29th International Conference on Informatics for Environmental Protection (EnviroInfo 2015)
Third International Conference on ICT for Sustainability (ICT4S 2015)

Investigation into the slow adoption of retrofitting

What are the barriers and drivers to retrofitting, and how can ICT help?

Christopher Weeks
Industrial doctorate centre in Systems
University of Bristol
Bristol
Email: christopher.weeks@edfenergy.com

Charles Delalonde
EDF Energy R&D UK Centre
52 Grosvenor Gardens
London
Email: charles.delalonde@edfenergy.com

Chris Preist
Industrial doctorate centre in Systems
University of Bristol
Bristol
Email: chris.preist@bristol.ac.uk

***Abstract*—In this paper we explore a number of reasons for the slow adoption of energy efficiency measures by householders. We use primary research collected over a two month longitudinal trial to define a number of the core barriers and drivers to retrofitting. The trial logged participants who were interested in energy efficiency measures but were still undecided about whether to install them or not. We conclude the paper by supplying a number of recommendations about how ICT can be used to help remove the barriers and enhance the drivers during this critical decision period.**

***Index Terms*—Retrofitting, Green Deal, Customer Engagement, Energy Efficiency Measures, ICT**

I. Introduction

Since the UK signed the Kyoto Protocol in 1998 [1] the UK Government has been driving to reduce the six greenhouse gases that are considered at least partly responsible for global warming. If we break down the allocation of greenhouse gas emissions to where the end use occurs, energy consumption in the residential sector accounted for 25% of all emissions in 2012 [2]. In households space heating has the largest environmental impact, as it accounted for 66% of total domestic energy consumption in 2012; the rest is broken down into: 17% for water heating, 15% on light and appliances and finally cooking that accounts for around 3% [3]. To build upon this issue within the UK we have a rising expectation around the level of comfort householders expect, for example in 1970 the average household temperature was 12°C, and it has risen to 17.6°C in 2011 [4]. These levels of comfort are replicated across Europe, with Nordic countries having the highest average indoor temperatures in the EU (22°C in Swedish houses), while Southern Europe has an average indoor temperature of 20°C [5]. To maintain these levels of comfort and reduce the overall EU carbon emissions, we need to re-think the configuration of our current housing stock within Europe. To achieve this there are two options:

1) Build a new energy efficient housing stock
2) Retrofit the current housing stock to be more energy efficient

If we investigate option one, in a number of EU countries over the last decade we have seen a tightening in the housing regulations for new builds. Since 2013 the UK building regulators define that new builds must have a 44% reduction in their target emission rate compared to 2006 standards [6]. However, new builds still make up a limited proportion of the overall European housing stock, with the proportion of properties built between 1991-2010 only being 14% in Southern Europe, 19% in Northern and Western Europe and 17% in Central and Eastern Europe [7]. Conjointly, the average rate of replacement is around 1% in both the EU [7] and the UK [8], and this rate of replacement is too slow to meet our required CO_2 targets, according to The Royal Academy of Engineering who state in their "Heat: Degree of comfort?" report that:

"Most of the houses that will exist in 2050 have already been built. New houses should be built to the highest standard of energy efficiency but that, by itself, will not be enough. If we are to meet the 2050 targets, major improvements will have to be made to the existing housing stock." [9]

These facts leave us no choice but to investigate option two, re-designing our current housing stock.

The social, economic and political factors are becoming aligned to make this both possible and desirable to retrofit the current housing stock. On the macro level, the European Commission's "Energy Efficiency Directive" puts direct requirements on the:

"energy distributors or retail energy sales companies to achieve 1.5% energy savings per year through the implementation of energy efficiency measures." [10].

Meanwhile on the micro level, there has been growing concern around energy costs in households, and a desire to reduce bills, though this does not always translate into householders making their properties more sustainable.

With the increased focus on reducing CO_2 emissions, we have seen an escalation in technological developments, both in current energy efficiency measures (solar panels, insulation, etc.) but also in ICT (information communication technology) devices, that now allow us to collect large amounts of quantitative data about individuals' households (smart meters, smart thermostats, etc.). In association, it has also been shown that a number of current energy efficiency measures are cost-effective if you apply a discount rate of 3.5%, which is in line with UK treasury guidance [11], and even in 1990 Carlsmith et al. stated:

"The constraint on efficiency improvements in the short term is not primarily technological. Instead there is insufficient implementation of existing cost-effective technologies." [12]

Therefore, even with cost-effective energy efficiency technologies, we still have the prevailing social issues that constrain householders from installing energy efficiency measures, and only those who are seriously committed for environmental reasons are implementing measures. This paper will look to investigate these social issues that are stopping householders from retrofitting.

Finally, it must be noted that this paper is building upon previous research in this field completed by the authors. In our previous research "Power law of engagement - Transferring disengaged householders into retrofitting energy savers" [13], we defined a unified framework to express the stages that householders go though in the process of retrofitting, and looked at the role ICT plays at each of the different stages. In conducting this previous research, we defined a vital intervention point between stage 5 (Evaluating Expert Advice) and stage 6 (Home Improver). This point in the process is where individual householders have shown an interest in energy efficiency measures, have received information about potential options from an expert, but still haven't made the commitment to install the energy efficiency measures. Therefore, within this research we place a large focus on that individual point in the decision process and the role ICT plays at this point.

II. The problem

In the introduction we defined a number of the core reasons behind promoting retrofitting, and showed that a number of stakeholders seek to benefit from the re-design of our current housing stock. However, as we will explore in section III, there is still a slow uptake of energy efficiency measures, and there are a large number of barriers and drivers influencing householders. To help increase the appeal of energy efficiency measures within the UK, The Department of Energy and Climate Change (DECC) has put together a set of schemes to help householders cut their energy bills [14]. The schemes look to correct the market failures, and they also look to remove the problem faced by large initial upfront capital costs. The two schemes that focus on retrofitting are:

1) Energy Companies Obligation (ECO) — Places an obligation on the larger energy companies which supply energy to the domestic sector to provide financial support for energy efficiency measures.
2) Green Deal — Helps householders or small businesses install energy efficiency improvements on their property without the upfront cost. To achieve this, a broad range of energy efficiency measures can be financed, or partly financed, through the Government.

The two programmes have seen mixed success. ECO has seen a large uptake, with over 1,217,667 installations, but the Green Deal has found it harder to get traction, with 445,804 Green Deal Assessments taking place, but only 21,665 measures installed through both the Green Deal Finance Plans and Green Deal Home Improvement Fund [15]. Rosenow et al. defined six criticisms of the Green Deal and ECO:

1) Contribution to carbon reduction — Green Deal and ECO are estimated to deliver only 26% of the carbon savings of previous policies (Carbon Emission Reduction Target (CERT) and Community Energy Saving (CESP)).
2) Potential barriers to uptake — Currently the Green Deal finance deals with the problem of initial upfront cost, however it doesn't affect other potential barriers like disruption, householders' time commitment or poor integration of the supply chain.
3) Design choices made and their implications — In a number of occasions it has been highlighted that bad design choices have been chosen, for example due to the supply chain not being ready for the rapid increase of solid wall installation, the Government modified the initial proposal, and now it is unclear if ECO will cover solid wall installation. In conjunction, subsidies have been removed for all lighting and appliance energy efficiency measures.
4) Supply chain capacity to deliver — The capacity of the supply chain can limit the number of installations.
5) Credit default risk — Under the Green Deal program, householders are taking out a loan on their property, therefore if householders are not able to repay the loan, this can cause a default on the loan; the risk then lies fully on the Green Deal provider.
6) Fuel poverty — The Association for Conservation of Energy showed that Green Deal and ECO would cause a 29% reduction in total fuel poverty spending, compared to the previous government schemes [16].

In reviewing the criticism of the two Government schemes, we want to explore the householder's decision process in more detail. We had a number of core questions surrounding retrofitting, especially in the context of the two Government schemes highlighted above. These questions are:

1) What is the householder's view of the slow uptake of retrofitting?
2) What stops householders taking out retrofitting measures during the process of the Government schemes?
3) How can ICT be used to remove a number of the barriers faced by householders when it comes to retrofitting?
4) How could ICT be used to increase the uptake of retrofitting?

These are the questions that are explored throughout this paper.

III. Review of research on the retrofitting decision process

In this review we will focus on the core decision process undertaken by householders when they are thinking about retrofitting. To achieve this we have broken the review into two core sections: barriers and drivers of retrofitting, which link directly to our core research questions.

A. Barriers

In investigating the reasons behind what is stopping individual householders from retrofitting, Wilson et al. [17] produced a table that summarises a number of the core barriers that householders face (Fig.1). Wilson et al. describe three core themes: finance, information and decision making; these core themes have also been supported by research conducted by Massung et al. [18]. In the descriptions of the barriers we start to see a number of the core issues facing householders, and a number of hurdles that need to be removed to help increase the level of retrofitting. The barriers described in Fig.1 place a large focus on the householder and even define the terms in relation to the responsibility faced by the householder, e.g. hassle factor, cognitive burden. However, in evaluating the barriers we must also explore the impact the external environment has on the householder, and start to investigate a number of failures that could be limiting the householder. In drilling down further into the literature, we start to see two types of failures that are occurring: market failures and behavioural mismatches [19].

1) Market failures: Market failures can be defined by the energy efficiency gap: that energy efficiency technologies exist, and that simple net present value calculations show them to be cost-effective at current prices, but they nevertheless have limited impact in the market [20]. In this context, individual householders are seen as rational agents based on rational choice theory [21], and they look to maximise their own expected utility. Consequently, the decision to have retrofitting measures comes down to the relationship between initial capital cost, expected future savings, and the increased utility provided to the householder. This will be described within section III-B. The market failures can be caused by a combination of factors, including:

1) Misplaced incentives
2) Discretionary fiscal and regulatory policies
3) Unpriced cost
4) Unpriced benefits
5) Insufficient and inaccurate information [22]

It is widely argued that to resolve these market failures there need to be market interventions, which can come in a number of forms, including emissions pricing, financing programmes or increased investment in information distribution [19]. It must be noted that a large number of market failure interventions happen on the macro-level and typically involve governmental organisations, who look to reduce the overall financial impact faced by householders. In designing the trial explained in section IV we want to explore the impact these market failures and market interventions have on individual householders.

2) Behavioural mismatch: Behavioural mismatch occurs when householders' behaviour is inconsistent with utility maximisation, as Howarth et al. states:

> *"Consumers are irrational in the sense that they do not evaluate energy-using technologies in a manner consistent with life-cycle cost criteria." [23]*

Barrier*		**Description of Barrier**
FINANCE	***upfront cost & capital availability***	• high capital costs • aversion to delayed gains (high implicit discount rates)
	split incentives	• investor & beneficiary are different (e.g., owner - tenant)
INFORMATION	***lack of information***	• imperfect or biased knowledge of energy costs • lack of awareness of potential energy savings
	low or misperceived salience	• invisibility of energy use and/or efficiency measures (e.g., cavity wall insulation) • low % cost of household budget • misperceptions of high and low energy using appliances
	social 'invisibility'	• weakly supporting social norms • weak social signalling / comparison
	uncertainty (trust) / contractor risk	• contractor credibility • unknown quality of work • unknown performance outcomes
	uncertainty (outcomes)	• unknown future energy savings or energy prices • unknown comfort or health effects • (related to high implicit discount rates – see under finance)
DECISION MAKING	***opportunity costs***	• crowding out of higher utility decisions (e.g., amenity renovations)
	cognitive burden	• high transaction cost of information search • complexity of decision (information processing)
	hassle factor	• anticipated disruption to domestic life from renovation work • perceived stress, hassle inconvenience of renovation work
	irreversibility	• irreversible investments, can't be trialled • loss of option value

Fig. 1: The Energy Efficiency Gap: Barriers to Energy Efficient Renovations [17]

Householders are living individuals that have different values, attitudes and beliefs towards energy and the environment, which makes them 'irrational agents' (in the sense they do not behave like the utility maximisers expected by economic theory). In this context we need to use techniques of analysis that derive from the psychology and behavioural economics fields of research, and we need to evaluate cognitive biases and behavioural anomalies. Frederiks et al. [24] composed a list of 11 cognitive biases that are related to householders' view of energy and that are predictable tendencies, below we have selected the core cognitive biases that have an influence on the decision to undertake retrofitting measures:

1) Status quo — householders resist change, and look to go with pre-set options, even in the context where alternative options would lead to greater personal and collective outcomes.
2) Loss averse — individuals commonly focus on losses associated with a new behaviour, whether it be financial,

physical, social, ecological, or time related, and tend to discount the potential gains.

3) Risk averse — householders prefer to avoid risk if the potential gain is a positive outcome. However, the opposite is also true in that householders would take a larger risk if the potential outcome was negative.
4) Temporal / spatial discounting — householders tend to avoid actions that are costly in the short-term but could be beneficial in the long-term. They feel things are less valuable if they are further away in time or space.
5) Conform to social norms — individuals tend towards the behaviours and actions of others within society. Even this is through descriptive or injunctive norms.
6) Rewards / incentives — look to increase individuals' extrinsic motivation, however they can be short-lived and inconsistent, and individuals may respond negatively toward them.
7) Trust — expertise, experience, openness, honesty and concern for others all help householders in their decision-making heuristic. It helps them assess risk and influences their cost-benefit appraisals.

In understanding the cognitive biases, and realising that householders aren't rational agents, we can start to see the problem from a different prospective. In this different prospective we see behavioural mismatch. Gillingham et al. [19] summarise the behavioural mismatch into three core areas of research:

1) Prospect theory
2) Bounded rationality
3) Heuristic decision making

It must be noted that these three core areas of research do cover a large number of the 11 cognitive biases described by Frederiks et al. [24]. In developing interventions to minimise behavioural mismatch, more focus must be placed on education, information distribution, and community led social change.

B. Drivers

In parallel to the barriers we must also understand the drivers: what is it that causes householders to install energy efficiency measures? The drivers that lead to energy efficiency measures are less explored within the academic literature [25], and this is an area we are looking to advance throughout this paper.

Pelenur [26] defined seven core motivations towards retrofitting: saving money, reducing environmental emissions, resource efficiency, warmth and comfort, aesthetics and space, health and safety and time convenience. Similar non-energy benefits were highlighted by Mills et al. [25]. In Oxera's 2006 report "Policies for energy efficiency in the UK householder section" [27], the key finding was that future energy savings had little importance in the householder's decision process, and that other non-energy factors had a greater influence. It must also be noted that in each of these core motivations there can be a large difference in what the terms mean to each householder, for example Huebner et al. [28] explored the meaning of comfort to householders, and found a whole range of meaning: warmth, space, light and cleanliness. Likewise, in evaluating the drivers that motivate householders there must be a key distinction between which drivers are intrinsic or extrinsic motivators:

1) Intrinsic — "the doing of an activity for its inherent satisfactions rather than for some separable consequence"
2) Extrinsic — "the doing of an activity in order to attain some separable outcome" [29]

The two types of motivation have been explored in a number of studies looking for energy reduction through behaviour change, but less attention has been applied to their impact on retrofitting.

IV. Monitoring Trial

To evaluate the questions stated in section II and to build upon the literature discussed in section III, we undertook a two month trial with a number of householders who were at the time trying to decide whether to undertake energy efficiency measures. Throughout this period we captured both quantitative and qualitative data through a number of methods. Firstly, we collected quantitative data from a smart phone application and a low cost USB temperature sensor, and secondly, we collected qualitative data from semi-structured interviews and questionnaires. The trial was design to track the core decision process of having energy efficiency measures installed, so that we can explore both the market and behavioural mismatches stopping householders from retrofitting, and build upon the current knowledge on drivers to retrofitting.

A. Participants

Participants were recruited through the EDF Energy Employee Green Deal trial. Each member was in the process of evaluating whether to install energy efficiency measures through the Green Deal Government scheme described in section II. It must be noted that participants had already shown an interest in energy efficiency measures, and therefore were already in a state of high engagement. Overall we recruited 12 participants: 58% females and 42% males. We also evaluated each participant's level of engagement with energy and ICT (Fig.2). The results showed that our participant sample was engaged in both energy and ICT, but more engaged in ICT then energy.

B. Smartphone application

The smartphone application provides a method of displaying energy and temperature data to the householders, while enabling the householder to input energy meter readings. In the trial we weren't evaluating the level of engagement with the smart phone application, it was only used as a tool to present and collect data from the participants. The application contained two main sections, which can be viewed in Fig.3:

1) Meter reading page — provides a method for the householder to supply their energy meter readings on a regular basis throughout the trial. Trial participants were asked to take both a gas and an electric meter reading once

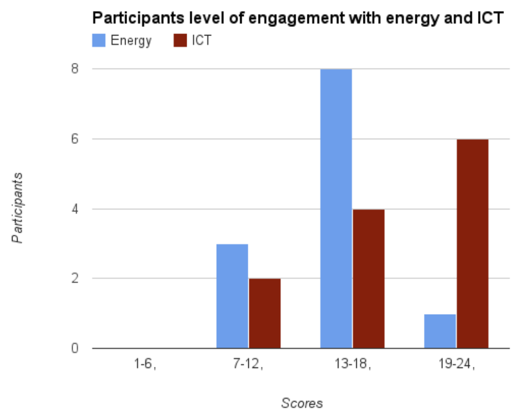


Fig. 2: Participants' level of engagement with energy and ICT

a week. We decided to allow householders to enter their meter readings manually, as currently within the UK there is still a low penetration of smart meters in the domestic energy market; presently only 621,600 installed out of a total of 52 million meters [30].

2) MyDashboard page — provides the householders with a method of looking at their energy consumption and temperature data. MyDashboard is split into three main screens:
   a) At a glance — displays the householder's total energy consumption for the selected period, as well as the average internal and external temperature for the period in a simple view that can be accessed quickly.
   b) In Detail — allows householders to see a graph of their energy consumption for the selected period, as well as, internal and external temperature data. The view provides the householder a more comprehensive view of their data, and allows them to see the relationship between their energy consumption and temperature over time.
   c) Energy Mix — provides householders with a ratio of the amount they have spent on electric and gas, which helps householders to start to infer where they could be saving energy.

C. Low cost USB temperature sensor

The householders were provided a small low cost USB temperature sensor, shown in Fig.4, to monitor the internal temperature of their property. The USB temperature sensor recorded the internal temperature every ten minutes, then after a month of logging the householders would upload the temperature data, and start logging for the second month of the trial. In collecting this data we could start to develop a consideration for the energy performance of each householder's property using the technique developed in Rogers et al. [31].

D. Questionnaires and semi-structured interviews

In the process of developing the trial, we felt it to be of great importance to develop a set of qualitative data sets. We collected 38 questionnaires and 6 x 45 minute interviews throughout the trial:

1) Preliminary questionnaire — investigated participants' current level of engagement in ICT and energy. The questions took the form of a six point Likert scale, and included questions such as: "How often do you review your energy bills?" and "How often do you use online banking on a mobile device?" The preliminary questionnaire also asked participants about their current heating patterns and periods as this information could be used to compare with the data collected from the low cost USB temperature sensor.
2) Trial questionnaires — each participant would take the trial questionnaire three times, once at the start, once at the midway point and once at the end of the trial. The key focus of the questionnaires was to allow us to evaluate how individual householders' views change throughout the trial. The questionnaire again took the form of Likert scale questions, and was split into two sections. The first section evaluated participants' likeliness to install energy efficiency measures, and the second section gauged participants' views on a number of the barriers and drivers highlighted in section III. The barriers investigated included: initial cost, disruption and uncertainty of savings; and the drivers included: environmental views, level of comfort and Green Deal / Government schemes. The results of the questionnaires are evaluated in section V-A2
3) Semi-structured interviews — at the end of the trial, each participant was asked if they would like to take part in a semi-structured interview. Six of the participants agreed. Each interview lasted 45 minutes and was split into two sections: current energy efficiency measures installed, and future Green Deal measures. In the first section, we asked participants to describe the current energy efficiency measures that they have installed in their property; we put a key focus on trying to get the participants to discuss the reasons why they had the measures installed. In part two, we evaluated the participants' views toward potential new measures that could be installed, with a key focus on exploring the barriers currently stopping them from installing the energy efficiency measures.

V. Results and Discussion

In this paper we will mainly focus on the qualitative data collected from the monitoring trial. This is due to a number of reasons: firstly, the qualitative data collected provided the best insight into answering our questions. Secondly, in the process of collecting the quantitative data, there have been a number of issues that have reduced the academic rigour of the quantitative data. This will be discussed in section VII.

A. Trial questionnaires

1) Experimental procedure: A symmetric Likert scale was presented to the participants for each barrier and driver. The

(a) At a glance (b) In detail (c) Energy mix (d) Meter reading

Fig. 3: Monitoring trial smart phone app

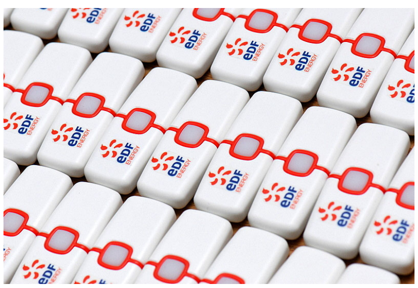


Fig. 4: Low cost USB temperature sensor

householders were presented with both positive and negatively oriented statements, for example:

- Positive statement — I would be willing to put up with disruption if the benefit of an improvement is great enough.
- Negative statement — I am unlikely to have an improvement done due to the disruption it causes.

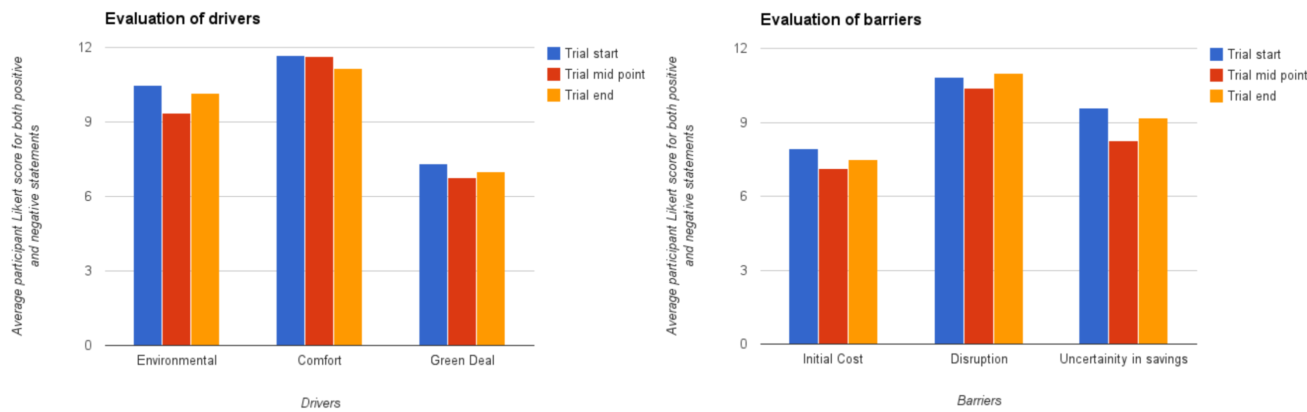
Each participant would express their opinion on the statements as either: "strongly disagree", "disagree", "neither", "agree" or "strongly agree" with the statement, then if the statement was positive the assigned values for the answers would be 1 to 5 in order stated above, and if the statement was negative the assigned values would be inverted 5 to 1. Finally, all the values from both the positive and negative statements were summed to create the participant's overall view; this was completed for all three trial questionnaires.

2) Results and discussion: In analysing the results from the trial questionnaire, we can start to evaluate the participants' views towards each of the barriers and drivers presented in the questionnaire; the results of this can be seen in Fig.5. Fig.5b shows that, during the course of the trial, disruption was the largest barrier stopping our participants from installing energy efficiency measures, closely followed by uncertainty in savings; both these factors are behavioural mismatches that link directly to the cognitive biases "loss" and "risk averse", stated by Frederiks et al. [24]. It is interesting to see that disruption was the largest barrier on participants' mind, especially as a large number of the Government schemes look to reduce the market failure of initial cost, rather than disruption. One factor that could be causing disruption to be the largest barrier is that our participants were currently taking part in the Green Deal process, which meant that the initial cost of the energy efficiency measures had already been factored into their decision process, and their attention was more focused on the installation process.

If we investigate the drivers, we can see that comfort is the biggest driver, followed closely by the environment and Green Deal scheme. It must be noted that the Green Deal was approximately a third less important a driver for householders than comfort and the environment, which highlights that even participants involved in the Green Deal don't see it as a large factor in their decision process. Finally, it is interesting to see that throughout the two month trial, the participants' views didn't see any major changes. However, we feel that the process of evaluating participants' views at the trial start, trial mid point and trial end, provides an interesting methodology that can be used in future research studies, especially as a householder's decision process is not a static event, but instead occurs over a time period.

B. Interviews

1) Experimental procedure: At the conclusion of the trial, six participants undertook semi-structured interviews, each lasting around 45 minutes. The interviews were recorded in audio format, then transcribed to provide our data corpus. We then undertook thematic analysis [32] with two overarching perspective themes that where taken from the design of the interview. The themes were retrofitting barriers and drivers.



(a) Evaluation of drivers (b) Evaluation of barriers

Fig. 5: Evaluation of barriers and drivers collected from the trial questionnaire

In evaluating the initial codes and patterns, the main author took an iterative approach of reading the data corpus, assigning some preliminary codes, then collapsed the preliminary codes into core themes that would lie within our two overarching themes. Once the core themes had been decided, we then looked to match the theme names to similar research defined within section III, as this would allow for comparison with other research. The final stage of the evaluation was to look at the co-occurrence between retrofitting and each of the drivers and barriers: the higher the value the larger the importance to the trial participants.

2) Results and discussion: The evaluation of the interviews generated 235 coded examples that where placed into ten drivers and nine barriers. The results are represented in TABLE-I and TABLE-II. In analysing the results, the first

Drivers	Co-occurrence value (similarity value)
Potential financial savings	0.27
Increased comfort	0.23
Subsidies / Discounts	0.15
Good accurate information	0.10
Current product broken	0.09
Environmental issues	0.08
Renovation already taking place	0.06
Trusted company or brand	0.05
Improve aesthetics	0.03
Social Influence	0.02

TABLE I: List of drivers to retrofitting

thing to note is that a number of the barriers that appeared in our interviews support the research done by Wilson et al. [17] and Massung et al. [18]. The results also support the drivers literature completed by Pelenur [26] and Mills et al. [25]. The first point to note is that finance was the largest factor to affect householders, both in terms of drivers and barriers. On the drivers side, it was highlighted a number of times that

Barriers	Co-occurrence value (similarity value)
Initial cost	0.21
Limited expert knowledge	0.19
Time consuming	0.13
Resignation	0.11
Bad communication	0.09
Limited control	0.08
Disruption	0.07
Damage to the aesthetics of household	0.07
Green Deal loan	0.07

TABLE II: List of barriers to retrofitting

the participants see energy efficiency measures as a method for reducing the amount of money they spend on energy. For example, when asking "what were the key factors for getting energy efficiency measures?", we received responses like:

P2 - "I think the monetary savings still is a big part".
P6 - "Saving money and being warmer"

In evaluating the relationship on the barriers side, a number of participants found the initial cost of a number of measures was too much, even under the reward (incentive) provided through the Green Deal scheme:

P5 - "would like micro-generation but the up front costs are a barrier".
P2 - "Solid wall insulation which is too unaffordable really"

This could highlight a failing in the Green Deal scheme, as one of its key features is to help correct the market failures highlighted in section III-A1, but it is still present in the results from our interviews. Additionally, in a small number of cases the Green Deal loan was seen as a barrier, due to the idea that the loan will pose participants with a challenge when it comes to selling their house. This generates a behavioural mismatch through the "risk averse" cognitive bias:

P3 - "I would go oh, don't want to pay that [Green Deal loan], you pay that [Green Deal loan] off and then I will talk about buying the property from you. I don't want to take on somebody else's debt, even though it is a property I am buying".

The next key factor to note, is that with our analysis of the questionnaires, comfort was a large driver for retrofitting, and it must take more precedence in encouraging individual householders to implement energy efficiency measures. How this can be achieved will be discussed in section VI-A.

In comparing the results we collected to the related research evaluated in section III, we feel there are two factors that are under explored:

1) Renovation / Broken products as a driver — In a number of cases participants showed an interest in implementing energy efficiency measures as part of a renovation, or to replace existing faulty or broken products within their household:

   P5 - "I think the other thing we were just finishing some renovations actually so we wanted to get our loft cleared out and because we were doing that then it made an ideal opportunity [for Green Deal]"
   P6 - "So it's like we need to get things done and then incorporate [energy efficiency measures] at the same time"

   If we can detect when a householder is going to undertake a renovation or replace a broken product, we can used this opportunity to promote the most energy efficient solution, while not having to worry about the "risk" and "loss averse" cognitive biases, as the householder has already accepted some level of disruption and financial burden.
2) Resignation as a barrier — Participants on a number of occasions displayed feelings of resignation towards both their current levels of comfort, and their ability to change the state of their household. It must be noted also that resignation could be caused by householders' limited knowledge on the potential solutions to the energy efficiency problems they face in their households:

   P1 - "the building is over 100 years old so it's going to be prone to damp"
   P3 - "You can see [the boiler] is old, you know it is old, it heats the water in a strange way, it works just about"

   We must take into consideration the householder's resignation about what is possible in their household. We must develop strategies that empower the householder to take on the challenges facing them. This could also help reduce the "limited control" barrier highlighted in TABLE-II.

Throughout this section we have evaluated a number of the barriers and drivers through analysing both the questionnaires and interviews conducted with the participants.

VI. Recommendations for the role ICT can play in encouraging retrofitting

In this section we will take a retrospective view on the previous sections, and look to define a number of recommendations about the role ICT can play in encouraging retrofitting. It must be noted that the recommendations are not in any set order.

A. Comfort

The first area of interest for us is looking at the ability to build upon the driver of comfort and to help reduce the barrier of initial cost, as these where core factors affecting our trial participants, as shown in sections V-A2 and V-B2. It has been shown that at the current average UK housing temperature (16.5°C) around 30% of the energy saving from heat-related measures is provided to the householders as improved comfort (warmth), rather than direct financial savings [33]. This is known as the rebound effect. However, when buying energy efficiency measures this increased comfort is not represented in the initial cost, nor is it expressed in a simple quantitative method to householders. In the trial, we collected data through a low cost USB temperature sensor that ended up being unsuitable for evaluating comfort. However, with the rise of smart thermostats (Netatmo [34], and Nest [35]), we have a much simpler method for collecting internal temperature at an increased frequency, which gives us a great opportunity to start evaluating the levels of comfort that each energy efficiency measure provides to the householder. These new ICT tools can start to display the increased level of comfort as a return on investment on the householder's initial costs. In our trial it was hard to represent comfort, but by utilising smart thermostats to develop models of comfort, we can start to provide householders with ICT solutions that allow them to monitor their level of comfort, rather than energy consumption, and the concept could be pushed further to the point where comfort is sold over energy, leaving the responsibility of energy efficiency measures to the energy companies rather than the householder. This development could help shift the social norm that locks communities into not considering energy efficiency measures.

B. Renovation

Secondly, in section V-B2 we highlight that current renovation work and broken products are both core drivers to installing energy efficiency measures. In this area ICT can play a core role in discovering when householders are thinking about getting renovation work done, or when they have under-performing products within their household. In the former scenario, ICT has shown great potential at predicting householders' buying habits; Google's advertising engine or Amazon's recommended products are two great examples. If we can apply similar ICT techniques to discover householders who are interested in renovation, we can provide them advice and recommendations on the best energy efficiency measures to suit their needs. In conjunction, renovation can be equated to a lifestyle change, therefore as Duhigg [36] showed this is also great opportunity to change householders' habits. In the latter, we see the development of low cost sensors, like the ones used in this paper, will increase the amount of data collected from within the household, therefore allowing us the ability to discover a large number of under-performing products, whether it be boilers, solar panels, window glazing or domestic products such as washing machines, fridges, or TVs. As these ICT products become 'Smart' through low cost sensors, it gives us a great opportunity to get householders to start thinking about more energy efficient options, and in this area we can apply the concept developed by Freedman et al. [37], where getting householders to agree to small energy efficiency changes (replace washing machine to A+ model, replace broken boiler) that are required due to faults can lead to the acceptance of large energy efficiency changes (micro-generation, solid wall insulation).

C. Initial cost of high price items

In our results initial cost, time, and disruption where core barriers stopping our participants from installing energy efficiency measures. Ambitious retrofitting comprises a major decision, and can only work if the right advice is available for the householder [7]. The authors feel that we need to take a different approach to encouraging the purchase of retrofitting measures. They must be seen as highly priced items, similar to the process of buying a new car, family holiday or having your house renovated. In applying this approach, researchers can start to investigate the psychological models that are appropriate for large one-off decisions. In parallel, this will change the role ICT plays in encouraging retrofitting. Firstly, householders increase their time commitment to investigate the alternatives when it comes to making large purchases, as they want to make sure their £2,000 - £15,000 is spent on the right product for them. Secondly, the decision process is taken over time, rather than at a single point. This concept was the driver for our previous research on the "Power Law of Engagement Model" [13]. In building up an ICT solution to combat this barrier of energy efficiency measures being high price items, we can evaluate work carried out in other industries like car manufacturers or luxury holiday companies. Car manufacturers are a good example [38], as they understand that few individuals are willing to order a £20,000 - £150,000 car online, however, they provide you the ability to customise, visualise and read all about the different features and combinations; you can even save your virtual car online so when you visit your local car dealer on the high-street they know your preferences. This tightly closed integration of ICT tools and customer experience over time provides the householder with an ICT journey from initial research, decision deliberation and purchase of the product; we feel a similar approach should be utilised to help encourage householders to install energy efficiency measures.

D. Resignation

The last recommendation surrounds the barrier of resignation and lack of control that a number of our participants faced. Kaplan [39] showed that helplessness can have a big effect on an individual's decision process. Therefore, one area of interest is how can you empower householders not to feel helpless when it comes to retrofitting, and how you can encourage them to become the designers of their own energy efficient household. ICT can provide tools offering an engaging method for householders to experiment with different designs and different energy efficiency measures, to think about how best to redesign their home. Effectively, this is providing tools to support, empower and engage householders with sustainability in design [40] of home refurbishment. In this approach, ICT needs to provide an engaging method for householders to experiment with different designs and different energy efficiency measures. This could take the form of simulations where the householders can experiment with different energy efficiency measures and different designs and view their impact in term of potential drivers (potential savings, comfort and environmental impact), and barriers (initial cost, time investment and disruption).

VII. Discussion

This paper has presented an evaluation of householders' decision process during the vital point when householders have showed interest in energy efficiency measures, but they are still undecided. However, in developing this paper there have been a number of issues that we would like to highlight to help future research. Additionally, we will also highlight the future research we want to complete. There were two factors that caused large issues throughout the trial. Primarily, in deploying the small USB temperature sensors, a number of the devices recorded the wrong time stamps, causing the data to be invalid. This meant that the quantitative data did not have the scientific rigour required. In future deployments of the trial we would implement a fall back sensor, or turn to more intrusive solutions like smart thermostats. Secondarily, the trial suffered from a number of participants having a low level of engagement in the trial. This meant that householders didn't provide enough meter readings over the two months to make any scientifically significant discoveries.

In future research we would like to explore a number of areas:

1) Investigate the psychological models behind encouraging householders to purchase highly priced products, and look at how these models can be applied to energy efficiency measures.
2) Develop the smart phone application further to include a number of the drivers and barriers that were highlighted as important throughout this trial.
3) Explore the integration of a number of data sets that can be collected from households, including temperature, energy consumption and movement data. In this process we are keen to see how the contextualisation of data can help to increase the uptake of energy efficiency measures.
4) The trial has shown a number of areas where the Green Deal could undertake a number of improvements. However, without a more in-depth study into the true causes of these concerns it would be hard to advise

policy change. Therefore, we would like to explore this area in more detail in future research.

VIII. Conclusion

In this paper we have undertaken a trial to investigate the core decision process facing householders when they are looking to implement energy efficiency measures. As part of this research we have reviewed secondary data, to provide a grounding to the research. Then to build upon this knowledge we collected primary data through a two month trial, which was evaluated and used to generate informed recommendations on how ICT can be used to encourage householders to retrofit their households to make them more energy efficient. Finally, we have defined a number of issues faced during the trial and provided a number of insights into potential areas of future research.

Acknowledgement

We would like to thank EDF Energy R&D UK Centre and University of Bristol for their support, and Alastair Byrne and Thibaut Possompès, for their help and insightful discussion. This work was supported by the Systems Centre and the EPSRC funded Industrial Doctorate Centre in Systems (Grant EP/G037353/1) and EDF Energy.

References

[1] U. N. F. C. on Climate Change, "Kyoto protocol to the united nations framework convention on climate change," vol. 25, no. February 2005, pp. 1–7, 2007.

[2] D. of Energy and C. Change, "2013 uk greenhouse gas emissions, provisional figures and 2012 uk greenhouse gas emissions , final figures by fuel type and end-user statistical release," no. March, 2014.

[3] ——, "Energy consumption in the uk (2013) domestic energy consumption in the uk between 1970 and 2012," vol. 2011, pp. 1–10, 2013.

[4] J. Palmer, I. Cooper, A.-A. Tillson, P. Pope, P. Armitage, M. Hughes, and D. Godoy-Shimizu, "United kingdom housing energy fact file 2013," *gov.uk*, 2013.

[5] R. Kemna, "Average eu building heat load for hvac equipment," Tech. Rep. August, 2014.

[6] M. Dowson, A. Poole, D. Harrision, and G. Susman, "Domestic uk retrofit challenge: drivers, barriers and incentives leading into the green deal," *Energy Policy*, vol. 50, pp. 294–305, 2012.

[7] M. Economidou, B. Atanasiu, C. Despret, and J. Maio, "Europe's buildings under the microscope," 2011.

[8] W. Swan, M. Wetherill, and C. Abbott, *A Review of the UK Domestic Energy System*, 2010, no. June.

[9] T. R. A. of Engineering, "Heat: degrees of comfort?" 2012.

[10] E. Commission, "Implementing the energy efficiency directive - commission guidance," 2013.

[11] L. D. Shorrock, J. Henderson, and J. I. Utley, "Reducing carbon emissions from the uk housing stock," 2005.

[12] R. Carlsmith, J. McMahon, W. Chandler, and D. Santini, "Energy efficiency: How far can we go?" *Proceedings of the 25th Intersociety Energy Conversion Engineering Conference*, vol. 4, pp. 74–77, 1990.

[13] C. Weeks, C. Delalonde, and C. Preist, "Power law of engagement: Transferring disengaged householders into retrofitting energy savers," *ICT for Sustainability 2014 (ICT4S-14)*, 2014.

[14] UK Government, "Helping households to cut their energy bills - Policy - GOV.UK," bibtex: UKGovernment. [Online]. Available: https://www.gov.uk/government/policies/helping-households-to-cut-their-energy-bills

[15] D. of Energy and C. Change, "Domestic green deal and energy company obligation in great britain, monthly report," no. January, pp. 1–11, 2013.

[16] J. Rosenow and N. Eyre, "The green deal and the energy company obligation will it work?" *9th BIEE Academic Conference, Oxford*, 2012.

[17] C. Wilson, L. Crane, and G. Chryssochoidis, "Why do people decide to renovate their homes to improve energy efficiency?" *Tyndall Centre for Climate Change Research*, no. June, 2014.

[18] E. Massung, D. Schien, and C. Preist, "Beyond behavior change: Household retrofitting and ict," *ICT for Sustainability 2014 (ICT4S-14)*, no. Ict4s, pp. 132–139, 2014.

[19] K. Gillingham, R. Newell, and K. Palmer, "Energy efficiency economics and policy," 2009.

[20] A. B. Jaffe and R. N. Stavins, "The energy-efficiency gap what does it mean?" *Energy Policy*, vol. 22, no. 10, pp. 804–810, 1994.

[21] J. Scott, "Rational choice theory," *Understanding Contemporary Society: Theories of The Present*, vol. 50, no. 1920, pp. 671–85, 2000.

[22] M. a. Brown, "Market failures and barriers as a basis for clean energy policies," *Energy Policy*, vol. 29, no. 2001, pp. 1197–1207, 2001.

[23] R. B. Howarth and B. Andersson, "Market barriers to energy efficiency," *Energy Economics*, vol. 15, pp. 262–272, 1993.

[24] E. R. Frederiks, K. Stenner, and E. V. Hobman, "Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1385–1394, 2015.

[25] E. Mills and A. Rosenfeld, "Consumer non-energy benefits as a motivation for making energy-efficiency improvements," *Energy*, vol. 21, pp. 707–720, 1996.

[26] M. Pelenur, "Retrofitting the domestic built environment: investigating household perspectives towards energy efficiency technologies and behaviour," 2013.

[27] Oxera, "Policies for energy efficiency in the uk household sector," no. January, 2006.

[28] G. M. Huebner, J. Cooper, and K. Jones, "Domestic energy consumption - what role do comfort, habit, and knowledge about the heating system play?" *Energy and Buildings*, vol. 66, pp. 626–636, 2013.

[29] R. Ryan and E. Deci, "Intrinsic and extrinsic motivations: Classic definitions and new directions." *Contemporary educational psychology*, vol. 25, pp. 54–67, 2000.

[30] D. of Energy and C. Change, "Smart meters, great britain, quarterly report to end september 2014," no. September, pp. 1–11, 2014.

[31] A. Rogers and R. Wilcock, "A scalable low-cost solution to provide personalized home heating advice to households," *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, no. January, 2012.

[32] V. Braun and V. Clarke, "Using thematic analysis in psychology," vol. 3, pp. 77–101, 2006.

[33] B. Boardman and G. Milne, "Making cold homes warmer: the effect of energy efficiency improvements in low-income homes," *Energy Policy*, vol. 28, 2000.

[34] Netatmo, "The Thermostat for Smartphone." [Online]. Available: https://www.netatmo.com/en-US/product/thermostat

[35] N. Labs, "Nest learning thermostat - fact sheet," no. 415.

[36] C. Duhigg, "The power of habit: Why we do what we do in life and business," 2012.

[37] J. Freedman and S. Fraser, "Compliance without pressure: the foot-in-the-door technique," *Journal of personality and social psychology*, vol. 4, no. 2, 1966.

[38] BMW, "BMW i8 - Build your BMW." [Online]. Available: http://mybmw.co.uk/r6x7z1m9

[39] S. Kaplan, "Human nature and environmentally responsible behavior," *Journal of Social Issues*, vol. 56, no. 3, pp. 491–508, 2000.

[40] E. Blevis, "Sustainable interaction design: invention & disposal, renewal & reuse," *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 503–512, 2007.