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Supporting Retrofit Decisions using Smart Meter Data: A Multi-Disciplinary Approach

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Abstract

The UK Government's flagship energy efficiency program, the Green Deal, provides retrofit advice for household occupants based on a technical house survey and an engineering modelling tool. Smart meter data provides an opportunity to give bespoke advice to occupants based on the actual performance of their home and their own heating practices as well as visualisations of hourly and daily energy use. This work presents initial results from one component of a complex multidisciplinary research project which aims to use smart meter and smart home data to design and develop retrofit decision support concepts. Home visits involving creative design based research activities were carried out in five homes. Household occupants were presented with two types of energy use report; 1) a Green Deal advice report which includes suggested retrofit measures and annual energy consumption figures based on a steady state modelling approach and; 2) a personalised energy use report, based on smart meter data collected in their homes over a 12 month period. The home visits were carried out with the occupants to discuss a range of possible retrofit measures and gather feedback regarding the communication method for advice about energy efficiency improvements. Initial findings from the home visits indicate that the provision of energy feedback using smart meter data did not directly influence the occupants to make energy efficient retrofits any more than the Green Deal advice reports. However, the visualisation of actual hourly and daily energy use enabled householders to make links with their lived experience and stimulated discussions about their energy use which may impact on their preconceived ideas about energy use and energy efficiency measures.

Introduction

Energy demand reduction in UK homes

The UK government has committed to an 80% reduction of 1990 carbon dioxide emissions by 2050 (DECC, 2008). A significant proportion of these savings will be required from the UK housing stock (Killip, 2008). The UK's housing stock consists of approximately 26 million dwellings and at least 20 million homes will require improvements to meet the climate change targets (Institute For Sustainability, 2011). Improving the uptake of energy efficiency measures is essential in reducing energy demand in UK homes. Although British people invest extensively to improve their homes, spending over £23 billion per year on repair, maintenance and improvements (Killip, 2008), UK homeowners face a number of barriers to retrofit. The most prominent barrier is that the costs of implementing energy efficiency measures relative to annual cost savings are too small to make the time and effort of planning and implementing retrofits worthwhile (Pelenur & Cruickshank, 2011), especially considering the likely disruption caused by installation processes (DECC, 2011). Further barriers constraining improvement options include: concerns over installation quality and time required to research and undertake a retrofit project, complex life stage issues such as starting families, having elderly parents or young children (Mallaband et al., 2012), the invisible nature of energy (Tang & Bhamra, 2008), and a lack of knowledge about where to find information or the format of information being inaccessible to non-experts (Chahal et al., 2011). Variations in attitudes towards energy and the environment highlight the issue that only limited numbers of the population will make an effort to increase the energy efficiency of their homes (Mallaband et al., 2012). Examples include the majority of new boiler installations being replacements for broken boilers or people extending their homes as opposed to purely improving energy efficiency (Green Alliance Blog, 2012). The complexity of the retrofit issue has also been further explored by Wilson et al. (2013) who find that homeowners rarely renovate in order to minimise their energy use and costs. Rather, home renovations - whether energy efficient or otherwise - are an adaptive response to challenges and pressures faced by homeowners in everyday domestic life. Examples of these challenges include competing uses for limited domestic space, a mismatch between aspirations and self-identities on the one hand, and the actual arrangement and design of the home on the other, or difficulties with the physicality of everyday living (e.g., access, warmth). Consequently, it is increasingly recognised that emotional as well as functional needs inform retrofit decision-making as much as processes of rational, goal-oriented thinking(Haines et al., 2006). Greater understanding and consideration of household occupants, their circumstances, decision making processes and barriers they face to retrofit is needed, especially during the development of appropriate tools to support decision making (Ferreira et al., 2013).

Supporting retrofit decisions

A number of decision support tools have been developed to support renovation decisions. Ferreira et al. (2013) reviewed up to 40 examples from simulation based tools that minimise operational energy and CO_2 related emissions, tools that assess environmental comfort, economic tools that purely seek to minimise costs from a financial perspective, and software based tools such as TOBUS (Balaras 2002) and EPIQR (Jaggs and Palmer 2000). Many of the tools involve a multi-objective approach and use genetic algorithms to assess large sets of alternatives and to achieve the best solution to minimise environmental impact and maximise profits, whilst considering factors such as cost, comfort and health. A number of services also exist in the UK that can be characterised as forms of decision support for UK homeowners. One example is Parity Projects' 'Home Energy Masterplan' which involves a detailed dwelling site survey designed to help homeowners identify the best possible approaches to improve their homes with measures that meet their needs and budget (Parity Projects 2015). A further example is the Green Deal Assessment: the UK Government's flagship energy efficiency program. The Green Deal Assessment uses an engineering modelling based tool to calculate dwelling energy performance and a personalised assessment of occupancy practices to advise on potential opportunities for energy saving, providing a list of recommended Green Deal measures and predicted payback periods (Institute For Sustainability, 2012). This form of decision support is of particular interest (and a focus of this paper) because it is a current, active and nationally delivered service, which provides information to UK homeowners about what they can do to save energy.

In view of the many factors that influence retrofit decisions (financial circumstances, life stage, challenges of domestic life, etc.), decision support should be personalised and tailored to the needs of individual households and homeowners (Vasconcelos et al. 2012). In current decision support tools (and most specifically the Green Deal Assessment as the focus of this paper), the extents of homeowner involvement in the early phases of design and development are unclear. One exception is, DECC (2011) who conducted extensive surveys assessing potential consumer demand and consumer responses to the Green Deal proposition (DECC 2011). To design effective decision support systems, the perspectives, views, preferences, values and uncertainties of homeowners must be considered in the design and development process (French et al. 2009).Creative design research approaches involving homeowners are being increasingly adopted in researching and designing energy feedback. There is an important opportunity to similarly involve homeowners in early phases of the design and development of retrofit decision support tools. A unique approach to researching and designing retrofit decision support tools that utilise smart meter and smart home data streams is co-design. Co-design is a design approach that treats 'users' as 'experts of their own experience', allowing them to play a much larger role in design by involving them in creative and collaborative activities at various points across the design process, to develop knowledge, and to generate ideas and concepts (Sanders & Stappers, 2008). The work reported in this paper is focussed on one part of a wider study that aims to use co-design techniques to collaboratively develop concepts for effective retrofit decision support tools with UK homeowners.

Aims and objectives

This work introduces initial results from a wider study of the impact of presenting energy use data to occupants on retrofit decision making. The first home visits (upon which this work is based) presented retrofit recommendations and energy consumption figures in the form of two reports; the Green Deal advice report based on modelled data using standard occupancy assumptions and the REFIT energy consumption report based on actual energy use figures measured by in the homes. The second home visit (future work) will use smart home data to present additional information regarding comfort and occupancy to the occupants. This paper aims to investigate the impact that the Green Deal energy consumption predictions and the actual energy use data have on retrofit decisions. To do this five objectives were set out:

1) Conduct a Green Deal Assessment on five homes in the UK.
2) Collect smart meter data over a 12 month period, and clean the data into a meaningful and accessible format (REFIT energy consumption report)
3) Compare measured smart meter data to the modelled data from a Green Deal Assessment.
4) Explore homeowners' reactions to both their Green Deal Assessment data and their smart meter energy data.
5) Explore factors influencing homeowners' retrofit renovation decisions.

Methods - a multidisciplinary mixed methods approach

The five homes discussed in this paper are part of a larger 20 household study selected as part of the REFIT project, a collaboration between Loughborough University, the University of East Anglia (UEA) and Strathclyde University (REFIT, 2015). REFIT aims to understand how new data streams from smart meters and smart homes can be used to inform retrofit decision making. The work presented here is highly multidisciplinary and the project partners contributed as follows: UEA – literature review and sampling design; Loughborough University School of Civil and Building Engineering – day to day management of the field trial, collection and analysis of smart meter data; University of Strathclyde – scalable database design and management with autonomous data checking; Loughborough Design School – creative methods for homeowner engagement and conducting the home visits.

Data collection

The homes were recruited via email and leaflet drops. 57 households responded and provided basic information about their household. The study homes were selected based on household occupants' familiarity with new technologies and whether children were present in the home. Within this framework the aim was to achieve as much diversity as possible with a small sample, however, due to the technical focus of the project and the exclusion criteria, relating to the constraints of the monitoring equipment, compromises were necessary. For example, the gas meter needed to be above ground so that the monitoring equipment could get a good mobile signal. This impacted on the sample as a significant proportion of dwellings in Loughborough are terraced and have their gas meter in the basement. The sample was skewed towards larger detached dwellings due to the exclusion criteria and the type of household that was interested in taking part in a technology study (Table 1). Results from the first round of home visits to five households in the overall sample of twenty households are presented here. Three of the homes visited were occupied by retired or semi-retired couples and the remaining two were occupied by families. All of the homes were detached, built during the last 50 years and heated predominantly by gas fired central heating systems.

A detailed building survey was carried out to collect the physical characteristics of the dwellings and some basic demographic details of the occupants. To simulate the smart meter data whole house gas and electricity use was monitored. The pulse output of gas meters was monitored by an external company and was reported in half hourly blocks (SMS, 2014). Household occupants were required to consent to their gas meter being exchanged with one that had a suitable pulse output. Data was collected on a daily basis via mobile communications. Electricity use was monitored every eight seconds for the whole house using a current transformer (CT) clamp, which sends its measurements wirelessly to a hub, which in turn is connected to a base station that sends its data to a gateway via a broadband internet connection. Measurements are pulled in real-time from the gateway to a database on a server hosted and managed by the University of Strathclyde. Tariff information was collected from each household to allow accurate calculations of annual energy costs. External weather conditions were collected at Loughborough University's weather station.

Table 1. Household descriptors of five case study homes

	House type	No. of bedrooms	Construction age	No. of occupants	Floor area (m^2)	Fuel type used for shower
House A	Detached	4	1965 - 1982	2	121	Electric
House B	Detached	4	Post 1999	2	184	Both
House C	Detached	4	Post 1999	4	208	Gas
House D	Detached	5	1983 - 1992	6	182	Gas
House E	Detached	4	1965 - 1982	2	116	Both

The two energy consumption reports

The Green Deal advice report

The Green Deal advice reports were compiled by a qualified Green Deal Assessor who conducted a physical building survey and occupancy assessment of each home using the Reduced Data Standard Assessment Procedure (RdSAP). RdSAP is a steady state building energy model and is the national calculation methodology for the energy efficiency assessment of existing dwellings in the UK (BRE, 2015). Following the assessment, each home was provided with a list of recommended energy saving measures. Each assessment resulted in a Green Deal advice report which included an Energy Performance Certificate (EPC), an Occupancy Assessment report (OA), a set of site notes and an .XML data file containing measurements taken during the assessment for each home. The EPC and OA documents were delivered to the homes via an online web link and email.

The REFIT energy consumption report

Based on the monitored gas and electricity data a number of figures were calculated and presented to occupants in the form of REFIT energy consumption reports (Figure 1). The reports replicated the figures presented in the Green Deal advice report but were based on smart meter measurements rather than modelled figures using RdSAP. Calculations required for the REFIT reports were annual gas and electricity consumption and visualisations of energy costs over a year, a week and a day, daily heating period and the annual energy savings for the measures presented in the Green Deal advice reports. The calculation method for each of these items is described below. The rationale for creating the REFIT Energy Consumption Report in this way was to provide energy use information in a simple, accessible format, which could be easily understood by the majority of the population. It is important to note that this study did not set out to explore the most appropriate means of visually communicating energy data; however, homeowners were given opportunity to offer feedback on the design and format of reports.

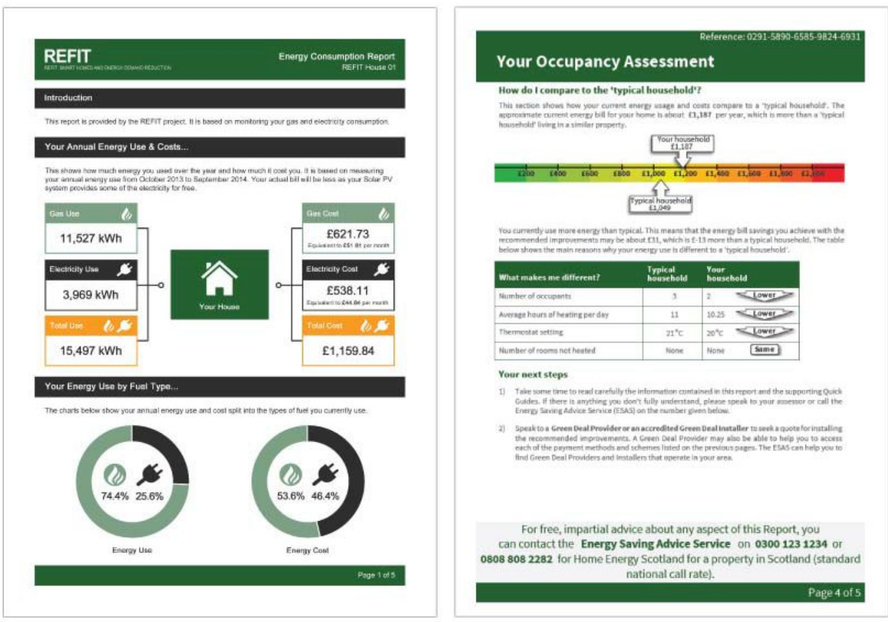

Figure 1. Examples of the REFIT energy consumption report (left) and the Green Deal advice report (right) for House A Calculating annual energy use figures

Calculating annual energy consumption figures based on the available smart meter data (data cleaning)
The annual energy consumption figures presented in the REFIT energy consumption report were calculated using an incomplete dataset. As a result, estimations had to be used for the missing data. There were four reasons why data was missing: 1) the home visit was carried out before a whole year of monitoring had taken place; 2) electricity data was lost from many of the homes between January 24th and March 5th, during a complete upgrade of the database for scalability and robustness and to revise the structure of the database to enable autonomous data checking, autonomous addition of sensor streams picked up from the gateway data stream and facilitate querying; 3) gas data for some days was lost in individual homes due to poor mobile signal; 4) periodic data loss from individual homes occasionally (of the order of a few hours to a few days) occurred when communications with the database failed, e.g., when householders turned off their router or base station or when sensors failed. Table 2 shows the data available from the homes. Missing data for single days were replaced by the consumption of that day the week before. For longer periods of missing electricity data the daily average for the missing days was calculated to be the average of the month before and after the missing period. This roughly accounted to the small amount of seasonal variation which can be observed in the monthly totals. For gas consumption, when longer periods were missing, this approach would have proved inaccurate due to the significant impact of external temperature on gas consumption for heating. Consequently, daily gas consumption was regressed against daily external air temperature, and the equation of the line of best fit was used to predict the energy that would have been used for the unknown period. This method was preferred to a degree day method which assumes that heating is used when the external air temperature is below a standard threshold without accounting for current occupant practices (Kane, 2015). It should be noted though that this approach is more appropriate in homes for which heating behaviour remained constant. For example, the approach was less successful in House E which was heated using a different heating schedule and set point temperatures for a period of the winter when the occupants were on holiday.

Table 2. Availability of data for calculating annual energy use figures.

	No. of days where data was available	
	Gas	Electricity
House A	356	286
House B	355	263
House C	365	284
House D	358	296
House E	316	204

Estimating annual energy savings using the smart meter data
As mentioned previously, the REFIT energy consumption report contains energy savings figures for each of the improvements measures included in the Green Deal advice report. Calculating the annual energy savings for these measures required two steps. First, annual energy use figures that were comparable with those predicted by the Green Deal were required. This involved weather correcting the measured gas consumption figures. The regression approach used to estimate missing gas data, described above, was applied. However, instead of using actual average daily external air temperatures, the average monthly external air temperatures used in the Green Deal modelling process were used. Second, the energy savings predicted by the Green Deal were adjusted according to the difference between the Green Deal annual energy consumption and the comparable weather corrected figures. For example, House C consumed 26% less gas than predicted by the Green Deal, the annual energy savings reported in the REFIT Energy Consumption report were consequently 26% less than predicted by the Green Deal. This resulted in larger savings in the homes where the measured energy use was greater than the energy use predicted by the Green Deal.

Calculating daily heating periods
Daily heating periods were estimated using the half hourly gas consumption figures for a winter month during which heating was used every day; if more than $0.1m^3$ of gas was consumed in a half hour period it was assumed that heating was in use. The half hour blocks where heating was in use were summed and averaged for weekday and weekend periods.

Summary of information presented to households
Assessing the accuracy of Green Deal predictions in not an aim of this paper, however this section provides a brief overview of the information presented to householders. The average measured energy consumption that was presented in the REFIT Energy consumption reports was 17,797 kWh per house (Table 3). Table 3 also

presents annual gas and electricity consumption from the Green Deal advice reports, the weather corrected measured data and the percentage difference between these figures; which was used to adjust the annual energy savings show in Table 4. The average weather corrected measured energy consumption was 20,143 kWh which was only 1% higher than predicted by the Green Deal advice report (19,991kWh). These figures are, on average, 2% lower for annual gas consumption (energy use for hot water and space heating) than predicted by the Green Deal and 7% lower for electricity use (energy use for lighting and appliances). Three of the five homes use less energy for space and hot water heating than predicted by the Green Deal Assessment. This will impact the potential energy savings related to building fabric upgrades. It should be noted that the Green Deal Assessment process estimates the energy end uses of space heating, hot water heating, lighting and appliances. In some of the homes the energy used for hot water heating is related to electricity consumption due to the use of electric showers. There is also a range in the fuel types used for cooking. These differences between homes will influence the proportion of energy used for different end uses as described by the Green Deal but not total energy use. Electricity and gas consumption measurements from the homes were disaggregated to assess the proportion of energy use associated with electric showers (Liao, 2014), however, only House A had significant annual energy use relating to the use of electric showers (330 kWh). Consequently, the allocation of energy use for this will not overly impact on the comparison between the two reports.

Table 3. Annual energy consumption for the five case study homes; measured, weather corrected and predicted in the Green Deal Advice report

		House A	House B	House C	House D	House E	Average
Gas consumption/ space and hot water heating	Measured (kWh)	11,527	12,900	16,737	8,387	18,515	13,613
	Weather corrected[1] (kWh)	15,539	14,271	17,430	8,826	23,732	15,960
	Green Deal (kWh)	12,445	15,603	21,971	9,675	20,473	16,033
	Percentage difference[2]	80%	109%	126%	110%	86%	102%
Electricity consumption	Measured (kWh)	3,969	3,891	4,499	4,673	3,887	4,184
	Green Deal (kWh)	3,770	1,787	4,722	5,943	3,566	3,958
	Percentage difference	95%	46%	105%	127%	92%	93%
Total energy use	Measured (kWh)	15,496	16,791	21,236	13,060	22,402	17,797
	Weather corrected[1] (kWh)	19,508	18,162	21,929	13,499	27,619	20,143
	Green Deal (kWh)	16,215	17,390	26,693	15,618	24,039	19,991
	Percentage difference[2]	83%	96%	122%	116%	87%	101%

[1] Measured figures adjusted to allow comparison with Green Deal predictions using regression method as described above
[2] Percentage difference between Green Deal prediction and the corresponding REFIT value estimated using smart meter data

Despite having a large floor area, House D has very low energy consumption for space heating. This is probably because the household uses a large solid fuel heater on a daily basis. House B used more electricity than was predicted and considerably less than the other homes. This is again surprising, as it has the largest floor area (The Green Deal bases electricity consumption on floor area and number of occupants, with a correction for low energy lighting, electric showers, tumble driers, electric cooking appliances and the number of cold appliances) and may suggest that an error may have been made in the Green Deal Assessment.

Table 4. Green Deal and REFIT estimated cost savings from retrofit measures

	Retrofit option	Annual Green Deal cost saving (Euro)	Annual REFIT cost saving (Euro)
House A	Loft insulation	29.21	35.56
	Hot water cylinder insulation	10.16	9.00
House B	New condensing boiler	77.47	81.28
House C	Hot water cylinder insulation	10.16	9.00
	New condensing boiler	101.60	90.42
	Solar hot water	49.53	44.08
	Tap heat recovery	8.89	7.91
	Hot water cylinder insulation	10.16	9.00
House D	Solar PV	267.97	N/A[1]
House E	Floor insulation	72.39	82.55

[1] A REFIT cost saving could not be made for Solar PV using the simple method devised because of time of day use and feed-in tariffs

Table 4 shows the annual cost savings presented to the occupants in the Green Deal advice report and the REFIT energy consumption report (all costs are reported here in € but were given to UK households in £ in the two reports). The largest percentage differences between the Green Deal and REFIT cost savings was 26% (House C) and 20% (House A). The discrepancy between energy savings, however, has little bearing when compared to the capital outlay for most of the recommended measures. For example, the most significant annual energy savings is the condensing boiler (Houses B & C) but this would cost approximately €2,500 and consequently the payback time is still significant. Less expensive measures such as loft and hot water cylinder insulation (e.g., House A) have much lower annual energy savings. The average energy cost for space heating for the five homes is approximately €777 and consequently the energy savings shown are low.

Visits to the REFIT homes

The method described in this section is focussed on one collaborative activity that forms part of a wider co-design approach being undertaken in the REFIT project, involving a number of activities with homeowners working towards designing concepts for retrofit decision support tools. Described below is one component of the wider co-design process; a card sorting activity and discussion conducted during visits to five REFIT homes that aimed to investigate both the factors that influence the homeowners retrofit decisions (such as their homes and circumstances, their values and futures), and the impact of two sets of energy report both in general and more specifically on the homeowners retrofit decisions. The visits were divided into two distinct phases (see Figure 3). The first phase involved discussing the Green Deal advice report and a collaborative card sorting activity using a range of co-design tools. The second phase followed the same process but instead based on the REFIT energy consumption report.

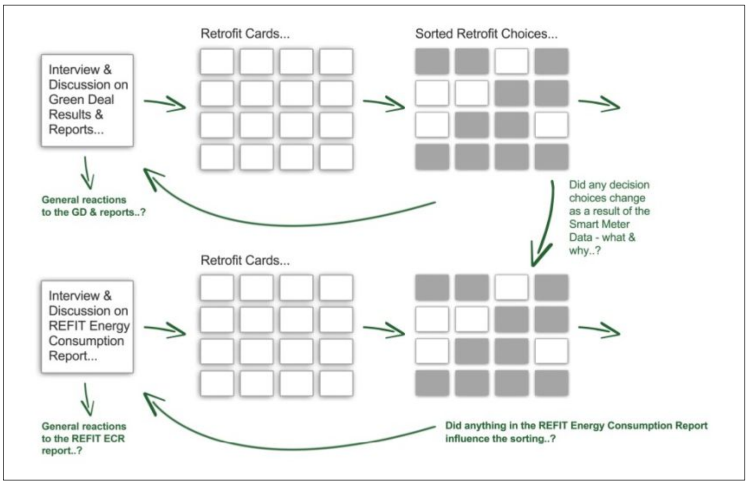

Figure 3. Co-design process during the home visits

Energy report discussions & retrofit card sorting exercises

The format and structure of the home visits shown in Figure 3 is as follows:

Step one: The homeowners were given an opportunity to read their Green Deal advice report before discussion opened with the research team to capture their reactions both in general and in relation to what they felt they might do to save energy as a result. The homeowners were given an opportunity to highlight elements they found interesting or difficult to understand and were assisted by the researchers in understanding any unclear elements or anomalies. **Step two:** The homeowners were then given a set of 42 cards representing the range of energy saving measures currently included under the Green Deal (DECC, 2011) and asked to place them into a set of ten pre-determined categories based on what the Green Deal advice report had told them and how well they thought each measure would work for them and their families. Both the card sorting activity and categories (Figure 4) were designed to provoke discussion of the factors that were influencing the homeowners' hypothetical retrofit decisions, such as their intentions, needs and desires, their circumstances, and their financial situations and futures. For example, the categories 'I would consider installing this but…' and 'probably not but I could possibly be persuaded…' were designed to prompt the homeowners to fill in the blanks and to provide reasons for assigning each retrofit measure to a category. During this activity, the researchers worked collaboratively with the homeowners, helping them to consider the retrofit measures fully by explaining the measures and categories, questioning the homeowners' reasons for the sorting measures as they were, and exploring reasons for previous retrofits (in the 'I have already installed this as much as I can…' category). A set of visual, paper-based probes was also placed on the table during the card sorting activity. The probes contained images of the homeowners and their home and text labels that represented both the general benefits and drawbacks of installing energy saving measures (such as reducing energy bills, improving comfort, installation hassle and disruption etc.) and the wider factors that influence retrofit decisions such as personal circumstances, possible futures, preferences and values. The probes were designed to prime the homeowners' reflections and to provoke deeper consideration of the range and variety of factors that were influencing the homeowners' card sorting. **Step three:** Once the homeowners completed the card sort, they were asked to return to their Green Deal advice report to explore what (if anything) had influenced their retrofit decisions, or if not what may have helped them to better sort the retrofit options both in general and with specific regard to the Green Deal advice report.

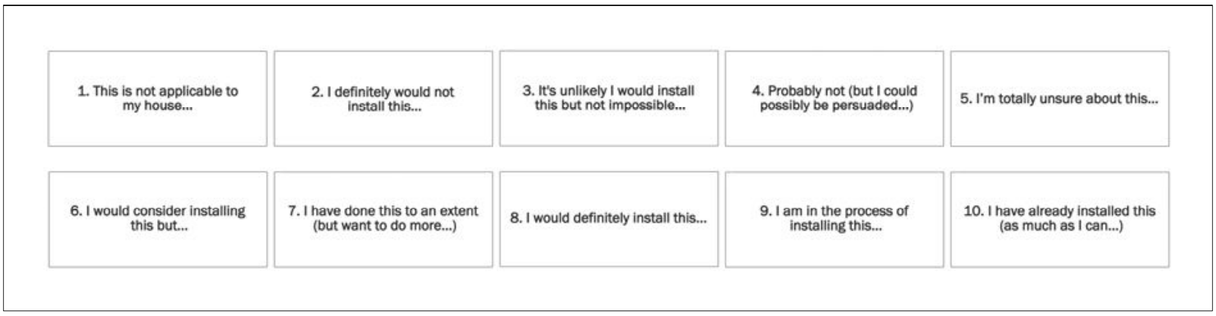

Figure 4. The Ten Card Sorting Categories (to which 42 energy saving measures were assigned by homeowners)

Step four: The homeowners were then presented with and given the opportunity to read their REFIT energy consumption report (based on their smart meter energy data) and were afforded the opportunity to highlight interesting or difficult to understand elements, again assisted by the researchers in understanding unclear elements or anomalies. **Step five:** The homeowners were then asked to return to the card sorting activity and were asked to sort the energy saving measures again, based on what the REFIT energy consumption report had told them and how well they thought each measure would work for them and their families, whilst also considering all of the factors that may influence retrofit decisions (represented by the probes described in step two). **Step six:** Once the homeowners completed the card sort they were asked to return to the REFIT energy consumption report to explore what (if anything) had influenced their retrofit decisions, or if not what may have helped them to better sort the energy saving measures (again both in general and with specific regard to the REFIT energy consumption report).

Results

Reactions to the Green Deal advice report

All five houses were energy aware and although the Green Deal advice report was well received and viewed as highly detailed by all five homes, a notable downfall was that the energy saving recommendations it produced appeared either predictable or unfeasible to each house. All of the houses believed that it failed to tell them anything new with regard to saving more energy. This was perhaps a result of there being little they could do to save energy (in view of their existing efforts) and because the recommendations were perceived to not be worth installing in relation to achievable savings (See Table 4). It did, however, identify one or more energy saving measure for each of the houses. In House A low cost and less disruptive measures (such as increasing loft insulation and installing a new hot water cylinder jacket) were preferred over higher cost or more disruptive measures such as floor insulation. Houses B and D raised concerns over return on investment for expensive measures as the Green Deal advice report recommended replacing a boiler for a more efficient gas condensing one (in House B) or installing solar PV (in House D):

> *"No way am I going to get a new boiler for the cost savings that would be, until the old one packs up" - House B*

> *"So we've done you know a good chunk. Got solar panels [thermal] for the water heating on the roof... So there's not massive amounts we can do without spending a load more money basically... Yeah, photo voltaic, obviously there's a cost involved with those. And at the minute it's prohibitive" – House D*

At the time of the home visit, House B believed replacing their boiler with a new one with only a slightly better level of efficiency was not cost effective in terms of the upfront cost and annual savings achievable. The Green Deal advice report, they believed, confirmed that their decision to wait until their recommended measure required replacing was correct. House D believed they had already made a fair effort in terms of energy saving measures (confirmed by the Green Deal advice report) and that other factors (i.e. financial circumstance and available roof space) remained prohibitive to making further energy saving changes. Further issues surrounding return on investment for higher cost retrofit measures (such as solar water heating and solar PV) were also seen in the visit to House E where it was noted that:

"I will be dead before I get my money back… and [rather than spend the money]…I would rather go on holiday" - House E

In this case, the homeowners were reluctant to outlay large sums for renewables in view of the relationship between long payback periods and their age, and their desire to spend their disposable income on holidays and travel instead. This attitude was reflected in their annual energy use, as they were the only house with higher energy consumption than predicted by the Green Deal advice report. House E also discussed the limitations of the Green Deal advice report, feeling that the report failed to give enough information on how measures were installed, what the implications of installing a measure would be (such as losing height in rooms if installing floor insulation), and its failure to accurately account for the current situation in their house by recommending low energy light bulbs be installed in light fittings that were used very infrequently. House D also raised similar concern surrounding the assessment of their windows:

"The windows, I'm sure those windows upstairs could be improved in the top bedrooms... So maybe some reference could have been made to that… it's double-glazed, so they're only allowed to say, yeah, that's double-glazed..." – House D

The homeowner believed the assessment failed to recognise the poor state of some of their windows, instead averaging the dwelling's glazing's level of energy efficiency across the complete dwelling. In this case, House D felt the Green Deal fell short due to constraints on the assessment process and should have recommended or at least considered replacement glazing. The Green Deal advice report was also perceived to have a number of benefits, the most prominent being prompting the houses to question their current efforts towards energy saving measures and in doing the process of undergoing a Green Deal Assessment was regarded as useful in solidifying that previous installations and efforts to improve efficiency were positive:

[In terms of energy saving measures] "We are on the winning side already"- House A

"It kind of just reaffirmed what we've done and we haven't missed anything sort of glaringly obvious…" – House D

In summary, the Green Deal advice report was perceived as having both positive and negative aspects. It was well received and perceived to be detailed (by all five homes) and in two instances it affirmed the homeowners stances on certain retrofit measures (such as waiting until a measure needed replacing in House B and C). It also helped homeowners to rule out measures that were impractical such as under floor insulation that would require extensive disruption (House E). The Green Deal advice report was also perceived to fall short by not providing installation information about the measures it recommended, or accurately considering usage of elements of the houses it was assessing such as lighting (House E) or the energy efficiency levels of existing glazing (House D).

Reactions to the REFIT energy consumption report

Exposure to the time series data shown in the REFIT energy consumption report triggered lengthy discussion over levels of energy use, and prompted all of the five houses to discuss their lifestyle, home, energy behaviours and what they could potentially do in the future to reduce their energy consumption. All five homes expressed interest and surprise in how the report highlighted the relative cost of electricity compared to gas. House D in particular expressed firm belief (when discussing proportions of energy use by energy type in comparison to proportions of energy cost by energy type), in that energy suppliers' should make efforts to visualise consumption more clearly where possible (e.g. for customers on dual fuel tariffs supplied by the same energy supplier):

"I think it would be good if they did that on all gas and electricity bills, rather than a load of flannel that you can't understand, if they did it like that, you'd have a fighting chance of making some decisions…" – House D

In general all houses found it interesting to try and recollect what they had been doing in relation to what the report was telling them about how they live in their home.

"It is quite interesting to look at these retrospectively" [in order to judge what they had been doing that day or week] - House A

The occupants of House D also found it interesting to try to work out or remember what may have been causing differences or anomalies in their energy use (such as the heating or an appliance being turned on) to ascertain daily living patterns, they also posed an interesting caveat to the snap shot of data they were being presented with. They believed they required more than just one day's worth of hourly energy use data and that a visualisation of a week or a month in the same format (hourly) would be beneficial in creating a clearer picture of what was happening in their home and what in particular may be causing differences or patterns in their energy use.

> *"To make an informed decision I'd have to see maybe a week's worth or a month's worth, and just flick through them and just see [what's going on…]" – House D*

House E's occupants were prompted to reflect on their actions and whereabouts at certain points during their previous year (when reviewing their energy consumption by month). They expressed concerns over their high baseline energy use whilst they were on holiday during the summer months and could not understand why it remained so high considering they attempt to conserve as much energy as possible when they are away from home. For House E the report raised awareness of the appliances that are on all of the time (e.g., their fridge, freezer and fridge-freezer, as well as PC and set-top box), highlighted by the visual differences between the baseline demand level and the level when they were at home compared to when they were away.

On the REFIT energy consumption report, all of the five houses' annual energy consumption and annual energy costs were compared to those of a similar physical dwelling (e.g. for House E, a 4 bedroom detached house built with a similar construction age and geographical location as their own). When discussing the comparisons, although House A expressed interest, satisfaction and amazement at being able to see how they compared to other similar houses, all of the houses made comment on the usefulness of such comparisons in that they are only useful if both the terminology and type of comparison is clear. House D, for example, expressed interest in comparing themselves to a similar house, with a very similar amount of people but without a solar thermal system, to see how the bars displaying monthly usage looked compared to their own:

> *"It would be interesting to see a house without solar heating, what the gas bill did in the summer, with five people or six people as it was…" – House D*

And when questioned about the appropriateness of comparison:

> *"It would have to be a similar house, of similar size and number of people" –House D*

House E also echoed this point, expressing concerns over what the terms 'average' and 'typical' meant, speaking of the need for clear description of exactly who and what they are being compared to. They clearly stated that the most useful comparison is being compared to a similar house and house (i.e. a similar physical dwelling with similar occupants and behaviours) to their own.

The impact of smart meter data on retrofit decisions

Although in many instances the REFIT energy consumption report did not affect the homeowner's views on retrofit in their *current homes,* (often due to life stage such as being of an age where longer term investments may not see a return, personal preferences such as spending savings on holidays, hobbies or amenity renovations and having done most of the feasible improvements anyway), it was still seen as beneficial in a number of ways. House B in particular made comment on the information being helpful if they were to replace any of their appliances in the future, when considering how electricity compared proportionally to gas in terms of units consumed and cost:

> *"The issue with appliances is that it absolutely reinforces that when you get replacements, it is sensible to really try and get [efficient ones]" - House B*

During the card sorting activity, homeowners from House A also affirmed this point, acknowledging that if replacing their appliances in the future when they broke down, they would look to more energy efficient models considering the relative cost of electricity to gas. Although information on their energy use had little influence on appliance replacement decisions at the time of the home visit, highlighting the relative costs of energy types played spurred homeowners into conceding that when the time comes to replace their appliances they should definitely consider more efficient ones. House B also highlighted how vital *having information* and *understanding it* is for energy-related decisions, when discussing how they had previously made decisions based on their own energy information when installing solar PV. In reviewing their REFIT energy consumption report, they reflected on the importance of this type of information in supporting and affirming the correctness of their previous efforts and decisions.

When questioned about the influence of the adjusted annual savings figures for replacing their boiler, House B felt there was relatively little effect on their decision to wait until their existing boiler failed due to the costs only marginally differing. Instead they believed that the information played a role in further confirming that their decision to wait was a positive decision at the time of the home visit. An occupant of House C also commented on the annual savings figures provided on the REFIT energy consumption report:

> *"All of the information we'd expect to see is there and more, and it's nice that you've put more thought and time into what the recommendations are (on the REFIT report), and made them even more factually correct than the Green Deal…"*

When discussing the REFIT energy consumption report, the occupant of House C applauded the effort and time taken to provide adjusted energy savings figures using the smart meter data, especially noting factual correctness as a merit. However, although House C commended the adjusted energy savings figures, again they were deemed to have little impact on their retrofit decisions. Instead, House C went on to discuss the potential role of energy data (specifically by week, by month and annually) with regard to influencing the replacement of their boiler (which was also recommended by the Green Deal Advice Report). Instead of the decision being a replacement at the time of failure or one purely based on upfront cost and payback, House C described how their decision was more calculated, based on the point at which the boiler's level of energy efficiency was beginning to degrade:

> *"I think it's not the point where the boiler will fail, unless the boiler ultimately breaks first, but it'll be at the point where you can see that the boiler's degrading… So it hasn't got to break, you know I'm an engineer enough to be able to figure that out I think…*
>
> *The Hive system is really good – they are keeping that data and you can have a look at that for the week, the month, the year and you know you can see something is going to cost 200, 300 500 quid more that year because its failing… because they don't just go they can degrade…*
>
> *So I'm at the point of keeping an eye on it and I think the Hive system is now my primary way of finding out how that boiler is getting on you see…" – House C*

House C believed that by reviewing and comparing their energy consumption data by week, by month and by year (using smart meter data as presented in the REFIT Energy Consumption Report), they would be able to make a better informed decision, determining more accurately the point at which their boiler would need replacing.

Additional impacts of participating in the home visits

Although the impacts of the REFIT energy consumption report were limited in terms of directly affecting retrofit decisions, one action (specific to House A) could be attributed to a combination of the Green Deal Assessment results and active participation in the home visit. House A reported an interesting impact on their energy saving efforts, first as a result of their Green Deal advice report. They consequently counted up exactly how many energy saving light bulbs they currently had following querying the figure given by the Green Deal advice report. They ascertained that the figure given (22%) was in fact correct and then went on to explore replacement light bulbs during the home visit tea break, purchasing a set of energy saving LED light bulbs while the researchers were present:

> *"I don't understand the lighting – [according to the report] how we have got low energy lighting in 22% of fixed outlets – because we have it everywhere apart from 2 rooms and the en-suite [takes % from the number of bulbs in the house]" -House A*
>
> *"If you get a pack of those [LED 50w replacements] we will save a fortune" -House A*

Although their REFIT Energy Consumption report (and the smart meter data it was presenting) had little direct impact on their retrofit decisions, participation in the home visit (including the Green Deal advice report highlighting their existing low percentage of energy saving light bulbs and the REFIT Energy Consumption Report highlighting the relative cost of electricity in comparison to gas) could be attributed to prompting House A to think more about their energy costs and previous efforts, prompting them to act. On a similar note House C also made comment on the usefulness of participating in the home visit, specifically the discussions and card sorting activities:

> *"I think the process itself [participating in the home visit]… it's meant to be learning from me… I'm learning from this process I think… because there are things here that I've not thought about… so this process itself [the card sorting and discussion] has helped…" –House C*

They attributed the process of seeing the full range of energy saving measures (on top of the limited recommendations on their Green Deal advice report) as enlightening as it raised awareness of alternative energy saving options that they had not previously considered. In summary, although the REFIT energy consumption report was limited in terms of impact on retrofit decisions, participation in the home visit process (in these two instances), at the very least prompted House A to act and replace their light bulbs whilst also raising House C's general awareness of the number and variety of potential retrofit measures.

Discussion

This work aimed to assess the impact of two energy reports (the Green Deal advice report based on modelled energy use figures and the REFIT energy consumption report based on smart meter data) on retrofit decisions. Home visits involving discussions and creative card sorting activities about retrofit decisions with households suggested that the data relating to energy savings and use in the home had little or no impact on the decision making process of the households partly because the energy savings were small compared with annual expenditure. This is not surprising in the context of previous research in this field which finds that retrofit decisions are often not purely motivated by energy cost saving opportunities (Wilson et al., 2013). However, exposure to and the discussions of the two sets of energy reports with the researchers prompted action in one home and occupants from other homes to think more about future changes. All of the households were stimulated to talk about energy use and retrofit potential by the energy reports and two of the homes stated that the learning's from their home visits would impact on their future decisions, but were not enough to encourage take up of the recommended measures at the time of the home visit due to a wider range of factors (such as upfront costs and disruption involved).

One barrier to action was that the measures were not fully explained in the Green Deal advice report and responses from occupants highlighted some basic misunderstanding. This is an area of potential improvement for the Green Deal Assessment and the home visits suggest that it could be beneficial for measures to be explained more fully during a face-to-face meeting. This would also allow more subtle barriers to be explored and potentially overcome, for example, results highlighted that the Green Deal Assessment failed to take account of the occupants' age and lifestyle and how they use their home when recommending measures (e.g. long payback times not being a good selling point to retired people and recommending replacing incandescent light bulbs for LED light bulbs in fixed fittings that are seldom used not being entirely appropriate).

Although all of the households found the comparisons with other houses on the REFIT energy consumption report interesting, more specific comparisons were requested (such as comparisons of similar physical dwelling and number of occupants). This type of comparison could be made viable when smart meters are rolled out over the coming years. The perception of the households discussed here was that in terms of their energy use they were already doing well in comparison with similar houses, however, if the 80% emission reduction targets for CO_2 by 2050 are going to be met, significant savings from even these 'winning' houses is necessary. The easy 'low hanging' measures such as draft proofing, cavity wall and loft insulation and using low energy light bulbs have been completed in many homes but these are still falling short of the energy savings required of the housing stock by the UK Government. If further savings are to be made in these houses and others like them, motivation to make changes that are more expensive and disruptive are required. This work suggests that the motivation for these changes, certainly in homes are already perceived as comfortable, is not going to come from showing occupants information on potential energy savings regardless of how the data is presented to them. The challenge is how to motivate households to ensure that retrofit measures such as renewables and solid wall insulation become more common. Two of the households discussed here installed PV as a result of the financial benefits related to the Feed in Tariff. An improved and extended subsidy is likely to be required if a measure like solid wall insulation is going to be taken up by in large numbers of owner occupied homes.

Finally, this work concentrated on the impact of smart meter data alone, and was shown to be limited; however, more detailed feedback is possible with smart home data, which can include more detailed assessment of comfort and occupancy. One of the households described here had high energy use but a relatively insulated home, it is likely therefore (and has been observed during home visits) that this household is heated to a very high temperature. This will be explored in further visits to the homes. The results of the initial home visits will be used to plan further home visits, which will include presenting more detailed data to the households. This will include data which has been gathered through smart home sensors and may include an assessment of comfort as discussed above. Results from enhanced building energy models, energy use related to household activities calculated using disaggregation algorithms and information on how the impact of the occupant's engagement with smart heating controls may also be discussed with the households depending on the findings from the remaining households.

Conclusions

A study of five homes has been presented which aims to explore the impact of smart meter data on retrofit decision making. Green Deal Assessments were carried out in and measured energy use figures based on smart

meter data were presented to the households. Follow-up home visits have been presented which highlight a number of issues relating to the impacts of the energy reports that were presented and how the factors influences the households retrofit decisions. The households were all relatively energy aware and consequently the results can only bring insight into a limited proportion of the UK housing stock.
The main conclusions of this work are highlighted below

- The Green Deal advice report and REFIT energy consumption report had limited impact on the household's intentions to make energy efficiency retrofits; however, the additional benefit of showing time series energy use data based on smart meter measurements aided in discussions which helped homeowners reflect on their energy use, prompting them question their existing energy saving efforts.
- A follow-up discussion about retrofit options which serves to better explain energy efficiency recommendations and also considers the life stage, personal circumstances and personal preferences of occupants could encourage retrofit decision making and dispel some of the potential concerns over certain measures.
- The householders studied here were interested in comparative energy consumption and the smart meter roll could be used to provide useful comparative energy use information to householders.
- Households that are energy aware are likely to have already made a number of energy saving changes but if climate change mitigation targets are to be met, significant government-led drivers, such as subsidies, are necessary to increase the uptake of the more expensive and disruptive measures.

Future work to roll out the methods presented here to the full sample of 10 homes is continuing and will include a second home visit which presents occupants with more synthesised results based on smart home data streams analysed across the four project partners.

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