Sensors, sense-making and sensitivities: UK household experiences with a feedback display on energy consumption and indoor environmental conditions.

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Abstract

Smart metering of domestic energy use allows consumer feedback through in-home displays (IHDs), websites or smart phone apps. Research has illustrated the need for additional 'sense-making' information to help households make informed energy-related decisions. This study investigates how household members respond when energy consumption data is integrated with information on indoor environmental conditions (IECs) and coupled with advice on energy saving actions. An integrated system of energy meters and IEC sensors was trialled in 19 predominantly social housing properties in the Midlands (England). Households were provided with a tablet computer and feedback was provided via a dedicated 'Energy Dashboard' web-based software application (app). The app was designed in collaboration with the social housing provider to display electricity and gas consumption data as well as data on three IECs: relative humidity, carbon dioxide and temperature. This paper draws on the findings from two rounds of semi-structured interviews with participants. All respondents using the app reported that they made use of the IEC data within the sense-making process, finding temperature and humidity to be useful in linking energy consumption, activities and household conditions. Interpretation of IEC data tended to increase with time as understanding increased. However, different users 'noticed', 'interpreted' and 'enacted' information differently as they integrated this with other sources of information, such as feedback from household members and experiential knowledge. The findings suggest that, whilst incorporating greater contextual information, such as IECs, into feedback displays can help users make sense of domestic energy consumption, the outcomes of the sense-making process will be different for different households. Nevertheless, the provision of such information appears to support householders to make decisions about their energy management that they feel appropriate for their household's wellbeing needs, within the bounds of their agency.

Keywords

Energy feedback; energy consumption; sense-making; household trial.

1.0 Introduction

The replacement of analogue energy meters by smart meters is making it possible for consumers to view real-time and historic domestic energy consumption data through web-based applications or dedicated In-Home Displays (IHDs) (Darby, 2010). These feedback displays have been described as “drivers of revolutionary change” in the way information on energy use is provided (Faruqui et al., 2010, p.1599). By making energy ‘visible’, the expectation is that feedback displays can help people to connect their energy consumption with particular behaviours, raising awareness of energy usage, and, ultimately, reducing energy wastage (Boomsma et al., 2016; Darby, 2006; Hargreaves et al., 2010). Driven by these expectations, the UK Government has mandated that all customers who have smart meters installed in their homes and small businesses should also be offered an energy feedback IHD, to “help consumers understand and change their energy usage, reducing bills and carbon dioxide emissions” (Ofgem, 2017, p.1).' The Government has aimed to have 53 million smart meters installed in homes and small businesses by the end of 2020 (Smart Energy GB, 2018). In addition to providing (near) real-time and historic electricity and gas consumption data in kWh, these IHDs must also present energy consumption data as a monetary cost, alongside the consumer’s ‘active tariff price’, and on pre-payment meters, information about debt or credit levels (BEIS, 2017).

An observed limitation of many energy feedback displays is the lack of contextual or “sense-making” information to support decisions about making lifestyle changes related to energy use (Buchanan et al, 2015, p.92). For example, it has been suggested that accurate and timely energy consumption data have the potential to help consumers “reduce the cost of comfort” (Darby, 2012, p.98), but a lack of information on indoor environmental conditions (IECs) within the home, such as temperature, humidity and air pollutant levels, makes it more difficult for individuals to connect changes in energy consumption with changes in comfort. Providing feedback on IECs, we suggest, has the potential not only to allow contextualisation of energy feedback but may also encourage consumers initially more interested in IEC data to take an interest in their related energy consumption. Combined energy metering and environmental monitoring systems are now widely applied in custom-built smart, low energy buildings (Ahmad et al., 2016), but there is a lack of studies that have investigated how these systems become incorporated into everyday household activities and sense-making processes in ordinary homes.

In this paper, we report on an *in situ* seven-month trial of a novel integrated energy meter and IEC sensor system and custom-designed, app-based feedback display with 19 households in the Midlands of England, 17 of which were social housing residents. The aim of the intervention was not necessarily to reduce energy consumption, but rather to explore whether the feedback display could support households in domestic energy management. In this paper, drawing on the findings from two rounds of semi-structured interviews with participants, we use a sense-making perspective to analyse how the feedback display was used in practice (both initially and over time) by different households, and to consider the potential utility of integrating IECs in a custom-designed energy feedback display, along with energy consumption data.

2.0 Making sense of energy management

2.1 Evidence from energy feedback trials

There is significant evidence to suggest that feedback devices have the *potential* to lead to a reduction in household energy consumption, and that this potential is increasing as feedback technology becomes increasingly sophisticated, for example, allowing for direct, real-time, disaggregated electricity and gas consumption feedback. In an extensive 2010 review of the results of 57 feedback initiatives conducted between 1976 and 2009, Ehrhardt-Martinez et al found that all forms of energy feedback (both retrospective and (near) real-time) resulted in a reduction in household energy consumption, with average savings across trials between 5.2 and 13.7% depending on the type of feedback. However, they also found significant variation in the outcomes of the trials they reviewed, with energy savings from 'aggregated real-time feedback' devices (like the IHDs being issued through the UK smart meter roll-out) being particularly variable, ranging between -5.5% and 32%. This variability is echoed by the findings of a review of 30 IHD trials, in which Stromback et al (2013) found energy savings from IHDs ranged from 3% to 19%.

As well as differences in the type of feedback provided and the type of feedback device, trials vary in sample size and participant recruitment (Kendel et al, 2017; Darby, 2006). Across the cohort of trials that Ehrhardt-Martinez et al (2010) reviewed, short (6 months or less), small scale (100 or fewer participants) trials delivered the biggest average savings (13.3%), around double that of larger trials, whether long or short. Similarly, McKerracher and Torriti (2013) in their analysis of the results of 33 more recent IHD trials, found larger sample sizes to be correlated with lower energy saving effects. As IHD trials have been increasing in size over time, this meant that more recent trials (conducted since 2005) gave much lower electricity conservation results. McKerracher and Torriti conclude that expected electricity savings from IHDs should be revised down to 3-5%. Some recent trials have even found that 'energy consumption only' IHD feedback has no significant impact on energy use at all (e.g. Nilsson et al., 2014; Schultz et al., 2015). It should also be noted that findings relating to IHDs specifically, may not translate to web-based interfaces which have to be actively opened rather than being on constant display (Smale et al., 2019) – although IHDs may also be kept out of sight (Hargreaves et al, 2010).

In short, better quality studies have consistently found average energy savings from energy consumption feedback to be a few percentage points at best. Buchanan et al. (2015) conclude that “the evidence that there is, does not make a compelling case for the efficacy of feedback in general in reducing energy consumption” (pp.90-91). This observed unreliability of energy feedback to produce energy savings lends weight to arguments that energy consumption is highly context dependent (Kendel et al, 2017). Similarly, Ehrhadt-Martinez et al. conclude that the most effective forms of feedback are likely to be those that “provide consumers with timely and detailed information that is presented in multiple ways, tailored to the consumer, and contextualised to provide meaning and motivation” (2010, p.*v*). To ascertain what helps to provide this “meaning and motivation”, we need to consider that people do not generally make explicit decisions about energy use; rather they are engaged in activities and routines that happen to consume energy (Shove, 2003; Boomsma et al., 2016). Engaging with users at the design stage, tailored installation and training and adding functionality on demand and in stages, is likely to be more successful than a blanket roll-out of one-size-fits-all feedback devices. Finally, there is a need for greater understanding about what happens to feedback devices, whether IHDs or apps, when they reach the home environment: exactly how they benefit the user(s), and how they become incorporated into domestic life and decision-making (Buchanan et al. 2014; Hargreaves et al. 2015; Strengers 2013; Wilson et al., 2015).

2.2 Sense-making

The concept of ‘sense-making’ provides a useful theoretical lens through which to consider the ways people respond to information such as energy use feedback (and other information that could be displayed on an IHD or app, such as IECs). Although variably defined and used, sense-making can be understood as involving “not only what is commonly called cognition, but also emotions, intuitions, spiritual hunches, and other ways in which humans are assumed to make sense of their worlds, both internal and external” (Dervin and Naumer, 2009, p.877). A sense-making approach rejects the notion of information as a static, external input to logical cognitive processing (Savolainen, 2006) and, instead, conceives of information as malleable, moulded according to different needs, contexts, and uses. Knowledge gained from formal sources of information is integrated with knowledge gleaned informally in the course of everyday life experiences and with an individual’s pre-existing knowledge, to create new understandings and meaning (Kuhlthau, 1991). Fundamentally, “sensemaking is about the interplay of action and interpretation rather than the influence of evaluation on choice” (Weick et al, 2005, p.409). The ‘information explosion’ of recent decades has highlighted the importance of information seeking and sense-making processes, with rising interest in how the massive amounts of data now available to individuals can be used to provide useful insight and support appropriate action (Pirolli and Russell, 2011).

Three interrelated constituent processes of sensemaking have been identified in the literature: noticing (or creating); interpreting; and enacting (Maitlis and Christianson, 2014; Sandberg and Tsoukas, 2015). These three processes are entangled and iterative. Whilst we address each separately in the following subsections for illustrative purposes, in practice, it is often not possible to draw distinct lines between these processes.

2.2.1 Noticing

Sensemaking is initially triggered by something that interrupts ongoing activities and habits, such as the introduction of a new policy or technology (Sandberg and Tsoukas, 2015). The trigger acts at a very early stage in information processing and constitutes the process of noticing, also sometimes referred to as a process of ‘creation’ because, in responding to these cues, individuals *create* an initial sense of the situation in need of interpretation (Sandberg and Tsoukas, 2015). Given a limited capacity for assimilating new information, they do this by selectively engaging with information that connects to their existing understanding (Kuhlthau, 1991). Different individuals may therefore notice different features depending on their existing knowledge and experience.

Energy feedback device designs can influence this process of noticing. For example, there is evidence that for those that use traffic light colours, the colour red when used to indicate that an appliance with a relatively high energy demand is currently in use, may be a trigger for urgent and immediate action to decrease electricity use, whereas green and amber may not trigger the same response, even though, over time, this appliance might use more electricity (Strengers, 2011). Here, web- and app- based energy dashboards may have an advantage over IHDs, because although they require a little more active participation from the user, they allow more nuanced designs and features (Bartram, 2015), which may help direct users’ attention in the early stages of the sense-making process.

The IHDs being offered to UK households are required to display energy consumption in monetary terms (DBEIS, 2017), as government commissioned research concluded that displays in pounds and pence were “more meaningful and effective as a prompt to behaviour change than display in kWh which was [found to be] a largely meaningless concept” (Navigator, 2012, p.3). However, the use of monetary metrics to support consumer sensemaking has also been criticised: there is evidence that emphasising financial savings can reduce consumers’ attention to the environmental impacts of energy use, so that saving money is the only trigger (Schwartz et al, 2015). Moreover, it has been argued that providing information on energy use in the form of (near) real-time monetary cost can be stressful for low income households or those living in fuel poverty, and may trigger decisions to be made which put saving money over comfort, or even risk wellbeing (Boomsma et al, 2017). For example, money may be saved by under-heating or keeping windows closed , leading to rising levels of humidity and CO_2, which can have a negative impact on respiratory health (Bone et al, 2010).

2.2.2 Interpreting

Once sensemaking has been triggered, a more active process is initiated, in which different sources of information are identified and drawn together to form a more complete sense of the situation (Kuhlthau, 1991). As 72% of UK households consist of more than one person (ONS 2017), domestic energy consumption is typically a social and collective process (Hargreaves et al. 2010). However, despite the collaborative nature of household energy management, several studies have found there is usually just one main feedback device user in the household (e.g. Foulds et al. 2017; Hargreaves et al. 2013; Schwartz et al. 2013), with some finding this to typically be a man (Grønhøj and Thøgersen 2011; Hargreaves et al. 2010; cf Strengers, 2014). This has evident implications for the sense-making process at the household level. Whilst Hargreaves et al (2010) observed that it was rare for energy data to be analysed collectively by the household, household members who do not engage with the feedback display will inevitably be brought into the interpretation process.

There is evidence that household members account for the comfort and happiness of others in the household within processes of interpretation (and the ensuing enactment). For example, studies have found evidence of decision makers in the household prioritising the needs of children (Gibbons and Singler 2008), elderly or less well household members, pets (Willand and Horne 2018) and guests (Groves et al 2017; Hitchings and Day, 2011), whilst the needs of less favoured others can also be side-lined (Willand and Horne 2018). Specific needs and relationships within the household therefore are likely to have a significant impact on how information is interpreted.

The primary device user may also become a channel through which energy feedback information is passed on to other household members (Schwartz et al, 2013) – either in words or actions – with an intention to effect change; a process sometimes referred to as 'sensegiving' (Rouleau, 2005). For example, it has been found that primary users of the feedback system may adopt an energy enforcement or surveillance role within the household (Hargreaves et al, 2010; Schwartz et al, 2013).

2.2.3 Enacting

Finally, the enactment process involves acting on the more complete sense made of the intervention. As the initial actions taken by the actors become part of the environment with which they engage, enactment (i.e. the further actions taken by actors) may lead to further iterations of the three processes, until “sense and action are in sync again” (Sandberg and Tsoukas, 2015, p.S14).

Acting on the sense that has been made of energy feedback depends upon (perceived and actual) capacity for change. Several studies have concluded that certain actions around the home are, or become, ‘non-negotiable’. This can be for a variety of reasons, such as, they save time (Head et al. 2016), they are perceived not to use much energy (Nilsson et al., 2014), or they are deemed essential for a comfortable life (Hargreaves et al., 2010). Strengers (2011) found that things that simply ‘needed to be done’ were not reflected upon, with users’ focus instead being on actions that were perceived as wasteful.

A person’s agency to act on energy consumption data is also limited by their resources (time and capital) and living circumstances (Darby, 2010). Thirty-five percent of accommodation in the UK is rented (Barton, 2017), and tenants are very limited in their ability to make changes to the property in which they live. Whilst higher income households may have less financial incentive to make energy savings, restrictions on the capacity of lower income households to alter their energy consumption have been identified. Households with a smaller budget are likely to already have lower energy consumption levels than higher income households (Vassileva and Campillo, 2014) and therefore be limited in their ability to act further. It has also been observed that, once lower income households have found a way to manage their budgets, they have a lower psychological resilience to changes in routine than those on higher incomes (Jacques et al. 2016), which influences the way in which they make sense of energy feedback.

2.3 More than energy feedback

Information-seeking is a key part of the sensemaking process, as individuals draw on multiple formal and informal sources of information in interpreting new situations (Kuhlthau, 1991). Hence, incorporating additional information beyond energy consumption (and its monetary cost) into feedback devices may support households in making sense of domestic energy management. Data on indoor environmental conditions (IECs) especially may help give meaning to energy consumption and aid in overall interpretation.

This is not to say that the provision of additional data would lead to greater reductions in energy consumption. In some cases, data on IECs may highlight situations where *more* energy should be consumed, such as to raise the indoor temperature to a healthy level. Whilst there has been little empirical research conducted on the specific impacts of energy use feedback and domestic comfort, some commentators have expressed concern that the provision of only energy and cost information may influence some consumers to prioritise reductions in energy use to the detriment of health and wellbeing (Boomsma et al 2017; Bone et al 2010). This is potentially more the case for those on low incomes who are typically using less energy than average already. Therefore, IEC feedback may be especially beneficial for such households, who may not know whether they are able to make further energy savings without a negative impact on domestic comfort and wellbeing. For example, notification that CO_2 or relative humidity is above the recommended range could trigger the householder to open a window or door, or use an extractor fan, to prevent the build-up of pollutants and the development of condensation and mould issues.

IECs are commonly monitored in smart homes, typically to automatically trigger an air exchanger if conditions are not ideal. In some cases, information on IECs (usually temperature) is communicated to the user, e.g. by SMS or email alerts, made available on a website (e.g. Acurite), or displayed on the thermostat itself (e.g. Nest). However, there is a lack of empirical research into how IECs may be integrated into feedback devices in a way that is useful to households, and, consequently, limited understanding of how IEC data is made sense of in the domestic context, in conjunction with energy feedback. To our knowledge, no previous studies have explored the impacts of measuring temperature, relative humidity and CO_2 levels in standard homes and presenting this information back to householders alongside energy consumption data in an integrated display. Consequently, little is known about how people make sense of and respond to this information in the context of their everyday domestic lives. This paper seeks to address that gap by presenting the findings of a seven-month trial that investigated the impact of an integrated in-home IEC sensor and energy metering system, linked to a custom-built ‘Energy Dashboard’ web-based application (app).

3.0 Methodology

3.1 Trial design

An integrated system of IEC and energy monitoring equipment (further described in section 3.3) was installed in 19 properties in the English Midlands between July and November 2016. Each household was given a Samsung Galaxy tablet to view the data being collected from their property via a custom-designed ‘Energy Dashboard’ Android app (further described in section 3.4) that updated information every 30 minutes. The app was activated in November 2016. The households were given a personal demonstration of how to use the dashboard app when they were given the tablet, using dummy data in most cases where this was before the app was fully activated. An online guide to using the app was also available on the project website, and a dedicated email address, checked daily, was set up for the participants to contact the research team with any questions or problems regarding any aspect of the trial or use of the app.

An initial round of semi-structured interviews was carried out with at least one person in each property (and in all cases the bill payer) between December 2016 and January 2017, at least four weeks after the app was activated. The purpose of the first interview was to explore the participants' everyday routine (focusing on things that use energy), the ways in which they make themselves comfortable in the home, and their initial impressions of the Energy Dashboard app. This feedback, alongside wider evaluation, was used to further develop the app, and a new improved version of the Energy Dashboard was released in March 2017. Further support for the app usage was given via the interviews and by email, if needed. As part of the project, a 'serious (video) game' was also developed to reinforce learning about energy consumption and indoor environmental conditions, and energy savings tips, and released to householders in April 2017. The game is not discussed in this paper but reported on elsewhere[1].

A second round of interviews was carried out with the participants in May and June 2017, to explore their experience of the trial, including the ways in which they had engaged with the app, and any changes to their domestic practices that had taken place. Participants received £70 in vouchers for taking part in the trial and both interviews. An additional incentive to participate in the trial lay in the fact that they were able to keep the tablet at the end of the trial.

Interviews lasted between 25 and 90 minutes and were audio-recorded and transcribed. A coding frame was developed from the first set of interviews, and extended following the second set of interviews. The transcripts were then analysed thematically with the aid of nVivo software.

The second interview marked the end of the active trial but with agreement of the participants, the sensors and transmitters stayed in place for a further 6-8 months to allow passive data collection (via the sensors only). During this period the dashboard was still

[1] Contact corresponding author for details

operational and available for the participants to use, but its use was not monitored and support was no longer available in the event of any problems or malfunctions.

3.2 Recruitment and overview of households

The trial was advertised by the social housing provider partner, Orbit. This included sending a promotional SMS text message to 372 customers living in their properties in 6 towns and local areas in the Midlands of England. The SMS read, *"Orbit is working with Cov Uni to better understand household energy use. Take part in our trial and receive £70 in vouchers. Find out more at http://www.orbit.org.uk/smarter_households/".* This included a clickable link to a website with more information about the trial and provided the opportunity for those interested in participating to submit an 'Expression Of Interest' (EOI) form. Promotional text about the trial and a link to the EOI form was also added to the 'Latest News' section of the social housing provider's website. Seventy-two EOI forms were received, and these households were sent further information, which framed the trial purpose thus: "The dashboard and game could help you to live the way you want, whether you are looking to save money, have a more comfortable home, or be more environmentally friendly". Nineteen households (Table 1) were eventually recruited (against a target of 20), based on their continuing willingness, availability, and equipment capabilities (meters were required to be inside or just outside the property, rather than in a communal meter cupboard; and the monitoring equipment was incompatible with prepayment and smart gas meters, as well as some older gas meters). All stayed in the trial up to its completion. Unlike many other studies (but similar to Burchell et al., (2016) and Snow et al., (2013)), most of the participants (14) were women. Where two names are listed in Table 1, both participants took part in at least one of the interviews. In 3 out of the 4 couples, the woman took the leading role in the interviews and activities of the trial. There is no obvious explanation for this over-representation of women. The lead researcher involved in recruiting and interviewing participants was female, which may have encouraged more women to participate.

It transpired some way into the trial that two of the households were homeowners and not social housing tenants. As the trial had already commenced, they remained participants for the full duration. Apart from these, all participants would have applied for social housing via their local council. This responds to the criticism by Abrahamse et al. (2005) that household energy intervention studies tend to take place with households of higher than average incomes.

ID	**Pseudonym**	**Property type**	**Household details**	**Self-rated level of household energy consumption**
H14	Arthur and Brenda	Flat	Retired couple	Medium
H15	Melanie	Semi-detached house	Working single parent, 2 young children	High
H19	Harry	Flat	Single adult, not working	Medium to high
H21	Kate and Stuart	Semi-detached house	2 working adults, 1 teenage child	High
H26	Tina	Terraced house	Working single parent, 2 children	Medium
H27	Tim	Semi-detached house	Single adult, working	Medium to low
H29	Darren	Flat	Single parent with disability, not working, child lives there part time.	Medium to low
H32	Liz	Semi-detached house	Working single adult and adult child.	Medium
H35*	Kay	Semi-detached house	Working single adult and 2 adult children	Medium
H36	Jacqui	Flat	Single adult, working	Medium to low
H39*	Becky	Flat	Working young couple	Medium
H40	Stephen and Janet	Bungalow	Retired couple	Medium
H41	Sharon	Flat	Single adult, not working	Medium to low
H43	Daphne and Bill	Semi-detached house	Retired couple	Medium
H44	Lyn	Flat	Retired couple, one with disabilities	Medium to high
H50	Gemma	Semi-detached house	Working couple and 3 teenage children	Medium to high
H54	Sheila	Bungalow	Retired couple	Medium to low
H55	Emma	Semi-detached house	Working single adult and 1 teenage child	Medium
H58	Lucy	Semi-detached house	Single parent, 4 children and 1 adult child during University holidays	Medium to high

*these participants owned their homes and were not social housing customers

Table 1: Trial participants

3.3 Monitoring system

The integrated monitoring system collected data on five key variables: electricity consumption, gas consumption, temperature, relative humidity, and CO_2 levels.

Measuring electricity consumption was essential to gain an understanding of energy use around the home. This was measured at the meter using a wireless transmitter capturing pulse data via a clamp. We also measured indoor temperature, relative humidity and CO_2 levels using wall-mounted sensors in the living room and kitchen of each property. The data was sampled at five-minute intervals and forwarded to the university server via secure file transfer protocol (FTPS) every 30 minutes. This meant that participants were able to view their electricity consumption, temperature, relative humidity and CO_2 data at five-minute intervals every 30 minutes. This contrasts with the IHDs being rolled out across the UK, which are required to provide almost instantaneous ('near real time') information to households from raw data directly from the smart meter.

As most of the participating households had a gas heating system, it was important to capture gas consumption, to complete the picture of energy use in the home. Previous studies have noted difficulties in finding affordable ways of monitoring gas, which have led to issues with patchy data (Buswell et al. 2016) or have had to resort to participants having to manually enter readings from their meter (Burchell et al. 2016). We found the most suitable solution to be the Loop Energy Saver, which connected to the property's internet router and provides 30-minute gas consumption data. Whilst the gas data was sampled at 30-minute intervals, the sensor supplier was only able to provide this data to the project team at the end of each week. Consequently, the gas data available via the Dashboard app was retrospective, not real time, with half hourly gas consumption data provided at the end of each week. Therefore, the Dashboard was designed to enable users to review the times of day that gas was being used each day, and the corresponding temperature, humidity and CO_2 levels, to help them identify any potential opportunities for reducing wastage, for example, times they were out of the house or times when the temperature seemed unnecessarily high.

We encountered some challenges in the implementation of the gas monitoring system which should be noted. First, due to a difficulty affixing the sensor head to curved gas meter screens, the Loop Energy Saver could not be used in 7 of the 16 properties with a gas supply. Second, in some of the properties where the system was installed, the quality of the data was unreliable, which meant we had to quality-check the data and disregard some periods of readings completely in some properties.

In this paper, we focus on the household members' experiences of using the Energy Dashboard and how the feedback provided was integrated into the households' sense-making processes around domestic energy management. Therefore, the quantitative energy consumption data collected through this monitoring system was not of primary interest for this paper. We provide an overview of electricity and gas consumption across the participating households for context (see section 5.4), but this is analysed and reported in greater detail elsewhere[2].

3.4 Design of the Energy Dashboard

To ensure the Energy Dashboard app met users' needs, it was co-designed with staff from the housing association during two workshops. We decided to engage housing association staff at this stage rather than residents, as they would have a broader understanding of the range of circumstances and needs across the properties; furthermore, residents had an opportunity to provide much more detailed input on the design during the in-home trial of the technology.

The original Energy Dashboard v1.0 design was created iteratively over the two workshops. The home screen displayed a series of dials showing the most up to date IEC levels and bar graphs showing daily electricity and gas consumption data in both kWh and cost, with cost calculated on the inputted customer's tariff (Figure 1). Traffic light colours were only used for IECs, not energy use, because they remove the neutrality of information. IECs have recommended healthy ranges (taken from the UK Chartered Institute of Building Services Engineers (CIBSE) guidelines), whereas optimal energy use is much more context dependent.

The Energy Dashboard app also included a 'Hints and Tips House', a feature in which points (non-redeemable) could be earned by tapping on appliances in a virtual house and reading associated energy-saving advice (Figure 2); a 'History' tab, allowing half-hourly data at any point in the trial to be explored by selecting a date from the calendar (Figure 3); and a function to set a goal and track progress.

[2] Contact corresponding author for details

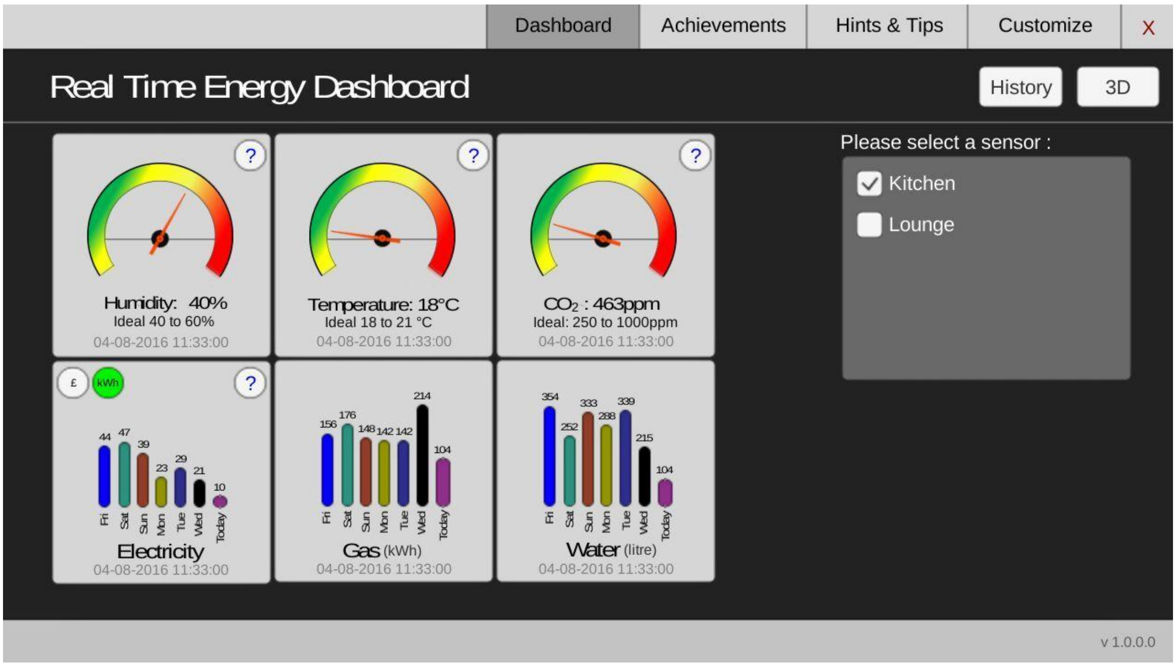

Figure 1: Energy Dashboard v1.0 'Home Page'[3]

Figure 2: Energy Dashboard v1.0 'Hints and Tips House'

[3] This first prototype included an option for displaying water consumption data alongside electricity and gas, which was removed in later versions of the app due to an incompatibility between the sensors and the participants' water connection points.

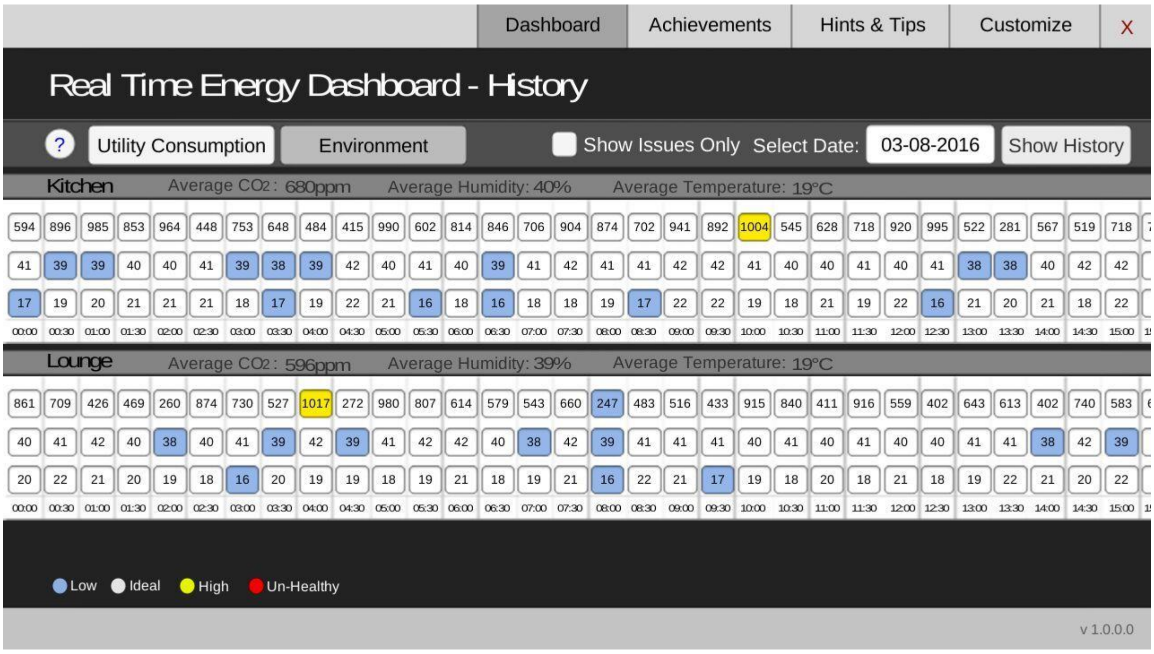

Figure 3: Energy Dashboard v1.0 'History': the environment page shows for each room the CO_2 ppm (top row), the relative humidity (middle row) and the temperature (bottom row) at half hourly intervals, with low and high values highlighted

At least four weeks after the original version of the Energy Dashboard was released to trial participants, the first interviews were held with the households in which their perceptions of the app were discussed. Following a review of this feedback and some additional usability testing with university students and staff, a revised version of the Energy Dashboard was developed (Figures 4-5). This included graphs showing half-hourly electricity use, and a summary of the daily, weekly and monthly usage with associated costs and comparisons against the last day, week and month. Although 'live' half-hourly gas consumption data was available to consumers via the Loop Energy website, it was not possible to integrate this data into the app until the end of each week. Therefore, the gas data displayed on the Energy Dashboard was for the previous week, and a link was provided to the participant's account on the Loop Energy website to give them easy access to their half-hourly data. Colour coding was also introduced into the energy data display to facilitate easier assessment of changes in household energy use over time. Orange was used to indicate energy use which was more than on the same day the previous week, and green where it was the same or lower. The History tab was also improved with colour coding. The 'Hints and Tips House' remained as in version 1.0.

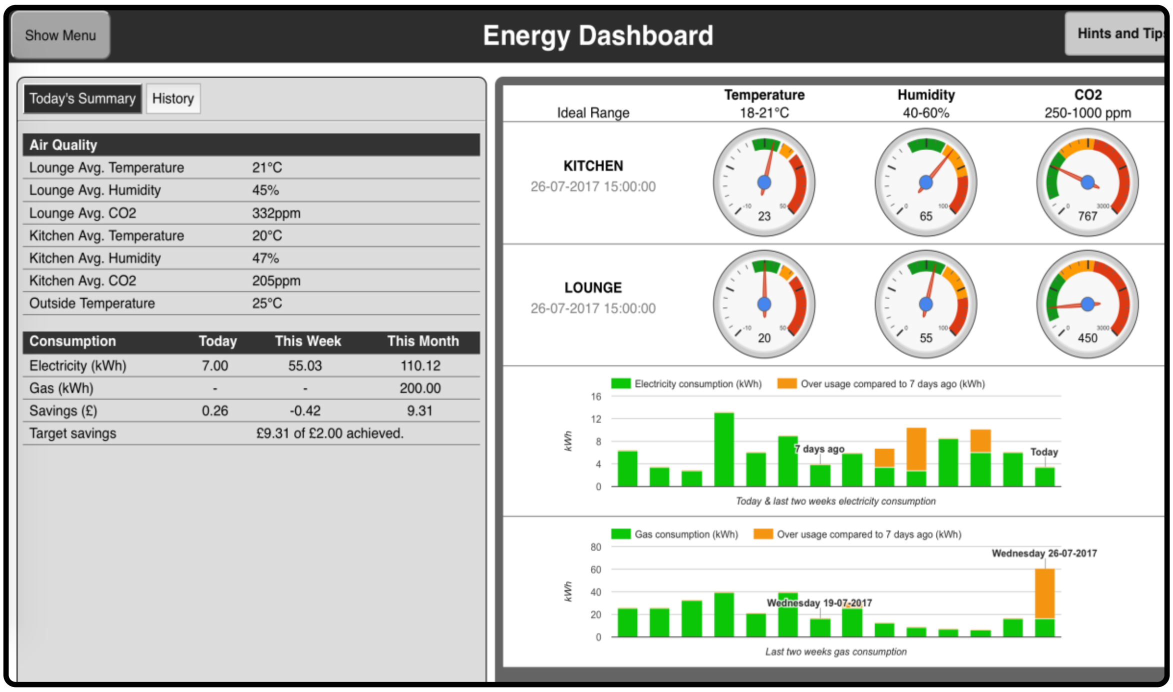

Figure 4: Energy Dashboard v2.0 ‘summary’ view

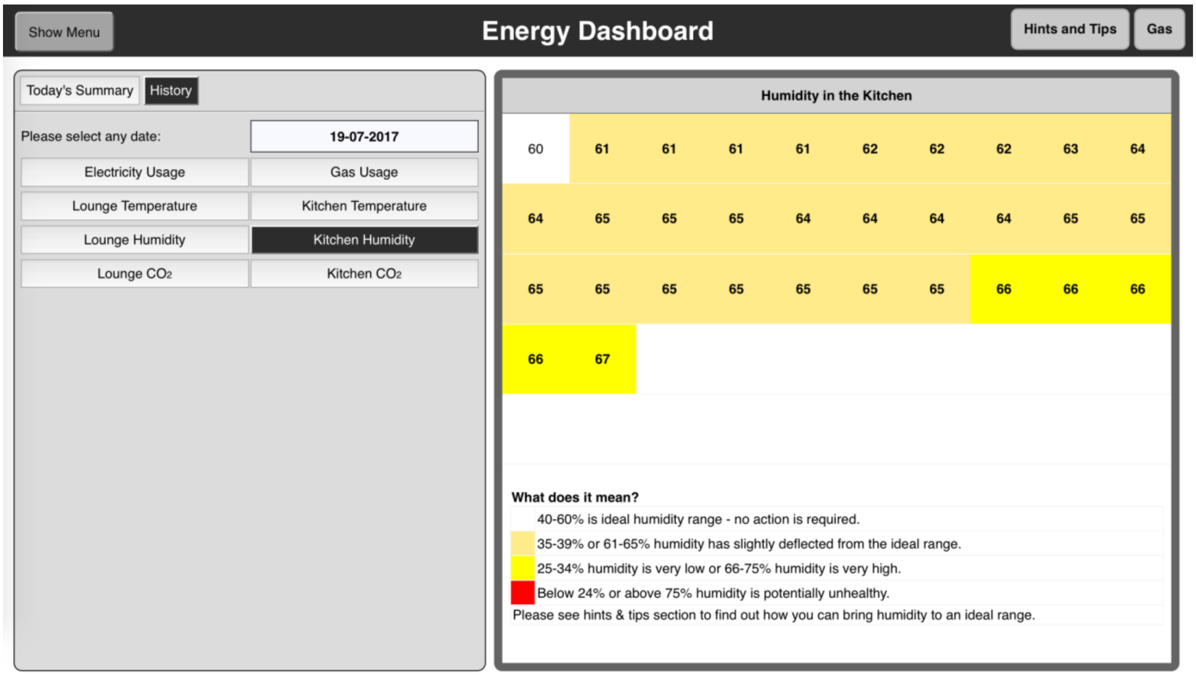

Figure 5: Energy Dashboard v2.0 ‘History’ view

4.0 Findings

In this section, we present our findings according to the three sense-making processes identified in the introduction: noticing, interpreting and enacting.

4.1. Noticing

In the first interview, conducted between four and eight weeks after the Energy Dashboard was provided to participants, 15 out of 19 respondents stated that they were using the app at least once a week, including 7 who were using the app at least daily. Only one participant reported that they were not making use of the Dashboard at all. The IEC dials were the most viewed aspect with two thirds of the participants checking these; most interest was in temperature as the most familiar aspect over which people felt they had most control, concurring with expectations, although the novelty of CO_2 attracted a smaller number of participants to that aspect. Hints and tips were actively viewed by 11 participants who were motivated by the immediate potential utility of these and, to a secondary degree, by the gamified aspect of collecting points. Around half were reviewing their electricity and gas consumption regularly, linking peaks in consumption with particular activities and appliances, and for a smaller number also noticing the costs associated.

There was some decline in the frequency of use of the app over the course of the trial; at the second interview, 10 participants said they were using the app once a week or more. Two participants were however using it more often than in the initial weeks, having got more used to it and what it could do. Of the six interviewees who stated that they had not engaged with the Dashboard for over a month, five cited significant changes in family circumstances, or health, or a move into full time work, as the cause for this fall in use.

All except one of the households at this later point stated that they engaged with the IEC data, with this information commonly used to create an understanding of healthy indoor conditions:

> *"I check the CO_2, because I'm always worried about CO_2. I don't know why, but it bothers me, and I check the temperature, and I look on these gauges, because I know, like this one, it's in the green. So, I know it's alright."* (Sharon, interview 2)

There was an apparent link between the information that was noticed or sought and the frequency with which the app was used. For example, Sheila described how looking through the 'History' view lent itself to weekly use:

"… on a Sunday, I have a wiggle through and see what's happening: oh £6.38 less than the previous week; that's because it got hot." (Sheila, interview 2)

whereas checking IEC levels might be done daily, or more often:

"It's part of my daily living…it's my routine now. Go on that. Oh look, it's still in the green, in the green, in the green…As long as I know all them [IEC] dials are within the green and they aren't nowhere near the red, I'm happy…" (Darren, interview 2)

The Energy Dashboard was explicitly designed not to focus on 'live' energy usage data as this type of display risks highlighting high wattage items even those used for short periods of time (e.g. the kettle) rather than helping to identify the things continuously left on or used for long periods. Consequently, participants were able to view their electricity consumption alongside their IEC data every 30 minutes (at a five-minute resolution). There was evidence that other elements of the design of the Energy Dashboard also influenced the information that participants particularly noticed. In an unanticipated way, the point-collecting feature in the 'Hints and Tips House' encouraged three or four participants to keep going back to this, even though the tips did not change. Visiting this screen regularly may have contributed to committing the tips to memory.

The tablet provided to participants as part of the trial was, itself, identified by some as a trigger to check the app on a regular basis. Many adopted the tablet into their daily lives for other purposes (such as checking emails, playing games, using other apps), which encouraged some to check the Energy Dashboard app. However, others who were regularly using the tablet for other reasons did not end up checking the app regularly.

4.2 Interpreting

Conversations at the first interview indicated that in the first few weeks the app users were using the app largely to create a general understanding, for example around half were viewing their consumption history data and interpreting it by linking it with their activities, a process of combining different sources of information (Kuhlthau, 1991) to understand what lay behind their energy consumption:

"It's the oven that spikes up and down. It's made us more aware of that, to a certain extent, doesn't it, really?" (Arthur and Brenda, interview 1)

"When I do look at it, I can tell when I've put my tumble dryer on and stuff like that, that's why I try and figure out, why did it go up then?" (Kate and Stuart, interview 1)

Viewing of IEC dials was largely informative at this stage, but engagement with CO_2 in particular was low as most participants were confused about what this was, and needed more explanation. The hints and tips were easy to interpret and popular as they offered immediate learning.

After seven months, participants were settling into a routine that gave them the information they desired at the intervals they found useful, moving from a 'discovery phase' to 'maintenance phase' (Li et al, 2011). All but one of the 10 weekly or more users were accessing energy usage information as well as IECs, and several were still looking at hints and tips. The preferred or most sought information however varied. This aligns with the information search process described by Kuhlthau (1991), whereby users transition from seeking general background information in the early stages of sense-making, to seeking out focused information relevant to their particular interest, once a clearer sense of the situation has been formulated.

There was a sense that, for some, the IEC data continued to be easier to interpret:

> *"I don't look at that bit [the electricity], because I don't understand really how to read it properly, but I read that bit [the summary] and I read the [IEC] dials because I know the dials. If it's in the red [the IECs], there's a problem."* (Sharon, interview 2)

As explained earlier, the Energy Dashboard design intentionally avoided using traffic light coloured dials for electricity and gas use to minimise the risk of colour legitimising energy reduction actions at all costs and to encourage instead a comfort-focused interpretation of the data. This design decision may, therefore, have reduced the level of engagement with electricity and gas consumption feedback compared to other energy use displays that do use colours.

Not all participants used the IEC colour coding to interpret the data however. For example, Darren used the app to check current conditions against his own sense of what was acceptable:

> *"I was thinking, "Well, it is a bit chilly in here. I wonder what it is? Click. Oh yes, it's about 15, 16 [degrees Celsius], which is below the 18, but it's still liveable. You know, you're not going to die. It's not minus one."* (Darren, interview 2)

One or two other participants adopted their own, higher temperature standard than the IEC indicator, where health conditions or limited mobility required them to keep the property at a warmer temperature than 21 degrees for comfort; this also made them reluctant to open windows or doors to bring CO_2 or humidity down.

There was also clear evidence that the IEC data encouraged users to consider the health and wellbeing implications of their domestic practices, as well as energy consumption and financial cost:

> *"I've made sure to open windows because I know – I've seen how humid it is and that it's, you know, not healthy for you to have it that high because I didn't know that before we did this. I'm not a clever clogs. I didn't know that much."* (Liz, interview 2)

It is important to recognise that the adoption and understanding of the Energy Dashboard app took place in the context of other forms of feedback. Participants described different ways that they would 'verify' readings on the Energy Dashboard, for example, considering who was in the home and what appliances might be in use; checking temperature with a digital thermometer.

The great majority of participants stated that they trusted what they were reading, especially after being able to verify it in other ways, in at least one case even modifying their habitual response to their usual sensory feedback:

Lyn:	*"A couple of times at night, I go, oh it feels a bit cold in here …and I'd look and go, hmm this says it's 21, it doesn't feel like that. But you know, I take it is warm enough …I'm guided by that really.*
Interviewer:	*So, would that change the way you react to feeling cold if you see the temperatures?*
Lyn:	*Probably, yes it must have done, because I'd go, hmm okay right, it's just me then, you know. So, carry on watching the telly and forget about it really."*

(interview 2)

As participants started to understand CO_2 better over time, after further explanation, at least 3 or 4 started to notice and actively interpret it more

> *"all of a sudden there is a big peak in it because there is someone in here. So it was fun to look at and see, 'Oh yes no one was in there then.' And then, 'Oh yes we were all in there.' Or, 'Oh that was just me in there.' "* (Stephen and Janet, interview 2).

However, CO_2 levels in most houses rarely reached unhealthy levels, so this data was usually of less significance.

As has been reported by some previous IHD studies, it tended to be the case that only one person in each household engaged with the app. The household member who originally signed up for the trial was generally the sole user of the app (except in one household where a man signed up, but his female partner was the main user). Despite this lack of direct engagement with the app by others, it was reported that some household members would ask the primary Dashboard user to tell them what the Dashboard was showing about their routine, echoing Schwartz et al.'s (2013) description of 'learning from the expert'.

There was also evidence of children monitoring other household members' behaviour as a result of the trial. For example, Tina, who had not deeply engaged with the trial's activities, noted that, following discussions at home relating to the trial, her son had started pointing out the family's energy-using actions.

None of the participants used the goal setting feature of the app to set themselves a specific target to achieve. However, it was clear that some users (at least 3) were setting themselves informal consumption related goals and challenges, typically staying within a specific budget, or making savings:

> *"…if I'm tempted, tempted to put the heating on or the tumble dryer on, then I'll just have a quick look. And then obviously because I keep an eye on the budget and I try… it's like a little game, like a little challenge to myself and if I achieve it, yay."* (Melanie, interview 2)

It could be surmised, therefore, that while participants were not necessarily engaged by the opportunity to set themselves specific goals that required them to make conscious changes, they were still interested to see if taking part in the trial had had any impact on their energy use. It is notable that participants requested an easy means of comparing energy use week-to-week in the second version of the Energy Dashboard (as described in section 3.4). Staying within the green areas of the IEC dials, rather than saving energy per se, was also an informal goal of some participants.

Two of the participants who admitted losing interest in the app cited a desire for 'instantaneous' energy information and were attracted by energy supplier-installed smart meters and IHDs in this regard. They felt that the value of such feedback would be the greater ability to pinpoint the effect of a specific activity or appliance.

4.3 Enacting

The 'Hints and Tips House' feature of the Energy Dashboard app was specifically aimed at helping users connect energy feedback with activities undertaken in the home, and was developed with the housing provider to ensure that the tips were appropriate and actionable by tenants. As noted above this was one of the more readily engaged with features at first, and at the first interview two or three participants noted that they had not only learned but already taken some of the recommended actions, for example

> *"when it was particularly cold the other week, I didn't actually undraw my curtains when it was really dull and murky, and I thought we are all out at work, keep the curtains drawn and it will keep the heat in. So I did."* (Kay, interview 1)

By the second set of interviews, several changes to actions around the home were noted by participants. The most commonly reported change was to laundry activities (washing or drying clothes), mentioned by 11 out of 19 participants:

> *"The washing's the main one, because I used to be terrible. You know, I'd wash one thing if I needed it, and I wouldn't think about it. I'd just do it, but now, I do one a week, and that's it. If I need anything, it's tough. It's got to wait."* (Sharon, interview 2)

Participants attributed this change both to learning from the 'Hints and Tips' feature, and using the app to identify peaks in electricity usage when doing laundry, through a process of interpretation. The impact on laundry activities may have been influenced by the fact that 74% of the primary trial participants were female, given that women do more household laundry than men in the UK (Scott and Clery, 2013).

Seven out of 19 participants reported a change in cooking or food and drink preparation behaviours, primarily around either kettle use or using a different appliance for preparing meals. For example, Tina described how she had switched to using a three or four tier steamer, to enable her to cook her meal on a single hob ring, rather than using multiple pans and rings. Five participants claimed to turn lights off more, and one to use the dishwasher less.

Although when we designed the 'Hints and Tips House' feature we aimed to avoid the most well-known tips, like turning off lights when leaving a room, 5 participants commented that they were already familiar with most of the tips provided. Nevertheless, some of these participants also noted that reading them again in the context of their energy usage data brought new weight and encouraged change:

> *"Because I kept reading them [the Hints and Tips] …that is what actually really made me think about the washing machine. Because I thought nothing of putting it on with a few bits in but not now."* (Kay, interview 2)

As noted earlier, some participants paid more attention to the IEC indicators and by the second interview they were finding the initially less familiar information on indoor humidity and CO_2 more instructive. Eight participants mentioned a change in airing or ventilation behaviours (such as opening windows or external doors), out of concern for humidity and to a lesser extent CO_2, despite that fact that this could even increase energy use, and therefore costs, if the heating was on. This is a way in which information on energy use was balanced against that regarding indoor conditions, and behaviour change appears to have been directly influenced by learning new information, and concern for a healthy indoor environment:

> *"…before [the trial] I probably wouldn't have even cared [about humidity], I wouldn't have even thought about it. Especially, like I said, about cooking and opening the windows, or just opening the windows when I had washing and stuff in here. I just wouldn't have been bothered probably before."* (Becky, interview 2)

Although the Dashboard was designed to suit tenants in rented accommodation, still not all participants felt able to make changes to their daily lives in ways that would affect the app readings. For example, Stephen and Janet stated that, although the app *"focused them"*, they had been taking daily meter readings for some time to monitor their electricity consumption and had already made the changes they felt able to. Kate and Stuart described the complexity of managing laundry with working hours and a limited supply of work uniforms, and how they have developed a system that works for them but *"doesn't work economically"*.

Several participants also discussed issues with their property that were affecting their energy consumption and indoor conditions but were out of their control, including inadequate extractor fans, poor quality storage heaters, and especially draughty windows and doors. Most of these felt that the housing association either would not be able to fix the problem or would not want to do it, although a couple were positive about the provider's upgrades and repairs. The housing provider however maintained that they would have welcomed conversations with tenants that arose as a result of the trial.

There was a less discernible impact on heating behaviours, only noted by a small number of participants (H15, H32 and H40). There was more of a sense that heating was considered 'non-negotiable' by participants (Hargreaves et al., 2010) and many were already being careful with it. The fact that the second interviews took place in May and June may also have meant that any such changes were less recalled than, for example, changes to washing routines.

While previous feedback device studies have observed an unwillingness amongst participants to make changes that negatively impact personal comfort (e.g. Hargreaves et al. 2013), our study found a greater unwillingness to sacrifice the perceived comfort of others. Several participants reported putting the comfort of children, or partners with health conditions above saving energy or their own comfort, even in cases where they noted that they sometimes struggle to pay for energy. Whilst there may be some degree of 'socially desirable responding' (Mick, 1996), similar findings have also been reported elsewhere (e.g. Gibbons and Singler 2008). Willand and Horne (2018) found that, in many cases, the amount of heating used was dictated by the needs of the least healthy and 'most cold sensitive' household member and suggest that, in these instances, "heating took on the meanings of caring" (p.64).

> *"… it's not easy, you know. I mean, your home is your comfort and what I'd be actually doing is taking away his comfort, and I can't do that…. I do try very hard and, bless him, he does try, but I can't bear the thought of him sitting here, just to please me, feeling freezing cold."* (Daphne, interview 2)

In a small number of cases, participants viewed their children's other energy uses as 'non-negotiable', however, more primary Dashboard users noted talking to children (or 'nagging') about changing their actions, mainly in terms of switching off the television and lights when leaving the room.

Interestingly, pets also featured as having an impact on actions which use energy, particularly in terms of heating and cooling (see also Willand and Horne, 2018). Kate and Stuart, for example, noted that other cats wandering in to eat their cat's food prevented them from keeping the back door open, and as a result they used fans instead in hot weather. Tina stated that she occasionally left a window open in bad weather if the cats had not returned home when she went to bed.

Despite this, overall, the participants appeared to be more open to reflecting on and entertaining the idea of lifestyle changes than participants in some previous energy feedback studies (e.g. Strengers 2011; Hargreaves et al. 2010, Head et al. 2016; Nilsson et al. 2014). Even where lifestyle changes were not desired or deemed necessary, there was evidence of learning in several houses, particularly regarding what appliances used the most electricity, humidity levels, and the true temperature of living spaces where this had previously not been known or had been deduced from an analogue thermostat.

4.4 Energy usage over the trial and beyond

The focus of this paper is on understanding how users integrated the Dashboard into household sense-making processes, rather than on the impact of the Dashboard on actual energy consumption. Nevertheless, the impact on energy consumption is relevant to the enactment stage and is naturally of interest. Whilst a thorough evaluation of the quantitative evidence on the impact of the trial requires much more analysis than is possible here, contextualising energy use in indoor environmental conditions and taking into account *inter alia* holidays, changes in occupancy and outdoor temperature; the below figures offer a visual overview of electricity and gas consumption over time. Figure 5 shows the fortnightly summed electricity consumption for 17 of the 19 participating households[4].

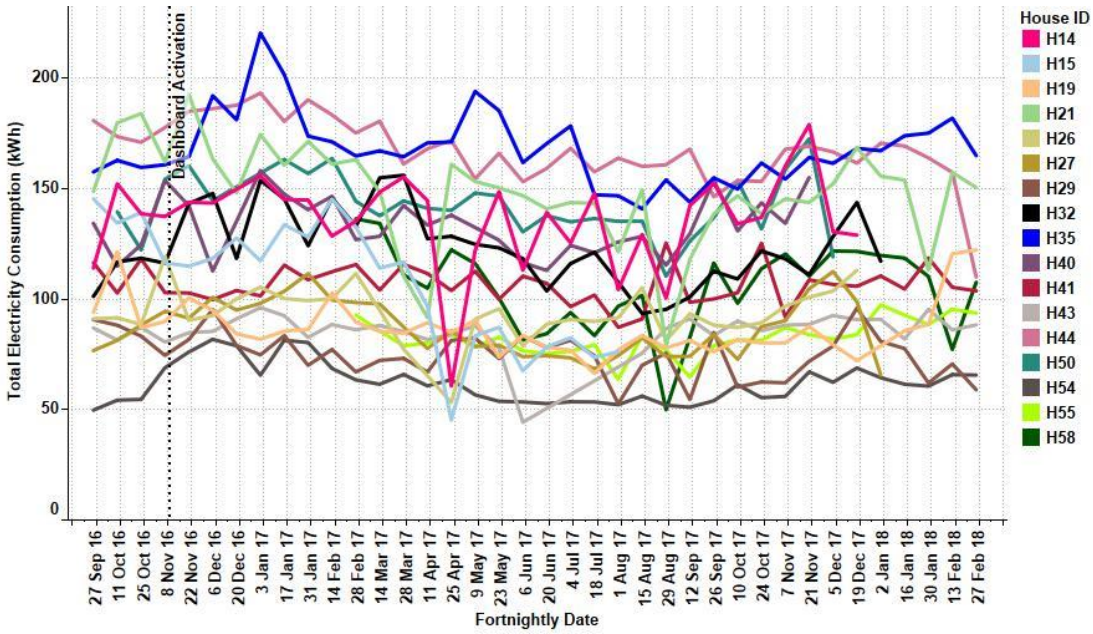

Figure 6: fortnightly total electricity consumption across 17 households

This indicates overall a gentle downward trend over time from winter 2016 to winter 2017, but with variation between households in terms of their picture. H35, one of 4 electric heating users (2 shown), seems to have reduced their winter peak, as have H21 and H54, not electric heating users, but H19, another electric heater, has not. H44 has gradually reduced electricity usage over time and H15 quite markedly so, although without a full year's data to compare,

[4] Two households are not shown due to anomalous or intermittent data, reasons for which cannot be fully ascertained but may be due to switching off the wireless transmitter, faulty equipment, or physical interference with the readers.

whilst H41 and H55 have remained quite consistent. H14, H32 and H58 remained extremely variable.

Figure 6 shows monthly total gas consumption for 8 of the 15 gas using households for whom monitoring was possible and reasonable data available. Unfortunately, recurring problems with the gas monitoring arrangements not under the control of the research team made data collection more difficult and accounts for the shorter timelines. As gas consumption in UK homes is mainly driven by heating use, it is important to consider differences in outdoor temperatures when making comparisons over time and so we have indicated the heating degree days for each month on the same figure.

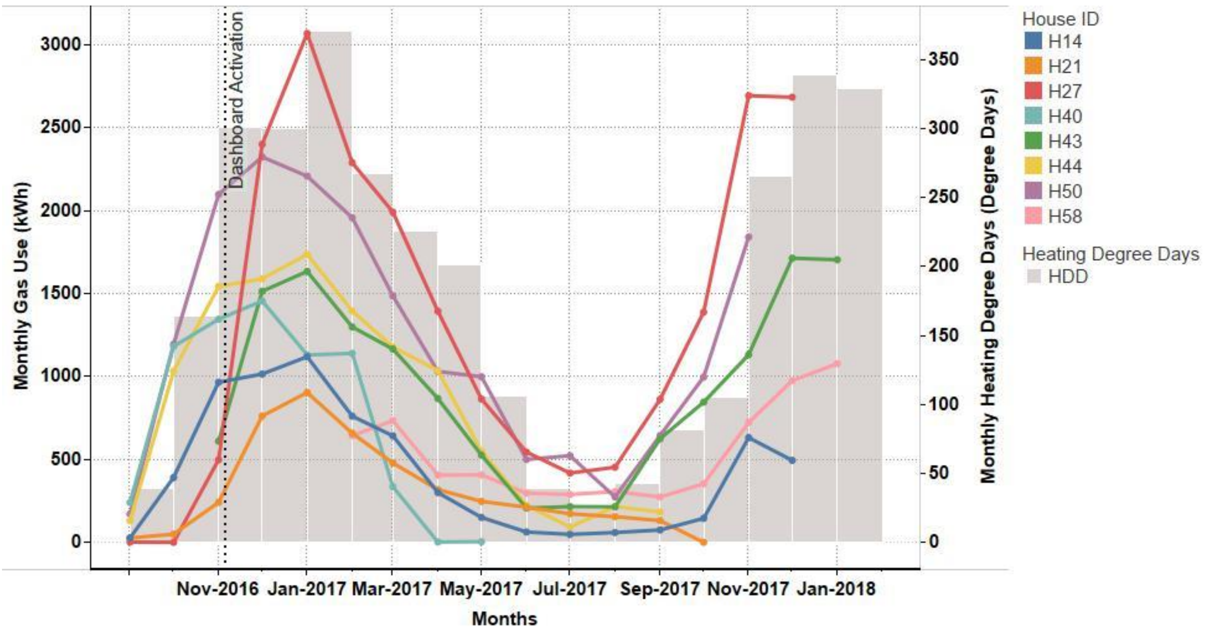

Figure 7: monthly gas consumption against heating degree days for 8 households

Because gas consumption is so much more variable over the year it is hard to ascertain a trend without the ability to make a year on year comparison, which would require a very long period of monitoring, unfeasible in our study[5]. The difference in gas consumption between autumn and early winter months in 2016 and 2017 seems accounted for by the difference in heating degree days (a function of outdoor temperatures), offering little indication that households using gas made substantial reductions to their heating usage; this would be consistent with the qualitative data and the positioning of heating as a non-negotiable (Hargreaves et al.,

[5] As most households pay energy bills by equal monthly instalments, their own billing records do not track variations in consumption

2010). The consumption data is not however able to tell us whether households were able to improve their comfort and indoor conditions for the level of consumption, which would be a positive outcome. Further analysis of indoor environmental conditions over the course of the trial can help illuminate this but is outside the scope of this current paper.

5.0 Conclusions

In this paper, we have explored how social housing tenants responded to a custom-designed 'Energy Dashboard' app that displayed their domestic electricity and gas consumption data alongside relative humidity, CO_2 and temperature in two rooms of the property, with a tailored 'hints and tips' on energy saving. Using the lens of sense-making, we investigated how the app supported households in 'noticing', 'interpreting' and 'enacting' changes in domestic energy management. This has provided novel insights into the potential value of incorporating additional 'sense-making' information alongside feedback on energy consumption.

While we found that different participants noticed and created different knowledge as a result of their interactions with the Energy Dashboard, all but one reported that they engaged with the IEC data in the interpretation process, with several participants finding this easier to interpret than energy consumption data. The traffic light style dials made noticing of IECs more likely, although not everyone used these colours in interpretation. Initially, participants engaged with the dashboard to form an understanding of their energy and IEC picture, with at least half combining data from the dashboard with their knowledge of their own routines to understand what most affected their energy consumption. At this point, out of the IECs the most familiar one of temperature was the most noticed, as CO_2 and to some extent humidity were less well understood. The 'Hints and Tips' feature was also popular as a source of easily interpreted recommendations that could potentially be put to immediate use.

Over time, participants settled into a routine of use for the features and frequency that suited them. Those who were using the app on a daily basis were primarily seeking current information, often on IECs, whereas those using it on a weekly basis were reviewing historic data. Further exploration is needed into whether using the app predominantly to make sense of past energy consumption using historical data is less likely to drive changes in energy use than using the app to make sense of current energy management choices using (near) real time data. However, what is clear is that participants appreciated a range of features which allow them to create knowledge and interpret information in different ways, according to what they were interested in. Over time, more attention was paid to the IECs of humidity and to a lesser extent CO_2, as these became more familiar through explanation by the research team and the Hints and Tips house, and more interpretation of these took place.

Some form of enactment in terms of behaviour change occurred in the majority of participant households, with changes to laundry and cooking practices, lighting and dishwasher use, and to ventilation habits in response to humidity and CO_2 data, even though the latter has the potential to increase energy use. The 'Hints and Tips House' appeared to play a useful role in supporting the enactment stage of sense-making, suggesting that this type of 'Energy Dashboard' app has potential to be used to support changes in energy use in a less resource-intensive way than community engagement processes. It is important to note however that the concept of actionable tips has received criticism for responsibilising energy users for making changes within the energy system, and for being restricted to a set of actions that can be taken without making larger changes to mind-sets or lifestyles (Hargreaves 2018; Strengers 2013). In the design of the 'Hints and Tips House' feature of the Energy Dashboard, we recognised that individuals (and particularly those living in rented accommodation) are only capable of making a restricted number of changes to their energy use and IECs. We also recognise that these actions sit within wider systems, which individuals are less able to affect. Some participants were prompted by the trial to identify property-related issues but most expressed a lack of desire to report these to the housing provider. The housing provider however felt that tenants starting conversations with them about their housing and changes they would like to have made, would have been a positive outcome.

Overall the households appeared to achieve a modest reduction in electricity use in the course of a year including and following the trial, but household trajectories varied. There is little indication of significant reduction in gas use once variations in outdoor conditions are taken into account, in line with literature that posits heating as often a 'non-negotiable' (e.g. Hargreaves et al. 2010; Head et al. 2016; Strengers 2011). However we found that energy uses and behaviours that were considered 'non-negotiable' predominantly related to the comfort and wellbeing of others (such as partners, children, and pets), rather than personal needs or desires.

We conclude that the dashboard app was successful in helping our participants to make sense of their energy use in the context of their indoor environmental conditions and in almost all cases resulted in some learning that the householders considered useful in supporting their domestic energy management. The incorporation of IECs alongside energy data in the display alters the normative emphasis away from energy saving per se, but IECs proved to be strongly valued in sense-making for most households, especially over time, and led to enactment of behaviour changes with the purpose of improving indoor conditions. While further analysis and research would be needed to quantify potential impacts on efficiency of providing IEC data alongside energy consumption feedback, our qualitative evaluation indicates that there is much potential for this enhanced level of feedback in enabling households to make sense of their energy consumption and to manage it in ways that reflect their wellbeing needs and priorities.

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