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How smart do smart meters need to be?

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ABSTRACT

Governments across the world are investing in smart metering devices that report energy use to the user with the aim of reducing consumption. However, the effectiveness of such In-Home Displays (IHDs) has been questioned, since savings are small. This is possibly because informing the consumer of their consumption in kWh, or monetary units, fails to give context, or inform of possible actions to reduce consumption. We investigate, for the first time, the effect of replacing the simple statement of energy use an IHD gives, with a detailed array of information specifically designed to improve consumer energy literacy and suggest behaviour change through personalised actionable messages set against a series of psychological value systems for context, and which can identify potential profligacy. The results from a carefully controlled field experiment show: 1) value framing and action prompts have a significant effect on occupants' behaviour, with the mean temperature of homes being reduced from 22.4 °C to 21.7 °C, and a marked reduction in gas consumption—22.0% overall and 27.2% in high consumers; 2) energy literacy increasing from 0.52 to 1.28 (on a 0–4 scale); 3) it is possible to target potentially profligate households, without inappropriately messaging others; 4) engagement is high, with 82% of the participants finding the system useful. These results emphasize the necessity of improving energy literacy when encouraging energy efficient behaviours and point to a new generation of smart meters with the potential to increase energy literacy, make much greater savings and impact climate change policy.

1. Introduction

The residential energy sector accounts for 23% of total energy consumption worldwide, placing it third after industry at 37% and transportation at 28% [1]. In developed countries the sector is even more important; in the US, for example, residential consumption represents 25% of total energy use [2] and in the UK 29% [3]. This translates to roughly 12% of UK greenhouse gas emissions [4]. In addition, it is projected that residential consumption worldwide will grow by an average of 1.4% a year from 2012 to 2040 [5]. Thus the sector is critical to both national energy policy and international climate change policy, and many attempts are being made to reduce residential consumption by influencing the behaviour of occupants.

Residential energy consumption is however a multidimensional phenomenon embedded within a socio-cultural and infrastructure context, and for this reason changing occupant behaviour might be expected to be complex. The focus of the research reported here lies in inducing behavioural change with the help of energy demand feedback via smart meters or ambient displays. Opinions regarding the effectiveness of such solutions to date are unfortunately not unanimous [6–12].

Approaches to energy feedback have so far tended to be one-size-fits-all solutions; however, with new developments in energy data management [13], more advanced feedback is now possible. The main contribution of the current paper to digital energy feedback research is twofold: i) in broad terms, it tests the effectiveness of a novel smarter, building-aware, and more user-personalised digital energy feedback in an experimental setting for the first time; ii) in more specific terms, it evaluates the effect of two new approaches to feedback – *internal values* and *tailored*

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action prompts, delivered via a computer tablet. It replaces the normal user- and building-blind smart meter concept with one that not only reports the energy used but recommends specific actions and works with the personal values of the user. For example, it might recommend turning the heating thermostat down one degree-centigrade, and explain this not just in terms of kWh or financial savings, but with respect to environmental gain or other personal values. The system tested here is a simplified version of a future building- and user-conscious approach that would report complex and tailored information to the user in written or spoken sentences. For example, "*I note that the heating turns off at 9am each weekday, yet your home appears to be unoccupied from 7am; would you like me to change the heating timing? This might save you £47 per year and the stop the emission of 218 kg of carbon dioxide*". Or, "*I note that your home might be over-ventilated when the heating is on, losing £98 of heat per year. You might like to keep most of your windows closed when the heating is on*". Such an approach, which we term *intelligent smart metering* (or ISM), requires knowledge of which values are most likely to prompt the user to act. These might be financial savings, the reduction of environmental damage, benefits to future generations, wastefulness, or some other concern specific to the individual.

ISM requires an energy (thermal) model of the building in order to predict accurate savings based on the building and its use, rather than on inaccurate typical values. To be cost effective, such a model would need to be automatically assembled from a minimum of sensor information so as not to overly increase the cost of the smart meter, for example a mix of utility meter data, room temperature, sub-circuit or high-frequency electricity data to infer occupation and maybe home CO_2 concentration (as a proxy for ventilation rate). The sensors needed and the accuracy of such an approach, which uses inverse modelling to obtain an accurate thermal model from a time series of data, have been reported by the authors in Refs. [14] and [15]. By creating such a model, the financial, and other, impact of any suggestions, for example turning down the thermostat by one degree, can be calculated for the specific home and reported to the user. In addition, inappropriate suggestions, for example suggesting a reduction in heated temperature in an already under-heated home, can be avoided.

One can imagine other advantages of the ISM approach, for example, the reporting of the presence of high U-Values in the fabric to utility companies for targeted intervention.

This paper attempts to discover if this new approach can be applied to a group of homes and if it generates changes in behaviour.

2. Background

Some research findings [16] suggest that continuous energy feedback might be an effective driver of energy-related behaviour change. For example, Barbu et al. [17] suggest that energy feedback provided to users via smart meters could *save* 5–15% of total energy costs. Similarly [18–20], suggest that energy feedback through advanced in-home displays (IHDs) could help to *save* up to 20% of energy costs, either for electricity or total energy bills. However, reality seems to fall short of such predictions. For example, in Ref. [21] a more modest average energy saving of 7% is reported across multiple utility pilot programs aimed at electrical energy conservation with the help of IHDs.

Current technological solutions for real time energy feedback suffer from multiple issues [22,23], for example: unengaged users; failure to address users' personal motivations and needs embedded in daily routines and social practices; information comprehension issues caused by abstract numerical information in kWh or financial costs; and inattention to users' personal characteristics [24]. It seems clear that users need something more to motivate and engage them than plain energy feedback in kWh or cost if we are to get energy reductions of 10% or more. Some research indicates that intelligent energy feedback that offers different feedback options might be effective [25].

Chiang et al. [26] have calculated that smart meters can pay back their installation costs in 4 years if the energy savings are 3% or more, although the observation that the utility company no longer need to visit the home to read the meter might currently be the main economic driving force for their installation. It is hence interesting to ask whether we might move the focus from a device that is mainly of use to the energy company to one that has equal utility to the occupant.

The question of what best motivates householders has received considerable attention from energy behaviour researchers, with varying success being noted. For example, attempts to stimulate savings through social comparison and competition have not achieved notable success [25,27–29]. One possible reason for this is the so-called boomerang effect [30], whereby when households are told they are using less energy than average they start to use more when they see what is 'normal' or 'permissible'. This suggests that if messages are to be sent to households, only those where there is some evidence of potential energy profligacy should be targeted with certain messages, and this is a key aspect of our study, and the one reason for its success.

The other key aspect is people's values. Different disciplines, including economics, psychology, philosophy, sociology and anthropology, have all tried to understand the role of personal values in conservation behaviour. From an economic point of view, people's values correspond to long-term preferences, and can be explained by decision theory [31]. In anthropology, values are 'cultural worldviews' and their role in pro-environmental behaviour is studied within climate change risk perception [32]. In social psychology, Schwartz [33] identified a number of personal values universal for all cultures and nations. From this perspective, personal values are defined as superordinate goals that serve as enduring guiding principles in peoples' lives [33]. Common to all these approaches is the idea that values are conceptually different from goals, opinions and attitudes: values reflect broad long-term preferences and so provide unity across a broad range of behaviours (a person who above all values their own self-interest will be self-interested in most settings); goals, opinions and attitudes, on the other hand, are much more situation-specific and changeable over time [34]. In the current study, we test personal values as motivators to energy-saving behaviour and focus on altruistic, egoistic and biospheric values, representing, respectively, concern for others, the self and the natural environment. These values were chosen from the various Schwartz's personal value sets based on research by DeGroot and Steg [35,36], who identified altruistic, egoistic, biospheric and hedonic (pleasure-seeking) values as the key value orientations highly correlated with pro-environmental behaviour. In this study, hedonic values were dropped from this set after pilot testing (with an opportunistic sample of 30 UK adults) found much lower engagement with such messages compared to the other three value orientations (which pilot participants found useful, and more engaging than energy messages expressed in standard kWh).

The final facet of this study concerned the nature of the action prompts. The literature hints that energy feedback may be effective when it prompts concrete personalised actions (for example, "Please switch off unused appliances", "Adjust your thermostat setting"), presumably because these do not require knowledge or problem-solving from the householder, as would a more general action prompt like "Reduce your energy consumption". However, at the moment we lack the empirical quantitative data needed to