

DEHEMS: A User-Driven Domestic Energy Monitoring System

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Abstract—**Persuasive energy monitoring technology has the potential to inspire sustainable energy lifestyles within the home. However, to effect positive ecological behaviour change, a more user-driven approach is needed for the development of the technology, where the design needs to be accompanied by study on user behaviours and motivations, and the prototype deployed and tested on large sample sizes to understand user preferences. We present DEHEMS, a wide-scale energy monitoring system that undergoes three cycles of design, development and usability assessment so that it can help facilitate energy literacy and environmental awareness based on user preferences. Through real-world deployment, survey and focus group studies carried out in the UK, we present motivations and constraints for saving energy, user assessment of the DEHEMS pilot system and identify some critical user expectations and concerns. We describe how the usability analysis is then incorporated into the design of the next generation DEHEMS system and demonstrate that the resulting system achieves 8% reduction in energy consumption within the first week of feedback.**

Keywords—energy monitoring, persuasive technology, pervasive computing, human computer interaction, user-driven design, evaluation / methodology, energy feedback

I. INTRODUCTION

Simple energy saving steps in the home have the potential to reduce 10% of the UK's carbon emission level, where domestic energy consumption accounts for 30% of the nation's total CO₂ output. Analysis by Darby [1] on smart metering that provides real-time feedback on domestic energy consumption shows that energy monitoring technologies can help reduce 5% to 15% of energy usage. Fischer [2] finds the most successful energy usage feedback are those that are given frequently and over a long time, provides an appliance-specific breakdown, are presented in a clear and appealing way, and use computerized and interactive tools. However, the design and development of energy sensing and display technologies tend to bring the user into the loop after the design process. Fischer points out that research into this area lack large-scale deployment and needs to be accompanied by a body of study on user behaviours, motivations and preferences. Fitzpatrick and Smith [3] assert that there is a

lack of argument on the design principles and rationale behind the development of most commercial energy monitoring gaps systems. The aim of the DEHEMS project is to plug these gaps by undertaking a large-scale deployment, where the system development applies three 'cycles' of User Driven Innovation methodology [4] for assessing and gathering user motivations, constraints and preferences in each cycle, so that the end product can provide a higher usability value and hence effect positive behaviour change in domestic energy consumers. In this paper, we describe the pilot Cycle 1 system, the results of the user analysis via surveys and focus groups, and the subsequent Cycle 2 system driven by the user requirements from Cycle 1.

The paper is organized as follows. Section II describes the DEHEMS development and user assessment methodology. Section III briefly presents the DEHEMS Cycle 1 architecture and user interface. Section IV presents user behavioural context in terms of motivations and constraints for saving energy. We then proceed to discuss the usability analysis. In Section V, we describe the Cycle 2 architecture driven by the usability assessments, and some preliminary results before we conclude our findings in Section VI.

II. DEHEMS METHODOLOGY

The objective of DEHEMS is to integrate and test the effectiveness of innovative persuasive strategies delivered via an intelligent electronic system infrastructure that is able to infer and reason the energy behaviour of the households, received from a number of different sensing technologies; (1) electrical mains circuit sensing, (2) individual appliance-level sensing, (3) gas mains sensing and (4) ambient sensing such as temperature. DEHEMS integrates and tests the effectiveness of the following persuasive strategies:

Multi modal user interfaces: PC-based website, a dedicated real-time energy display device and ubiquitous interfaces such as digital photo frames and mobile phones.

Data visualisation: Feedback of energy consumption via graphical information, colour coded alerts, textual tips and alerts, and emotionally engaging narrative pictures that reflect the state of the household's and the neighbourhood's energy usage.

Data interpretation: Real time energy consumption, historical consumption, family member consumption, comparison against general households in DEHEMS, comparison against grouped households of similar characteristics, comparison for online social networking users, and context-aware personalised energy saving tips and alerts.

User Driven Innovation (UDI) is a product development approach that is user-centric, in the sense that the prototype of a novel technology is simply the starting point where users become part of improving and refining the innovation to obtain a higher user value, as opposed to commercial innovations. Our test bed of households in the UK cities of Manchester, Birmingham and Bristol and the Bulgarian cities of Plovdiv and Ivanovo are termed as the Living Labs [5], a part of a network of EU-wide user groups that enable experimentation and co-creation with real users in real life environments. Based on the UDI principles, we apply a cyclic learning / development process that undergoes three cycles of requirements gathering, design, implementation, deployment and behaviour assessments. The system is progressively incorporated with innovative persuasive strategies and improved based on the feedback from users, who are active actors in the system, instead of passive receivers. The objectives of Cycle 1 are to gather user requirements by understanding the different facets of the users' 'wish list' in technical, usability and innovation terms, and to grasp the technical and usability challenges when the technology is deployed within homes. Cycle 2 will focus on testing the effectiveness of the different feedback strategies, while Cycle 3 will concentrate on integrating new ideas for user interfaces and the most effective feedback strategies.

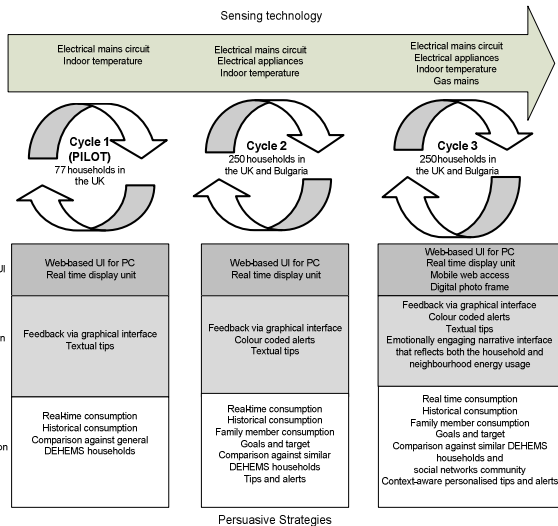


Figure 1. The three cycles of DEHEMS development process. Persuasive strategies and sensing technologies are progressively integrated for a methodological assessment of the system and user acceptance.

The Cycle 1 DEHEMS system has been deployed into 77 households in the UK Living Labs for a period of six months from March 2009. To understand the background of energy

behaviours of users in the Living Labs, and to form a behaviour context for the usability analysis, we conducted an online survey for the participants across all three cities, where 45 responses were received. For the usability assessment of the Cycle 1 system, four focus groups were held in Bristol and Birmingham. Thirty people took part in the focus group studies after experiencing the system for four months, to help us extract user-preferences and pinpoint design concerns. The comprehensive quantitative and the NVivo based qualitative analysis is available online [6].

III. DEHEMS CYCLE 1 ARCHITECTURE

This section focuses mainly on the design of the Cycle 1 DEHEMS home infrastructure and the user interface. More information on the semantic intelligence and server support can be found in previous publication [5].

A. System Architecture

The primary characteristic of the DEHEMS architecture is to gather and communicate energy consumption data from a large number of sensors (and households) for comparative analysis, so that we are better situated to assess the effectiveness of the different persuasive strategies. Therefore, the system focuses on the communication and storage aspects.

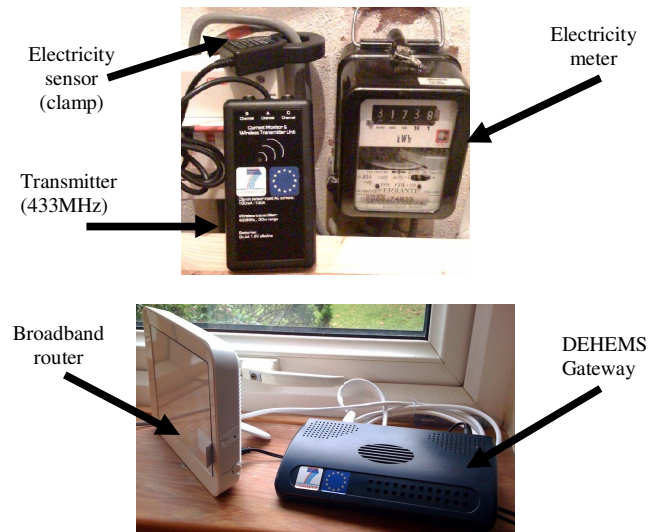


Figure 2. Sensor clamped around the electricity mains circuit communicates with the DEHEMS Gateway connected to the home broadband router.

A Current Cost [6] manufactured current transformer sensor coupled to a 433 MHz FM radio modem is clamped around the electricity mains circuit, that through the process of induction, outputs a current reading onto a low cost A/D converter. The resolution is 12-bits with readings taken approximately every 6 seconds. For the purpose of data collection and keeping sensors within the home lean in processing power, memory and its functionalities, we built the DEHEMS Gateway that comprises a data collection mechanism and data aggregation function for processing data received from the sensors, and an external communication

module that uses TCP/IP to communicate with the DEHEMS server via the in-home broadband router. The Gateway was implemented on a router platform that contains 5 Ethernet ports, 2 USB and a serial header for the insertion of a 433 MHz radio receiver. All data received by the Gateway is forwarded to the Web Service and attributed to the household at the server. The main chipset is an Infineon system on chip that runs OpenWRT, a lightweight Linux distribution with limited memory 8MB of RAM and 2MB of flash storage. OpenWRT has modules for common TCP/IP services like DNS and DHCP.

B. User Interface

The Cycle 1 DEHEMS Dashboard as shown in Figure 3 is intentionally basic in its feedback information and simple in its design. The principle of ‘express enough meaning but not too much’ for designing interfaces for home use, as stipulated by Hindus et al. [9] will be tested progressively throughout the three cycles. The objective is to determine *how much is too much?* to sufficiently produce positive behaviour change in domestic energy users. Thus, in the next two cycles, by extending the granularity of feedback information, we will be able to determine through our analysis, information that does not contribute to behaviour change, or is simply deemed unnecessary by users. Consequently, the Cycle 1 DEHEMS Dashboard as shown in Figure 4 displays real time energy usage in kW, cost of energy usage, energy saving tips, energy usage history (hourly, daily, monthly), along with a comparison against DEHEMS-wide average energy usage. For real-time display, we use the Current Cost energy monitor unit that displays real-time energy usage in kW updated every 6s, cost per month, energy savings per month (kW), bar chart for energy used during night time, day time and evening time of the previous day, the weekly usage (kWh), time and temperature.

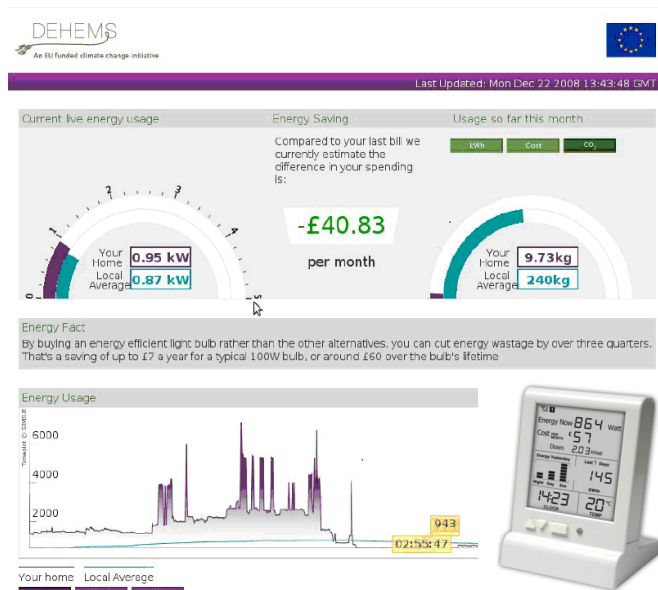


Figure 3. Cycle 1 DEHEMS Dashboard and display device

IV. DEHEMS CYCLE 1 EVALUATION

With the support of the local authorities of the Living Lab cities, we were able to recruit volunteer households for a wide-scale system deployment, undertake surveys for gathering user context and requirements and conduct focus groups for our usability study. Understanding user context such as motivations for saving energy and the constraints for implementing energy saving behaviours enables a better understanding of user preferences and how the energy monitoring system can work with users to achieve the best possible behaviour change. We distributed questionnaires that spanned a wide range of topics; demographics, billing, home energy rating, computer, Internet and social networking usage, environmental consciousness (recycling habits, motivations for energy saving, responsibilities, etc.), appliance understanding and usage habits, energy saving behaviours, and online privacy issues. 45 responses were received, distributed evenly among the three UK cities, where the households demographics are mainly properties with two or three bedrooms, have middle-class annual income range (£20k-£80k) with two to four occupants mostly with young people.

A. Understanding User Behaviour Context

The survey responses enabled us to understand the belief system and the constraints for energy behaviours in the Living Lab households. The user context can be summarised as the following; (1) The target domestic audience who mostly come from working class and middle class income attribute energy saving as mainly a financial concern rather than environmental, thus a shift in the mindset of households from financial motivations towards saving energy as a means for reducing carbon footprint would yield a more pronounced effect on satisfying environmental policies. (2) Our analysis on constraints for saving energy shows that (a) financial constraints prevent improvement to their homes and appliances, (b) a lack of opportunity to practise energy saving steps exists due to limitations in the design of their homes and appliances and more importantly, (c) a lack of knowledge about appliances, about how to save energy, and about the impact of their own energy consuming habits. However, users do show interest to save energy, where further education and energy literacy can help improve their energy behaviours. The following lists in more detail the key user context.

Motivation for saving energy indicates financial reasons. Key factors for survey respondents wanting to reduce energy usage are split unequally between financial savings (‘keeping bills down’, 66.7%), and environmental concerns, specifically reducing carbon footprint (25.6%). However, there is a very high level of environmental consciousness; 88.4% are proactive recyclers of paper, plastic, cardboard, glass and metal/cans, and when asked ‘Who should take the greatest responsibility for environmental protection (government, companies or individuals)’, 72.7% consider individuals play the most important role. Thus the fact that *saving energy is perceived as a financial problem* is a critical barrier for

ecological behaviours, as some energy saving steps such as updating the boiler or purchasing Grade A appliances would require a high initial investment, and reduce financial savings.

Constraints that hinder energy saving behaviours:

(1) **Financial constraint** is cited as the main reason for not switching to more energy efficient appliances, making home improvements, or installing an energy monitoring system. Overall 69.2% claimed they would install energy monitoring if the cost is below £50, and none would do so beyond £300.

(2) **Limitation of appliance and home infrastructure.** This is especially apparent in standby power use, where 50% of the 80 reasons given are to do with appliances not having an 'off' switch (e.g. microwave), requiring standby mode in order to function (e.g. clocks), having inaccessible switch positions (e.g. washing machine and dryers), or needing to be connected directly to the mains supply (e.g. alarms).

(3) **Lack of information on energy efficiency of their household and appliances.** 91.1% do not know their own home's energy performance rating. Lack of awareness regarding standby power causes impatience and laziness in switching off appliances and makes up the rest 50% of the reasons for standby use, which is still apparent in appliances such as set top boxes, televisions, computer monitors, DVD players and microwaves. There is also a clear lack of knowledge about the energy consumption of home appliances. For example, 53.5% assume the kettle, hot water shower and washing machine are the highest energy consuming appliances if switched on for 20 minutes whilst in reality, a cooker hob, oven and grill have the highest peak energy [10]. Only 18.6% correctly cite the cooker and the oven. Thus there is a clear opportunity for DEHEMS as the medium for energy literacy.

The top three common energy saving behaviours are switching off appliances when they are not in use (32.1%), switching to energy efficient appliances (26.1%) and home improvements such as insulation and double glazing (15.3%). A total of 37.7% of the households are also interested in the future seeking to reduce dependency on appliances and technology, such as using the washing machine and dryer less, walk to school and work, use less lighting, etc. Thus the DEHEMS system needs to capitalize on this interest by providing more information on sustainable lifestyle. The user context analysis supports findings by Dillahunt et al. [11] whose survey on low-income households in the US shows that interest on the environment is high for such group, but technology needs to overcome financial barriers to facilitate a 'green' society.

B. Usability Results and Discussion.

The four focus groups were moderated by the local authorities of Birmingham and Bristol, where participants consist of primary householders (parents and head of households), and have mostly responded to the questionnaires. The discussion were focused on the usability and usefulness of the DEHEMS system, to extract the benefits of the system, problems interacting with it and ideas on future improvements. Participants cite several benefits of DEHEMS:

DEHEMS encourages behaviour change. Participants are unanimous in remarking that DEHEMS provides new and

interesting information on their energy usage. As one participant stated, 'We have become a more eco-conscious family, this is fascinating. We are comparing the use of wood-burning energy with others. This system is helping/enabling that comparison.' When asked if behaviour change is long term, all agree that it is so, as one person said, 'Yes, we stuck with that; we're aware of the lights, we're aware of the washing machine. And we're just being more aware and mindful and careful. I think it's an excellent idea, I really do'. Some examples cited include stopping dishwasher usage, changing light fittings to fit energy efficient bulbs, boiling less water in the kettle, changing to a smaller sized freezer, reducing temperature for the washing machine, switching off appliances instead of leaving them on standby mode ('...the microwave is turned off when it's not in use. The toaster is turned off when it's not in use. You can't turn the electric oven off when it's not in use. But, you know, little things.').

DEHEMS encourages information sharing. Participants point out that their friends and family are impressed with their city council's efforts and wish they had similar initiatives in their own neighbourhood. As one woman said, '...my sister is green with envy, she really is. Because suddenly she said 'Well what else do you get in Birmingham?'' Information on energy consumption of the household is shared to family and friends by word of mouth, and by demonstrating energy saving behaviours. Some took it further by researching online on energy saving steps.

There are distinct roles for a handy display unit (but with brief information), and the DEHEMS Dashboard that gives in-depth information and remote access (but requires login effort). Some do not even view the web interface Dashboard as they favour the ease of the local in-home display unit, while others find the meter-like information on the display unit to be too complex. Interestingly, most users who like the display unit use it as a game for investigating their real time energy usage by switching on and off various appliances and viewing the impact. One man said, '...and so I began to think you know, nobody else is up in the house, nobody's watching television, nobody listening. So what is costing money? And so I'd go around the house and finding out what's on standby and what to switch off, and switching things off. And I was fascinated!' Those who like the web interface are computer literate, interested in more detailed feedback and enjoy the ability to remotely access their home to monitor home activities. Remote access also enables users to infer home activities when they are away, thus demonstrating that this technology has the potential to become the platform for activity sensing applications. As one woman commented, '...you can see if you're kids are having a party!'

Participants are especially interested in comparing their homes to other households. The comparison against the average energy use among homes participating in DEHEMS is found to be useful for checking against their own energy usage. However, some do have doubts about whether the data is really comparable. As one person pointed out, 'Don't want to compare usage of household with another. If the system

could compare like with like that would be useful, i.e. a household with four children with another of the same, etc’.

Participants find the energy saving tips interesting and would like to see more detailed facts on energy.

Participants admit their lack of knowledge and would like to be motivated with information on ways to save energy, their appliances and environmental impacts of using energy.

Electrical power curve enables users to identify appliance activities.

An interesting discovery from DEHEMS is that users are able to investigate by themselves which appliances are switched on and running, and which appliances are consuming energy while on standby. For example, as one person describes, ‘...I found that by switching the washing machine off even though it was really just waiting for the next load of washing to come out and one to go in, it was using approximately 70 percent of what it was, when it was running...just amazing’. Another mentioned, ‘...the first time I saw it shoot up I couldn’t believe it, it was because somebody had gone into the shower. And I started watching this again and again. And this has both fascinated and horrified me...’ This indicates that we need to investigate and justify the benefits of having extensive, expensive and complex appliance-level monitoring against the current simpler infrastructure of having a single sensor at the mains.

Users point out several key factors that they feel the DEHEMS system should improve on, some of which are the following.

Participants stressed the need for gas monitoring and appliance details.

As one participant put forward succinctly, ‘Gas. I spend three times more money on gas than I do on electricity’. This is supported through the survey results where 60.6% of hot water, heating, cooker, oven, cooker hob and grill across 45 households are powered by gas. Information on the energy consumed by different appliances is also requested.

Participants pointed out the need for the user interface to be children and youth friendly,

such as innovative tangible and ubiquitous interfaces, besides being inclusive of disabilities. One woman pointed out, ‘After my kids initially looked at the kit they didn’t really want to know more...I do think that it is more about presentation because I think they could enjoy it if they made it more kiddy friendly, touchy, buttony (that) they could get away with...’.

Participants would like to be continuously motivated to maintain their interest in the system via interesting facts on energy and the environment, and stimulating interfaces. They also demand information that can help them to get others interested as well. As one person said, ‘Clear information to help convince friends, colleagues, etc; regarding ECO facts, saving energy, etc. The system could do this.’

Information confidentiality and validity. Some have concerns on their privacy if their appliance usage is monitored. Participants questioned where the DEHEMS server is located, what data is being uploaded, what information is provided to us and if there is possibility for a ‘Big Brother’-like monitoring. There is also concern on the validity of cost information on their energy usage. Some participants have

compared DEHEMS data against their energy bills. Due to such doubts, the effectiveness of presenting financial savings is not clear. It is also necessary in the future to stress that DEHEMS is not a replacement for their energy meter, but instead a medium for energy literacy and monitoring.

Some participants prefer not to be connected continuously to the Internet as they are not in the habit of doing so, and are conscious of the energy consumed by the router. One person said, ‘...we suddenly had to leave the Internet on twenty four hours, whereas before we never did, so that was actually why I nearly said no to actually doing it...’)

The need for wireless and minimalistic infrastructure is stressed often. Participants are not appreciative of the multiple wires for the equipment, such as the need for an Ethernet cable and power cables for the local display unit and DEHEM Gateway. The additional cables cause a false perception that the system itself consumes high energy.



Figure 4. Appliance-level sensing with the Plugwise Zigbee sensor network.

V. THE RESULTING DEHEMS CYCLE 2 SYSTEM

Most of the usability analysis is transformed into user requirements for the subsequent Cycle 2 system. Appliance and gas monitoring (for some households) is included, thus the home infrastructure is extended to incorporate (1) Plugwise sensors [12] that attach to appliances’ plugs, and transmits electricity measurements wirelessly via Zigbee to the DEHEMS Gateway, as shown in Figure 4. The Zigbee mesh is a local peer-to-peer network until arriving at the USB receiver that interfaces through the USB port on the back of the Gateway. Up to 10 appliances can be sensed and given that they are all mains powered, there is no battery life issue. The Zigbee network must be configured prior to installation within the DEHEMS Gateway using the standard Plugwise software. (2) A gas sensor (prototype, will be deployed in Cycle 3) that has an optical character recognition module is attached to the household’s gas meter to transmit meter readings via 433MHz to the DEHEMS Gateway. The feasibility of gas sensing is yet uncertain; an optical sensor that requires technical know-how for calibrating it and transmits data via radio frequency can cost up to £600! Monitoring individual gas powered appliances is not financially feasible, is difficult to configure and different sensors are required for the variety of gas meters.

Due to the use of appliance-level sensors, and the necessity for broadband communication, we will unfortunately not be able



Figure 5. Clockwise from top left: (1) Cycle 2 Dashboard with live energy usage of the home and the Living Lab, comparisons against lowest, average and highest usage in the Living Lab homes and energy saving tips. (2) Comparison against homes fitting a selection of criteria. (3) Individual appliance real-time, weekly and monthly consumption. (4) Historical daily, weekly and monthly power usage.

to satisfy users who require minimalistic infrastructure. The server monitors disconnections and sends alerts by email to notify users to check their connections. For scalability purpose (to support 250 households), the Web Service stores data into a time series database that uses column-wise techniques to compress and store statistics against the readings. The database is based on the open source project Hypertable [13]. Energy data stored in the time series database is summarized and parameterized in order to be abstracted according to the definition in a household model database using OLAP. Energy pattern analysis can then be performed based on the represented data for eventual feedback to end users. The system incorporates an intelligent semantically enhanced reasoning tool that enables personalization of energy saving techniques and comparison among groups of households with similar characteristics such as the number of rooms, occupants, type of house, location, etc., as shown in Figure 5. Future publications will focus on these aspects.

The Cycle 2 DEHEMS Dashboard extends the granularity of feedback information based on the use cases drawn up by the users, such as appliance level feedback, gas energy consumption, personalised energy saving tips that can be rated

on its effectiveness, facts on carbon and energy as environmental issues, goals and targets for both households and individual family members, alerts when necessary, social networking for information sharing etc. We deliberately removed estimated cost saving information in the Cycle 2 Dashboard and added more carbon related information to lead users who are financially motivated towards environmental education, and to assess whether users continue to save energy even without cost information. Snapshots of the current Cycle 2 DEHEMS Dashboard is shown in Figure 6. We will also eventually introduce users to more innovative display devices such as the ubiquitous digital photo frames with emotionally engaging narratives visualizing real-time energy consumption of the household and their neighbourhood.

At the time of writing, the Cycle 2 system has just completed the deployment stage for 250 households across the UK and Bulgaria. The first 7 days of measurement is the baseline period and the DEHEMS Dashboard becomes available to users after the first week. An early analysis shows that the system already has positive impact on users. For instance, the average daily energy comparison between the baseline period and the following 7 days where users have access to the

Dashboard shows that there is around 8% reduction in daily energy consumption. Figure 6 shows the results of comparison between the baseline week and the feedback week for 126 households in the UK. For the purpose of preserving the integrity of the data for this measurement, we only consider households that have sent more than 7200 samples out of the expected 14400 daily samples. The daily average energy consumption per household is obtained by summing the power consumption measured every 6s over the number of samples per day, and multiplying by 24 hours.

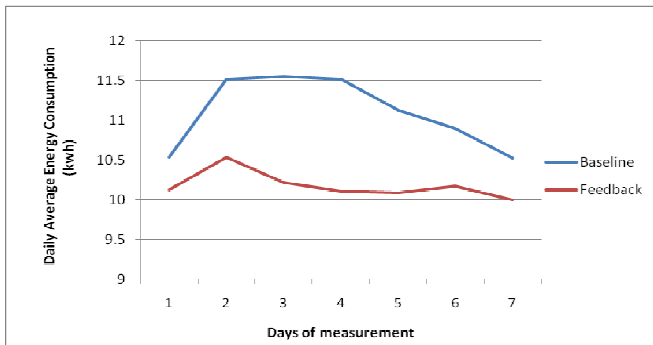


Figure 6. Average daily energy consumption comparison between the baseline week and the subsequent week.



Figure 7. Average daily energy consumption according to number of bedrooms.

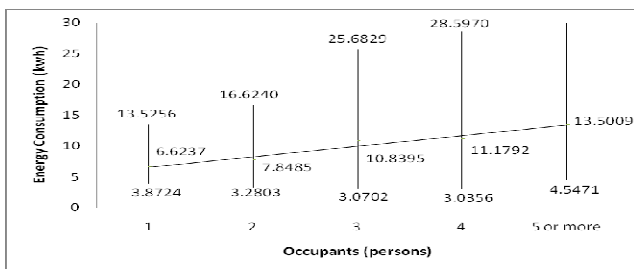


Figure 8. Average daily energy consumption according to the number of occupants in the households.

One of the result of Cycle 2 measurement is that we can improve and personalize feedback on energy consumption of individual households; we can profile the average daily energy usage according to the number of bedrooms, number of occupants, and property type (the number of households in each group in Figures 7 and 8 varies from 5 to 75 households). One example of feedback is to inform a 2-occupant, single bedroom flat consuming 17kWh daily energy that their

household is consuming energy equivalent to a 3-occupant, 3-bedroom household (Figure 9). Profiling will also be used for positioning the household in the right usage level category; low, medium and high energy consumption.

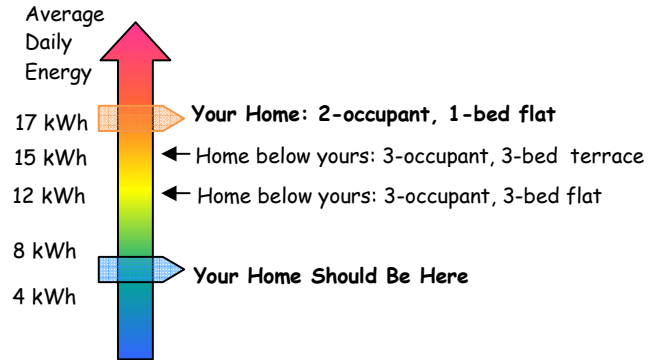


Figure 9. Example of feedback based on household profiling.

In future work, we will undertake more detailed data analysis, surveys and focus group studies to investigate behaviour changes between groups of households with a combination of energy monitoring equipment (at electricity mains and appliances) and user interfaces (Dashboard and display unit), and to determine system components and feedback information that do not contribute substantially to behaviour change, or simply deemed unnecessary by users. The results of Cycle 2 will then be fed as user and system requirements into the final Cycle 3 system.

VI. RELATED WORK

DEHEMS sets itself apart from existing technology-based domestic energy monitoring work [2] in terms of its large-scale deployment and user study, where the system development methodology is driven by user preferences and motivations. It defers from state of the art technologies such as Wattson [14], AlertMe [15], Plogg [16] and WattBot [17] by having an Internet-enabled data collection, warehousing and analysis back-end support, thus providing a richer feedback mechanism and information such as comparison against groups of similar households and personalised energy saving techniques. The Wattson leads in terms of ambient interfaces (light changing colours according to consumption levels); however, Fitzpatrick and Smith [3] did find that the ambient interface too abstract and causes users to prefer more direct and easily interpreted data. The use of online social networking tools to display personalised real time energy information and raise social competitiveness and awareness is still underutilised [18] even though social norms have been identified as a powerful persuasion tool for behaviour change in the psychological domain. Other interesting on-going work still in early design and implementation stages relate to innovative user interfaces, examples include emotionally engaging narrative using LCD displays on extension plugs that visualizes a tree shedding its leaves when energy is being overused [19] and glowing power cords [20]. Another area of

research that has the potential to replace extensive and expensive monitoring infrastructures is non-intrusive appliance load monitoring using sophisticated statistical signature inference algorithms to analyze the current and voltage waveforms [21], or solutions that use ambient sensors to detect appliance footprints [22]. However, the effectiveness of these techniques is still unclear, as they are yet to be deployed and tested in the real world.

VII. CONCLUSION

The pilot Cycle 1 study on user context revealed that saving energy is seen as a financial matter rather than environmental, and a major constraint for saving energy is the lack of information or awareness on appliances, daily habits and the environmental impacts. Thus DEHEMS aims to raise energy literacy and environmental consciousness by providing personalized steps for saving energy and feedback on energy consumption.

The results of the DEHEMS Cycle 1 usability analysis demonstrate that users undergo immediate behaviour change to the extent that they replaced energy inefficient appliances and changed how they use their appliances. The long term effects are still unclear, although after 4 months of deployment, the changes are still sustained. Users also tend to share information on their household's energy data, thus indicating that online-social networking tools might become useful to propagate wide-spread information sharing. Users also find distinct roles for in-home display devices that provide instantaneous feedback and PC/web-based interface that provides detailed feedback and information. A display device in the home offers users an exciting opportunity to investigate the surge in the power load caused by home appliances; users demonstrate the ability to infer energy consumed by the different appliances, indicating that the benefits given by extensive and expensive sensing infrastructure need to be substantiated. Users also show an affinity towards comparing their own usage against other similar households. Energy saving tips and antecedent information on the effects of energy on the environment is still appreciated, and users would like to receive information to help convince friends and family as well. We hope that the next generation of DEHEMS system that already shows 8% reduction of daily energy consumption within the first week of feedback will satisfy some of the user concerns and preferences, and reveal in further detail which feedback information, visualization technique and display mechanisms are most effective, to what extent, and how these can be integrated onto a single affordable home infrastructure to bring forth long term behaviour change.

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