespread installation of sensors (e.g. all windows, internal doors, occupancy in all rooms) a comprehensive understanding of influences on a home's heating patterns cannot be gained – i.e. the data can raise as many questions as answers, perhaps a more pertinent question is what are the most important things to measure in a home? Importantly, the work suggests that the evaluation of Smart Home data requires an understanding of social and contextual influences on space heating within a dwelling (e.g. ventilation behavior, built form, etc.). If Smart Home data were used to inform retrofit decisions, by an independent advisor, it would be essential to involve the occupants in the assessment process. The quality of data provided by Smart Home systems is also fundamentally influenced by social and contextual factors (e.g. sensor placements, maintenance of the system, etc.) and such issues may have the potential to influence the wider adoption of Smart Home technologies (e.g. the financial cost of upgrading heating systems). It has been highlighted elsewhere that research into Smart Homes has frequently taken a technological standpoint [15]. Further research is required to explore the Smart Home concept from a user perspective; this is an approach that the REFIT project is pursuing through ongoing research. Future work also intends to develop analytical techniques to conduct a more systematic evaluation of this dataset which will include an assessment of the energy saving potential of the systems installed and where these systems could be improved with more intelligent controls.

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