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The role of information and communication technologies (ICTs) in household energy consumption—prospects for the UK

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Abstract Growing concerns about climate change and energy security have led to a strong focus on energy demand reduction and energy efficiency within United Kingdom (UK) energy policy. At the same time, information and communication technologies (ICTs) have become pervasive in society and this has brought with it new policy options which use them as enabling technologies. One such policy option planned for implementation in the UK is the use of smart meters and real-time displays to encourage people to become more aware of their energy consumption and possibly change their energy-related behaviours. Smart meters and display units by definition link individuals, technologies and society, and their effectiveness is influenced by a range of factors. Ten semi-structured stakeholder interviews with industry, government and academia and a review of literature were conducted in order to identify which factors are most likely to contribute to the effectiveness of implementing smart meters and real-time displays in the UK. Further analysis showed a number of key themes and perspectives on behavioural change, particularly as they relate to household electricity use and the role of smart meters in the UK energy policy, including the role of ICTs in energy demand reduction more generally.

Keywords Information and communication technologies · Household energy consumption · Behavioural change

Introduction

Energy is invisible but important. “Most people have only a vague idea of how much energy they are using for different purposes” (Darby 2006, p. 3), and yet different forms of energy have played a major part in economic development (Helm 2004) with for instance “electric light, electric motors, electronics and other manifestations of electricity” making modern industrial society possible (Patterson 1999, p.1). Historically, there has been a focus on increasing the supply of energy to meet the growing demands of both industrialised and industrialising societies (Helm 2004, p.2). The United Kingdom (UK) was chosen as the focus of this paper as it represents a good example of a society where energy policy has shifted towards managing demand for energy, initially due to fears of rising energy prices after the oil crises of the 1970s (Patterson 1999), and more recently due to increasing concerns about climate change and the security of energy supply

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(DTI 2007, p.6).[1] These are issues also relevant to other societies. The International Energy Agency for instance sees that curbing energy consumption and its related greenhouse gas emissions (GHG) and tackling climate change are key twenty-first century challenges globally and households have a key part to play in this (IEA 2009). In the UK, household energy consumption contributes 13% of total GHG emissions (HM Government 2009). The UK government has set a target to cut households' GHG emissions by 29% on 2008 levels by 2020 and to cut total GHG emissions from all sectors by at least 80% by 2050 compared to baseline year 1990 (HM Government 2009).

At the same time, there is a growing awareness of the roles that information and communication technologies (ICTs) can play in energy systems (Erdmann et al. 2004; Knowles and Goodman 2005; Laitner 2000). Although the direct impact of ICTs on energy is to increase consumption because they use energy and their use is growing (Koomey 2007), several researchers have argued that ICTs could indirectly reduce demand for energy by for example improving efficiency (Young 2006), providing information to encourage more sustainable consumption patterns (Erdmann et al. 2004) and facilitating "e-materialisation" (Erdmann et al. 2004, p. 9; Wilsdon and Miller 2001, p. 22), which is a structural shift in the economy from energy-intensive products to less energy-intensive services. One example of a policy which relies on the use of ICTs as an enabling technology to reduce energy demand is the introduction of smart meters and real-time displays (DTI 2007) as a potential way of managing energy "better". The UK government has announced a national roll-out of smart meters in the coming decade and is, together with major energy industry companies, trialling various smart meter and display technologies via its Energy Demand Research Project (EDRP) which involves over 50,000 UK households (Ofgem 2009). This paper explores the roles that ICT technologies can have in managing household energy consumption. The "Methodology" section outlines the methodology and theoretical framework used in this paper. A framework of key trends in domestic energy consumption in the UK and the behavioural challenge of household energy consumption, including socio-economic behavioural theories, are outlined and discussed in "The context of household energy consumption in the UK" section. The paper then moves on to explain how technologies such as ICTs could be implemented to encourage behavioural change (Chapter 4). Reflecting on the theoretical framework and semi-structured interviews, three levels of stakeholder views are identified and explained: (1) economic, (2) socio-psychological and (3) technology-based system-level views (the "Results from stakeholder interviews" section). Finally, the "Conclusions and recommendations" section concludes by outlining lessons learnt for UK energy policy and identifying areas for future research.

[1] As of 28 June 2007, the Department of Trade and Industry (DTI) was superseded by the Department for Business, Enterprise and Regulatory Reform (BERR). Department of Energy and Climate Change (DECC) was established in October 2008 and deals with UK energy and climate policy.

Methodology

Previous research has highlighted the complexities linked to the study of household energy consumption (see for instance Abrahamse et al. 2005; Ek and Söderholm 2010; Maréchal 2010; Martiskainen and Watson 2009) and that interdisciplinary research is required to understand household behaviours related to energy consumption (Steg 2008). This paper analyses the views of stakeholders from ten in-depth semi-structured interviews to determine key themes linked to deploying ICTs in the household energy system in the UK. A case study strategy of research was followed, in which evidence gathered from multiple sources is triangulated so that the different sources corroborate each other (Yin 2003). The analysis and interviews were supported by a literature review of behavioural research theories and studies to provide understanding on key issues and strategies for affecting energy consuming behaviours in households. The literature review analysed academic papers, 31 experimental intervention studies, policy documents, and private sector and non-governmental organisations' reports, involving a comprehensive review of technical and informational energy efficiency options, as well as behavioural theory and policy measures.

Terminology

This paper concentrates on the application of different ICTs in the home setting in order to better manage and influence energy consumption. Previous research has established the following key definitions, which are used in the context of this article.

- *A smart meter:* a meter which measures energy use electronically and communicates this data to other devices. Smart meters enable a range of new functions such as remote meter reading, time-of-day tariffs and real-time usage information (Darby 2006; Owen and Ward 2007).
- *Direct display*: Displays are devices which are used to visually display meter data. They can for instance clip on to existing meters and display the available data or be stand-alone and display accurate and more detailed data provided by smart meters (Darby 2006; Owen and Ward 2007).
- *Energy behaviour*: Energy behaviour is a consequence of different behaviours such as using electrical appliances, lighting and setting the thermostat level (Becker et al. 1981).
- *Feedback*: Households can receive feedback on their energy consumption and this can take several forms. Feedback can be daily, weekly or monthly, and it can be linked to certain goals to reduce consumption (for instance 10% reduction over 1 year). Feedback can be given in various forms including paper bills and different direct displays linked to smart meters (notably Darby 2006).

Interview design

Semi-structured interviews were chosen because they allow people flexibility in their chosen responses while still providing some structure for comparability between interviewees (May 2001, p. 123). The interviewees were selected to represent key organisations of actors in the UK energy sector in relation to the introduction of ICTs such as smart meters. Companies and organisations were initially contacted via e-mail, using a standard description to explain the aims and objectives of the research project. Time constraints of the project limited the final number of interviewees to ten. A list of interviewees is provided at the end of the article (see the "Appendix" section at the end). Interviews were conducted in person between June and July 2007 and typically lasted for 1 h. The interviewees represent a wide range of different sectors that either have an interest in or direct involvement with smart meters and real-time displays. These included energy suppliers, smart meter and real-time display manufacturers, government officials, academics and non-governmental organisations. Interviewees were asked questions about their views on the prospects, strengths and weaknesses of smart meters and real-time displays, especially in relation to:

- The prospects of smart meters and real-time displays and the factors contributing to their effectiveness
- What information content smart meters should include
- What are their strengths and weaknesses
- Barriers and solutions for future development
- Relationship with other energy saving strategies and wider government policy

Some interviewees requested anonymity, and to achieve this, all interviewee comments are non-attributed. Analysis of the semi-structured interviews highlights the key themes discussed by interviewees and reflects on existing research on energy consumption in the household sector. Key objectives of the analysis summarised in this article are how households' energy-using behaviours can be understood and what the potential of ICTs is in encouraging behavioural change.

The context of household energy consumption in the UK

There are three aspects to energy consumption in UK homes: (a) the structure and quality of the housing stock, (b) the energy performance of the appliances installed within the houses and (c) the behaviours of the householders themselves. This paper mainly concentrates on the behavioural aspects of households but will also outline the state of UK's housing stock and general trends in household energy consumption as a background to the behavioural challenge and UK's energy policy. There are almost 26 million homes in the UK, two thirds of which are estimated to still be in existence in 2050 (Boardman et al. 2005). Existing housing stock in particular is an issue contributing to high energy-related emissions (Roberts 2008) and many people can be seen to be "locked-in" to poorly built and inefficient houses, thus having little control over the emissions their homes produce. Around 10 million new homes are estimated to be built by 2050 (Boardman et al. 2005), and the UK government has indicated that all new homes should be zero carbon by 2016 (DCLG 2008). Given that the rate of new built houses is elatively low compared to the existing housing stock, upgrading the existing housing stock will have an important part to play in shaping the UK's emissions in the coming years (Foresight Sustainable Energy Management and the Built Environment Project 2008). In addition to the quality of the housing stock, the system which links UK homes to the wider energy metering network is also rather dated. "Basic" domestic meters accurately measure the amount of electricity and gas supplied to homes but they do not record time-of-use of energy, cannot be remotely controlled, and need to be physically read to obtain metering data, making the system as a whole inefficient. Most of the domestic UK energy metering stock has not radically changed in over a century despite consumer electronics and ICTs being widely adopted in many other fields (Owen and Ward 2006).

Additionally, although houses in the UK may be inefficient when it comes to insulation, they are generally considered to be more comfortable than 30 years ago. The use of both central heating and electrical appliances, including ICTs, has risen considerably since the 1970s. For instance, the average internal temperatures in centrally heated UK homes were 13.8°C in 1970, compared to 18.2°C in 2004 (BERR 2008a). Around 80% of energy used in households is linked to space and water heating (HM Government 2009). In addition, households' purchasing and use of electrical appliances has increased considerable over the past decades, partly as a result of trends in consumerism and fashion, and the average household has almost three times the number of electrical appliances than 30 years ago (see Fig. 1; DTI 2007; BERR 2008b). In particular, the use of consumer electronics and ICTs is increasing, and a recent Energy Saving Trust (EST) report predicted that they will use the equivalent energy of 14,700 MW of installed power plant capacity by 2020 (Owen 2007, p. 3).

Despite the fact that most modern appliances have improved in terms of their energy consumption, they also have features which can counteract these savings. For instance, standby modes have been linked to increased energy wastage (EST 2006). This is the case, particularly in the UK, where around 71% of consumers regularly leave appliances on standby and 63% leave lights on in unoccupied rooms (EST 2006). While white goods are labelled according to their energy consumption and almost 70% of cold appliances sold in Europe are rated at the best performing level, the majority of consumer electronics, however, remain without energy labelling (Bertoldi and Atanasiu 2007). In addition to the housing stock and appliances, energy consumption from the household sector is linked to the behaviours of those who occupy the houses. The use of appliances as well as households' purchasing behaviours, and the options available to them, form an important aspect of domestic energy consumption. The apparent invisibility of domestic energy use often means that households are detached from their gas and electricity use, especially if they pay their bills by direct debit—an automatic payment from their bank account (Roberts and Baker 2003). Habits such as turning the lights on/off and using appliances and heating systems are especially important regarding household energy behaviours. Furthermore "bad" habits such as leaving appliances on standby and the lights on were estimated to cost the UK economy around £11 billion between 2006 and 2010 (EST 2006).

Energy behaviours

Energy behaviours are influenced by wider societal, as well as personal factors, including both internal factors (attitudes, beliefs, norms) and external factors (regulations, institutions and society as a whole; Jackson 2005), and more recently research has also highlighted factors such as cultural norms and fashion (Owens and Driffill 2008). In order to change people's behaviour, both internal and external factors need to be taken into consideration (Jackson 2005; Stern 2000).

Economists and social-psychologists have developed various models and theories in order to understand how behaviours are formed and how they could be changed, and an extensive review of models is available from Jackson (2005). One of the most widely used behavioural theories is the "rational choice" model of neoclassical economics. This theory is based on the notion that people weigh the expected costs and benefits of different actions and choose

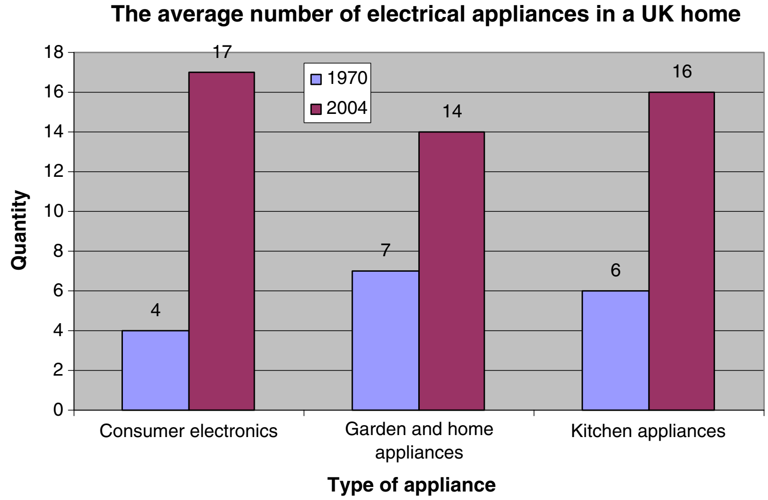

Fig. 1 Trend in electrical appliance ownership 1970 and 2004 (DTI 2007)

those actions which are most beneficial or least costly to them (Jackson 2005). Rational choice theory was used as a basis for much of the early 1970s energy conservation research (see for example Becker 1978; Bittle et al. 1979, 1979–1980). Later environmental research has used models such as the theory of planned behaviour which is based on the principle that person's beliefs on how difficult or easy a behaviour is influences his/her decision to conduct that behaviour, including a strong notion on person's ability to choose his/her actions (Jackson 2005). The theory of planned behaviour has been one of the most widely used in pro-environmental behavioural research, including research in recycling, travel mode choice and energy consumption (Jackson 2005). Despite the wide use of these models, they are however limited in their scope as they do not account for factors such as social norms, emotions and habits, i.e. the actions people undertake without really having to think about them. Much of energy behaviours are based on habits. One model which highlights the influence of habits on behaviour is Triandis' theory of interpersonal behaviour. According to Triandis' model, behaviour in any given situation is a function of what a person intends, what his/her habits are, any situational factors and the conditions in which the person operates (see Bamberg and Schmidt 2003; Jackson 2005), taking into account person's beliefs about what the outcome of their behaviour will be. In order to change habits and routines, old behaviours need to be broken down before new ones can form (Gärling et al. 2002; Stern 2000). Habits and routines can be difficult to break as they are ingrained in people's behaviour—hence, selecting the best measures to encourage behavioural change in domestic energy consumption can be challenging.

Previous research (Abrahamse et al. 2005; Darby 2006; Martiskainen 2007) shows that several intervention measures have been tested over the years in order to change households' energy consumption. Several of the intervention studies were based on rational choice theories and the notion that as long as people were given right information about their energy consumption and its cost, they would make rational choices over that information and behave accordingly. However, behaviours are complex and intervention measures should go beyond basic rational choice theories which have been highlighted in previous research, especially in terms of providing people feedback on their energy consumption in order to make them more aware of their behaviour (Darby 2006). In order for the UK government to introduce behavioural change measures in its energy policy, there is a need for more evidence on which measures would be the most influential in UK conditions (DTI 2007). For policy makers to be able to design effective behavioural change measures, they need to first identify how our behaviours are formed and how they could potentially be influenced.

UK energy policy

The UK's energy policy has key objectives of reducing energy-related emissions, securing energy supplies and reducing fuel poverty (DTI 2007; HM Government 2009). A framework for the mandatory emissions reduction target is set in the Climate Change Act which includes measures such as annual carbon targets (OPSI 2008). Under the Act, the UK has legally binding GHG emissions reduction targets of 34% by 2020, and at least 80% reduction by 2050 compared to 1990 baseline levels (HM Government 2009; see also EC 2009). Key policy instrument for household energy consumption in the UK is the Carbon Emissions Reduction Target (CERT, previously known as the Energy Efficiency Commitment). This was launched in 2002 and runs in 3-year phases, with the latest phase of CERT extended to 2012 (HM Government 2009). CERT requires energy supply companies to undertake energy efficiency measures in the household sector. These have mainly included technical measures such as loft and cavity wall insulation and energy efficient lighting (Defra 2007). However, ICTs such as smart meters and real-time display units can have a potentially important role in CERT. Technical fixes to housing stock have been incorporated to UK's energy policy for some time but considering changes to user behaviour and encouraging energy consumption reduction via behavioural measures is a relatively new addition to policy thinking. The Climate Change and Sustainable Energy Act 2006 (HM Government 2006) made it possible to include behavioural change measures, as well as micro-generation, within UK's energy efficiency policy. There is relatively little evidence on how much various behavioural change measures could contribute towards the total CERT targets and further quantitative research is required in this area. The UK government has also announced a national roll-out of smart meters. In the 2007 Energy White Paper, the government stated that all domestic energy customers would have smart meters by 2017 (DTI 2007). However, this timeline was extended to 2020 in the government's 2009 Low Carbon Transition Plan (HM Government 2009).

The role of ICTs

Traditionally energy meters in the UK have been fairly low-tech and positioned out-of-sight, hence the data they provide is often not seen by the householders (Owen and Ward 2006). Real-time visual displays provide a solution to this problem by displaying the data via a digital screen from energy meters or mains electricity cables, often wirelessly so that it can be positioned anywhere in the home. So far the provision of energy-related data by smart meters and real-time displays has been studied mainly within narrow disciplines and there have been limited trials with varied results (Abrahamse et al. 2005; Fischer 2007). Early indications from studies conducted for instance in the US and Norway on smart meter systems suggested that households who received feedback on their energy consumption could save up to 15% of their consumption (Darby 2006), however, long-term studies of these results are yet to be tested in UK conditions. More importantly, these technologies allow feedback to be tailored to each user's individual requirements, making it possible to present feedback in the easiest, simplest and most convenient way to the householder (Darby 2006).

According to a report for the Institute for Prospective Technological Studies, ICTs "pervade all sectors of the economy, where they act as integrating and enabling technologies" (Erdmann et al. 2004, p. 3). However, several researchers have observed that although the ICT revolution has touched the energy sector, its potential impact has not been widely recognised so far and even less so when the explicit focus is on reducing carbon emissions (Pamlin and Szomolányi 2006; Young 2006). In the energy system, ICTs directly increase demand for energy because not only do they use energy, but also the use of ICTs is increasing (Koomey 2007). The impact of ICTs on energy consumption varies depending on the context and they could enable a decrease in energy consumption overall (Erdmann et al. 2004; Knowles and Goodman 2005). ICTs have for instance been used in the energy system for trading at the wholesale level, thereby improving the efficiency of trading since the UK electricity market was liberalised in 1998 (Helm 2004). They have also improved the efficiency of energy generation and distribution (Erdmann et al. 2004).

ICTs enable low-cost metering and communication systems and in particular, can potentially encourage households to adopt more sustainable consumption patterns (Erdmann et al. 2004) by providing personalised feedback about their energy consumption via smart meters and real-time displays. Hence, ICTs could be key facilitating technologies in enabling energy savings (Erdmann et al. 2004). However, researchers agree that this may only be achieved if it is guided by appropriate policies and strategies (Erdmann et al. 2004; Knowles and Goodman 2005; Pamlin and Szomolányi 2006). While other countries such as US, Norway, Italy, Canada and Sweden have introduced smart meters to domestic customers, the UK is still in the early stages of development. It could also be argued that the UK has been slow in comparison to other countries to deploy various feedback measures such as better bills, and previous research has suggested that these should have been introduced much earlier than the government's planned schedule (Roberts and Baker 2003).

Results from stakeholder interviews

Energy use has key impacts on our society, be it economic, societal or environmental. In such an economically and politically important system with considerable inertia, the views of stakeholders can give insight into the debates surrounding different energy policy measures such as the roll-out of smart meters and real-time displays. This section summarises results from ten semi-structured interviews with representatives from the energy industry, government, academia and non-governmental organisations, highlighting common themes that emerged from these interviews. A full list of interviewees is provided in the "Appendix" section at the end of this paper; however, as some interviewees requested anonymity, all interviewee comments are non-attributed. The majority of our interviewees considered the prospects for smart meters and real-time displays being rolled out in the UK to be good, in agreement with previous research that "smart metering will and should happen" (Owen and Ward 2007, p. 4), and most also felt that smart meters and real-time displays were likely to have some impact on energy use. Interviewees agreed that smart meters are an improvement on the electromechanical meters found in most UK homes, and the key strengths are that they can provide real-time feedback to users and suppliers, which can then be utilised in a variety of ways. Views about the future of displays were more varied. One interviewee commented that "displays don't have to arrive at all" but that they are likely to because they are low cost and have the potential for early carbon savings, which will help the government meet their short-term targets for reducing carbon emissions. An interdisciplinary analysis shows that different themes emerged from the stakeholder interviews, which were based on *economic*, *socio-psychological* or *technology-based system-level* assumptions.

Economic themes

Taking an economic perspective on behavioural change, one respondent took a purely rational choice theory position by saying that the key strength of real-time displays is the provision of better information for consumers so that they are better informed and can make "better judgments", enabling them to exercise rational choice and minimise their costs. According to this rationale, real-time information about consumption and cost should be displayed as a minimum to maximise the effectiveness of smart meters and displays. However, as previous literature shows, information alone has not been proven to be effective enough to change households' energy consuming behaviours (see for example Abrahamse et al. 2005; Darby 2006). Other interviewees in this perspective emphasised that cost is "one of the key prohibiting factors", and not only the cost of providing and installing smart meters, but also the cost of updating "data handling and billing systems" so that they can store, process and use the data. According to one respondent, estimated costs for introducing smart meters range from £7 to £10 billion.

In terms of possible future directions, respondents thought smart metering and real-time displays "should be left to the markets" because "there is not one perfect smart meter solution". In response to concerns raised about the competitive market as a barrier to the successful implementation of smart meters and displays, they argued that the market would deliver different solutions to different consumers whereas blanket regulation would be more likely to produce a "one size fits all" solution. The economic rational choice model tends to dominate commercial and policy-making decision processes (Jackson 2005). However, for programmes such as the introduction of smart meters and real-time displays, which link individuals, technologies and society, quite a few of our interviewees felt that a range of other factors must be considered, including socio-psychological motivations such as habits and routines as discussed in the

"UK energy policy" section, and technological and institutional drivers and constraints.

Socio-psychological themes

Those who took a socio-psychological perspective tended to accentuate the importance of human factors to the effectiveness and potential future of smart meters and real-time displays. While one interviewee suggested that there are "lots of low hanging fruit" in terms of consumers saving energy, another argued that "whatever you do, some customers won't care and other customers will" due to the importance of psychological factors such as attitude.

Some of those questioned explained that "instant information on electricity use seems to have a wake up effect" and that therefore interaction with the display would be crucial, consistent with the importance of psychological factors such as the need to "unfreeze" habitual behaviours and make an emotional connection with the display. According to this view real-time displays allow consumers to see their real-time energy use clearly for the first time, enabling them to become aware of habitual behaviours and the socially embedded, invisible nature of energy. Various strategies for achieving this effect were suggested, from making feedback appealing, intuitive and simple to ensuring that people need to interact with it for other reasons by including features such as a clock or travel information.

Some respondents felt that there was uncertainty about how the design of displays might influence behavioural change. It is not yet clear what information should be displayed, how it should be displayed, and where the display device should be situated to encourage the greatest change in behaviours (Fischer 2007). These factors could be important for changing people's energy-using behaviours via psychological mechanisms such as breaking old habits and forming new ones. Several interviewees also suggested that consumer engagement would be a key issue, with one describing "how engaged the consumer is" as the most important factor and suggesting that education programmes and awareness-raising activities are therefore crucial. Another respondent identified the "need for a longer term change of culture". From this perspective, psychological and social factors are likely to be important for encouraging the consumer engagement and long-term cultural change that are required to reduce household energy consumption.

While some interviewees talked about education, others focussed on marketing. One suggested that "marketing links would need to be made" to ensure that energy efficiency becomes "a factor in buying decisions". Other respondents suggested that real-time displays could "create market demand for low energy products" and that they may be "a springboard" for other innovations such as "tailored advertising" delivered to you, depending on your home energy use patterns, and "home energy management systems" where a central system manages your home energy use by controlling appliances and switching them on and off as necessary. However, these sorts of innovations will depend on consumers' levels of understanding and on targeting the right products to the right consumers.

Technology-based system-level themes

Some stakeholders held the view that whether smart meters and real-time displays are effective or not will depend on their specification and on resolving current uncertainties about which technologies to use. For example, some respondents made a clear distinction between smart meters and "clip-on" real-time displays. Advocates of clip-on displays thought that providing consumers with real-time information in a prominent place in the home is what would make smart meters and real-time displays effective. Owen and Ward (2006) have argued that smart meters alone would not have this effect because they are usually positioned out-of-sight. Darby has suggested that providing clip-on displays could facilitate energy demand reduction in households and that "any development of 'smart metering' needs to be guided by considerations of the quality and quantity of feedback that can be supplied to customers" (Darby 2006, p. 4). Important factors for the effectiveness of displays were identified as the information that is displayed, how it is displayed, the way the devices look and ease of use and where the devices are situated or whether they are portable.

However, the Energy Retail Association (ERA), an organisation that represents Britain's domestic electricity and gas suppliers, has argued that providing clip-on displays without smart meters will divert resources away from smart meters and may confuse consumers because the data provided by clip-on displays can be inaccurate (Energy Retail Association

2007). In our interviews clip-on displays were also described as "limited" because communication from the meter or the mains electricity cable to the display is only one-way, which means that the display is "not interactive" and therefore unlikely to keep people engaged. Advocates of this view thought that two-way communication between smart meters and displays was important because this would allow the supplier to "aid the consumer via new products" and communicate with people "in ways that suit them". Important factors for the effectiveness of smart meters were argued to be accuracy of information and the capabilities enabled by two-way communication between smart meters and utilities.

Thus, there is a debate between key stakeholders about whether clip-on displays should be rolled out quickly to encourage potential energy demand reduction in a shorter timescale (Darby 2006) as proposed by the government (DTI 2007) or whether accurate real-time displays should be rolled out with smart meters to avoid disputes about inaccurate data (Energy Retail Association 2007). This provides an example of how the views of key stakeholders are likely to influence the implementation of smart metering and real-time displays.

There are also potential system-level implications from the outcome of this debate. Clip-on displays can only receive information from meters and thus communication is one-way (Owen and Ward 2006), which does not require any changes to the current metering stock. In contrast, displays that directly communicate with smart meters and then between the meter/display and the energy supplier imply two-way communication, which would necessitate system adaptation of software systems, organisational structures and institutions. It would also enable new functionality such as the provision of personalised messages from energy companies to householders to encourage them to save energy depending on their actual energy use (Lees 2007) and according to one stakeholder, "a more useful relationship between customers and energy suppliers". This illustrates the co-evolutionary nature of technologies and behaviours and how there can be links between micro and macro level processes (Rip and Kemp 1998). At a macro level, two-way communication would necessitate widespread system changes but it would also enable new smart meter functionalities and new interactions between technologies and behaviours on a micro level. Within this framework, technology diffusion can be viewed as a transformation process whereby new technologies are incorporated into new technological regimes, new regimes supersede old ones and "behaviours, organization, and society have to rearrange themselves to adopt and adapt to the novelty" (Rip and Kemp 1998, pp. 387–389).

In addition to the specification of the technologies themselves, the strategy for their roll-out could affect their success in promoting behavioural changes. According to one respondent, there is a difficult trade-off between rolling out smart meters quickly to ensure that the potential benefits are realised as soon as possible and delaying roll-out to ensure the technology is sufficiently mature. Smart metering technology as well as the associated costs are evolving rapidly (Lees 2007) and some interviewees felt that there is a "significant risk" that the speed of technological change will mean that today's smart meters will rapidly become outdated and could be expensive to update. Additionally, as one respondent commented, the UK government does not have a good track record for managing large technology-based projects and therefore if the roll-out was unsuccessful or more costly than expected, it would be "a massive fiasco". This provides an example of a difficult control problem in which governments have the most control over technological choices when technologies are new and the least is known about their impacts (Rip and Kemp 1998).

Lessons learnt for UK energy policy

Several of those interviewed expressed concern that the government should take a more cautious approach and wait for the results from trials and analysis to find out "what works" before developing smart metering policy, particularly given the risk "of buying into the wrong technology" and since smart metering technologies are changing very quickly. These respondents felt that the government should consult and then set "appropriate minimum standards" to ensure flexibility and maximum impact.

Rolling out smart meters and real-time displays to every household in the UK also requires a high degree of industry coordination, but in the UK there are competitive markets for wholesale, retail and domestic electricity, as well as for metering services. Some stakeholders pointed out that under these competition rules, suppliers cannot collaborate to find the optimal solution for rolling out smart meters. In particular, several interviewees expressed concern that competition in metering services means that there are no market incentives to make smart meters compatible between suppliers. However, in a competitive market consumers can change energy suppliers. If a supplier installs a smart meter in a home and then the occupant changes to another supplier, the smart meter becomes an expensive "stranded asset" to the first supplier who is no longer benefiting from it being there. Compatibility was seen as a major issue before the 2007 Energy White Paper (DTI 2007), but since then energy supply companies have been working together to define minimum specifications for the basic functionality required by a smart meter and how to ensure that they are compatible with different suppliers' systems (Energy Retail Association 2007). However, some respondents felt that this issue will require government action to ensure that there is a coherent industry approach. One option would be to transfer ownership of meters to the network operator, which has been the case for most international smart meters rollouts (Owen and Ward 2006).

Some of our interviewees also argued that ensuring interoperability in a competitive market is likely to lead to "lowest common denominator" smart meters. They pointed out that suppliers do not have an incentive to produce expensive smart meters with complex specifications if the benefits are likely to be appropriated by other suppliers when a consumer decides to change from one supplier to another. Since the technology is likely to be in place for at least 15 years, one interviewee suggested that smart meters should be designed to be "future proof". They need to be compatible with future technologies and easy to update. "Modularity and flexibility" in smart meter designs were felt to be important features for achieving this. Owen and Ward have also reported that "future flexibility and adaptability remain important principles in an environment which is extremely dynamic in both technical and cost terms" (Owen and Ward 2007, p. 22).

Even if the problem of interoperability is solved, the majority of interviewees suggested that uncertainty about future policy could be a barrier to introducing smart metering in a competitive market and could lead to inaction on the part of suppliers. Research suggests that energy suppliers are unlikely to invest in expensive smart meters if there is uncertainty about what requirements will be stipulated by future government policy (Owen and Ward 2006). The potential influence of competitive market processes and future government policy on the specifications of smart meter technologies provides another example of the significant influence of interactions between individual technologies and institutional factors. Thus the ability to enable behavioural change via smart meters and real-time displays is dependent on both technological and wider system choices.

Interviewees agreed that there is a need for complementary policies to address "the whole issue of energy efficiency" and that smart meters and displays should work alongside other strategies for reducing domestic energy consumption, such as improving the energy efficiency of electrical appliances, and installing insulation. There was consensus that all strategies were important and likely to develop over time, but one respondent stressed that "it needs action from all parties to bring it together". Respondents felt that smart meters and real-time displays could encourage people to change their behaviour, especially with the introduction of time-of-day pricing to give people a financial incentive. Several people pointed out that the amount of energy used by appliances in particular depends not only on their energy efficiency, but also on their size. According to one interviewee, an energy efficiency standard "doesn't discourage you from buying bigger, it just improves the energy efficiency" of that product. This was used as an argument for integrated policies that work together to achieve genuine reduction in total energy consumption. These arguments support the conclusion that although appealing to personal responsibility and encouraging behavioural change are important because a large proportion of energy use is behaviourally determined, measures based on improving energy efficiency are also necessary because some behaviour is determined by the available technologies.

Smart meters can measure energy exported as well as imported, which could encourage more microgeneration because consumers could both buy electricity from the grid and sell it back (Owen and Ward 2006). Interviewees felt that although there are issues to be resolved such as how much people should get paid for the electricity they generate, smart metering and microgeneration should be "mutually enforcing". Most interviewees felt that the future of smart meters depends on future policy. One interviewee highlighted that what happens after CERT will be "a key factor".

For example, if the government introduces a "supplier obligation" based on a "cap and trade scheme", in which energy suppliers have to ensure that average emissions per customer stay below a specified level, then suppliers "will have to look at behavioural measures" to meet their obligation. This would shift the responsibility for working out how to engage with customers onto the energy companies. According to the same respondent, companies are likely to introduce innovative tariffs in response to this type of policy.

Conclusions and recommendations

Households' energy consuming behaviours can be complex and are influenced by several factors such as cultural and societal settings, country-specific regulations and on a more domestic level the type of housing people live in and how they behave in their homes, including the purchase and use of various household appliances. Research suggests that providing households better feedback on their energy consumption can make them more aware of their every day behaviour and how these link to energy consumption. Technologies such as ICTs can be viewed as being both harmful and beneficial in relation to energy consumption. They can on one hand increase consumption via increased amount of electrical appliances, but at the same time ICTs can be at the forefront of new innovations which provide better feedback to households on their energy consumption via technologies such as smart meters and real-time display units.

Three themes emerged from our stakeholder interviews: economic, socio-psychological and technology-based system level, and respondents views on the implementation of smart meters were analysed accordingly. Key issues for the implementation of smart meters included consumer engagement, marketing strategies, cultural changes and the way feedback is presented (making it appealing, intuitive and simple). Respondents felt that smart meters and real-time displays could encourage people to change their behaviour, especially with the introduction of time-of-day pricing to give people a financial incentive. However, it was noted that the energy efficiency of households should also be improved by implementing measures such as insulation and improving the energy consumption of appliances. Furthermore, there was a clear debate between key stakeholders about whether clip-on displays should be rolled out quickly to encourage energy demand reduction in a shorter timescale or whether accurate real-time displays should be rolled out with smart meters to avoid disputes about inaccurate data.

The analysis shows that taking an interdisciplinary perspective highlights important considerations that may be overlooked under the assumptions of rational choice that often underpin commercial and policy-making decision processes. Some important policy considerations for smart meters and displays are the need to "future proof" the technologies by designing in modularity and flexibility, the importance of analysing the impacts of technology choices from a system perspective as well as at the micro level and the need for smart metering policies to be fully supported by and integrated into other energy policies. Despite widespread support for smart meters and real-time displays, there are still uncertainties and questions about a range of issues, including, but not limited to:

- Which smart meter and real-time display options are cost effective
- What is technically feasible
- What is effective in terms of changing behaviour and changing it for the long term
- How to foster public acceptance and engagement

There is a need for further empirical, interdisciplinary research to understand how smart metering and display technologies will influence households' energy consuming behaviours in practice and to gain a greater understanding of the interactions between technologies and behaviours in society more generally.

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Appendix

List of interviewees

- Charles Hargreaves, Head of Energy Efficiency, Ofgem, 22/6/2007.
- Pedro Guertler, Senior Researcher, Association for the Conservation of Energy, 26/6/2007.

- Alastair Manson, Consultant, Energy Retail Association, 26/6/2007.
- Geoff Hatherick, Head of Consumer Policy, DBERR, 2/7/2007.
- Sarah Darby, Research Councils' Energy Programme Research Fellow, Environmental Change Institute, 3/7/2007.
- Bob Lowe, Marketing Manager, Horstmann, 3/7/2007.
- Government Official, Defra, 4/7/2007.
- Jane Franklin, Commercial Metering Manager, Npower, 4/7/2007.
- Alan Knight-Scott, Regulatory, Legal and External Communications Manager, EDF Energy, Home Technology Programme, 4/7/2007.
- Richard Woods, Business Development Director, DIY Kyoto, 4/7/2007.

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