Identifying the opportunities for ICT based energy demand reduction in family homes

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July 3, 2015

Abstract

It is widely recognised that the residential sector will play an important role in achieving UK national targets for reductions in energy consumption and CO_2 production. This will be achieved through efficiency gains in devices, improvements to the building fabric and systems, more effective utilisation of devices and through accepting lower levels of comfort and convenience. Home Energy Management Systems (HEMS) and other Information and Communication (ICT) based solutions are attractive because they offer help in managing device/systems and can be applied to reducing consumption while (potentially) mitigating the impact on comfort and lifestyle. This paper attempts to quantify the energy reduction potential for HEMS/ICT through a systematic treatment of monitoring data from real family homes. The analysis describes for the first time the notion of the 'Reduction Effort Balance' that exists between capital expenditure and acceptance of less comfort and convenience and it is demonstrated that HEMS/ICT could influence up to 50% of the possible energy demand reduction. The findings also suggest that it is highly unlikely that energy reduction targets will be met without changes to occupant lifestyle.

Introduction

The UK targets for energy demand reduction are challenging and will impact energy consumption in the built environment in particular. Domestic energy consumption accounts for about 30% of the UK total and hence forms an important target area for these measures [1]. Energy reduction in homes, however, is not just a matter for retrofit measures, it depends on a number of variables such as: appliance ownership, control settings for space heating, hot water and appliance use patterns and the number of people in the home [2, 3, 4, 5, 6, 7, 8].

Better space heating control is a key factor in achieving significant energy demand reduction and there are currently 'smart home' systems on the market such as Control4 or VeraEdge Z-Wave Home Automation which increase the control users have over their consumption [9, 10]. Smarter heating controls, can give real time feedback and/or automatic adjustment of indoor temperatures. Devices such as the Nest thermostat try to predict occupancy to enable wasted heating to be minimised. Advanced home energy management systems (HEMS) such as Honeywell's Evohome aim to make the control and setting of heating parameters more straightforward, empowering the user to take energy saving action [11, 12].

This paper forms part of the work from the LEEDR project: a recently completed, multi-disciplinary study into demand reduction in UK homes. The question addressed is the extent to which HEMS and other ICT enabled 'smart' systems (referred to in this paper as HEMS/ICT) can influence energy reduction in real family homes.

Method

In order to understand the potential role of HEMS/ICT in facilitating energy reduction in the home, a three stage approach was adopted:

1. carry out detailed monitoring in typical, mid-sized, UK family dwellings;
2. from literature, develop models of the impact of a set of common reduction measures;
3. review which reduction measures might be enabled/facilitated by HEMS/ICT; and then,
4. calculate the aggregate impact of these measures using consumption data and models.

Description of the homes

The study is focused on 11 family households in the Midlands region of the UK which are all owner-occupied. The construction year of the buildings ranged from 1900 to 2000, with most houses being constructed in the 1950s and 1960s. All except one have cavity walls and most had undergone some degree of insulation retrofit and installation of double glazing. The homes where a mix of detached and semi-detached buildings with one mid-terrace. A number of these have been extended with conservatories and/or masonry extensions and were generally 3-4 bedrooms, although a couple of the buildings were larger than this. The householders varied in terms of education, income and environmental awareness. Family sizes ranged from single-parent households with two family members to three-generation households with seven occupants. All homes had central heating; mostly driven through a combi-boiler that supplied hot water. Several had a traditional hot water cylinder based system. The ages of the heating systems varied from 1 to 2 years old up to 10 years old.

These dwellings are quite typical of a great many homes in the UK. The average combined gas and electricity consumption for homes of this type in the UK is about 20MWh/year, of which 17MWh/year is gas since the majority of space heating and hot water provision is delivered through gas-fired boilers. The homes studied here on average, consumed 13% more gas and 79% more electricity than the UK national average, although the range in the sample was from about 20% less, to over twice the national average. The variability in consumption is typical. The slightly higher average consumption is likely to be because the sample does not contain lower income households and most homes were occupied during weekdays to some degree.

Monitoring

Monitoring was undertaken continuously for 2 years and included: mains gas consumption; mains electricity consumption; monitoring of sub-circuits and appliances within the building; temperatures around the home and outside; activity within rooms through PIR (Passive Infrared) devices; some window opening activity; and hot water consumption. Measurements were made using a combination of the AlertMe system[1], a bespoke high resolution gas measurement system and hot water measurement devices that comprised of temperature measurements and an in-line flow meter (See [13] for more details).

Electrical measurements were sampled every minute, PIR and window opening devices were also at minute resolution, temperatures were measured every two minutes and gas and hot water every second. The data was rationalised to 1 minute samples to make data processing more straight forward. An average of 50 measurement channels per dwelling were made, the data was

[1] In March 2015, AlertMe was acquired by British Gas.

filtered and unreliable data removed. For the analysis reported here, a check was made to ensure that all necessary measurements were available on a daily basis throughout the monitoring period, rejecting those days where there was missing data. From these available days, a typical set of days was derived for each month of the year, and the analysis performed on these 'typical days', scaling up the results to provide annual reductions. In this way only complete data is used in the analysis, while capturing seasonal effects: outdoor air temperature in particular.

Modelling energy reduction

A review of energy reduction strategies was carried out in the literature. The main published opportunities for domestic carbon emissions reduction used in this work can be found in: more efficient heating and electric production, more efficient supply [14, 15, 16, 17, 18, 19, 20], retrofit and sealing of the building stock [21, 22, 16, 23], improved heating systems technology [24], more advanced heating and home controls [8, 25, 26]; greener lifestyle, occupancy and user choice [27, 28, 23, 29, 5, 30, 31, 32]; enhanced appliances and lighting technology [27, 33, 34]; and the application of ventilation control systems [35].

A subset of possible reductions affecting energy consumption was selected on the basis of the applicability to the homes in the study and the ability to model the impact on energy reduction based on the detailed monitoring data. 14 reduction measures were modelled and are listed in Table 1. These breakdown into 3 broad categories:

Lifestyle: these do not necessarily cost anything, but require the user to accept a lower level of comfort and convenience than they are used to; reductions in convenience include the user having to undertake additional activities in order to reduce energy demand.

Replacement: items that require small to moderate investment, but are not particularly disruptive, such as replacing an old appliance;

Retrofit: major undertakings that usually affect the building fabric or heat production (i.e. the boiler) that imply a significant cost and undertaking.

The approach taken here, was to consider a plausible range of reduction measures to provide a context for the role of HEMS/ICT in achieving expected reductions as we move towards 2050. Of the measures given in Table 1, six benefit from further explanation:

One fridge freezer: applied only in those households with more than one fridge/freezer, i.e. the reduction would be achieved if only one fridge and one freezer OR one fridge-freezer is used. This measure is considered a lifestyle change because it can affect the family routines for shopping and storing food.

Heating only when home: the data is used to estimate when householders are at home and hence when the heating could be switched off. The savings are therefore calculated by aggregating the energy that has been consumed at times where in the analysis we consider the householders to be absent.

In use heating: controlling the temperatures in individual rooms based on their use and occupancy has been estimated by analysing the reduction in energy that would be achieved if the occupants were to heat the whole house for only one hour in the morning, the living room for the whole evening and to heat only one specific room if someone is at home during the day. The temperatures in the 'unused' rooms are maintained to at least 16°C.

Table 1: Energy reduction measures at a glance.

Type	Affects	Measure
Lifestyle	Reduced comfort & convenience	One fridge-freezer
		Minimal standby loads
		No tumble drying
		Heating only when home
		In use heating
		No heating over 15℃
		Heating to 17℃
		Minimal ventilation
Replacement	Cooking appliances	Replace cooking appliances
	Cold appliances	Replace fridge-freezer
	Laundry appliances	Replace laundry appliances
	Digital media devices	Replace media equipment
	Doors	Insulated doors
	Lighting	Replace bulbs
Retrofit	Loft	Loft insulation
	Walls	Wall insulation
	Floor	Floor insulation
	Windows	Triple glazing
	All building	Sealing
	Heating system	New boiler

Heating to 17℃ : setting the thermostat to 17℃ , hence the energy reduction is based on heating the home to a maximum of 17℃ . The energy required to heat the building to more than 17℃ (as monitored in practice) is therefore considered to be the reduction potential.

No heating over 15℃ : minimising the duration of heating the house. When the outside air temperature is at over 15℃ , it is assumed that the internal temperature will be around 17℃ so there is no need for space heating. In the UK the internal heat gains from people and appliances tend to be sufficient to raise the internal temperature a couple of degrees.

Ventilation: householders only ventilate the home to the minimum level required to satisfy the physiological needs of the occupants (i.e. to be able to breath and to remove CO_2 and other contaminants). The method estimates the heat lost through ventilation during the monitored period and this is converted to a ventilation rate. This rate is compared to the theoretical minimum and the energy required to heat the air over this level is considered to be the reduction potential.

Sealing: the sealing of gaps and cracks in the structure to avoid infiltration of cold air. Infiltration is the outside air that finds it way into the building that is not intentional - i.e. through the opening of windows. It's uncontrollable and hence by sealing cracks this is minimised. In the calculations the energy saving is based on the results from published field studies [36].

All the measures in Table 1 were modelled and used to filter the monitoring data to represent each case resulting in two sets of data, one baseline and one with the reduction measures applied. Using the monitored gas and electricity consumption data from the baseline model, the actual total annual energy consumption can be estimated. The filtered data describing the home with reduction measures was then run through a model to calculate the resultant energy consumption, by estimating the gas and electricity use. The baseline and the filtered results were compared and the procedure repeated for any combination of reduction measures. The principles of the modelling approach can be found in [37].

This approach is necessary because reductions do not necessarily aggregate in series, particularly in relation to heating and hence they must be treated simultaneously. For example, the reduction in the volume of gas used after changing the boiler for a more efficient one and setting lower temperatures in the home are interdependent. The published impact on energy consumption from trials have been used to generate realistic estimates of the reductions that might be expected. Models are also based on published values for new materials (U-value, for example) and systems (e.g. power consumption of a new device) where possible.

To give some scale to the potential reductions, the total reductions were compared with a notional 2050 reductions target. The reduction target is based on published values from the Energy Saving Trust [38] and is the consumption that achieves an 80% reduction in CO_2 emissions, based on the 1990 national average performance for a three-bedroom, semi-detached property, normalised by the average gross internal floor area.

An 80% reduction from these figures led to a primary energy target of 115kWh/m^2/year and an emissions target of 17kgCO_2 /m^2/year [38]. This figure was also comparable to those published by DECC [39], which reported national figures for each 2050 scenario.

Results and discussion

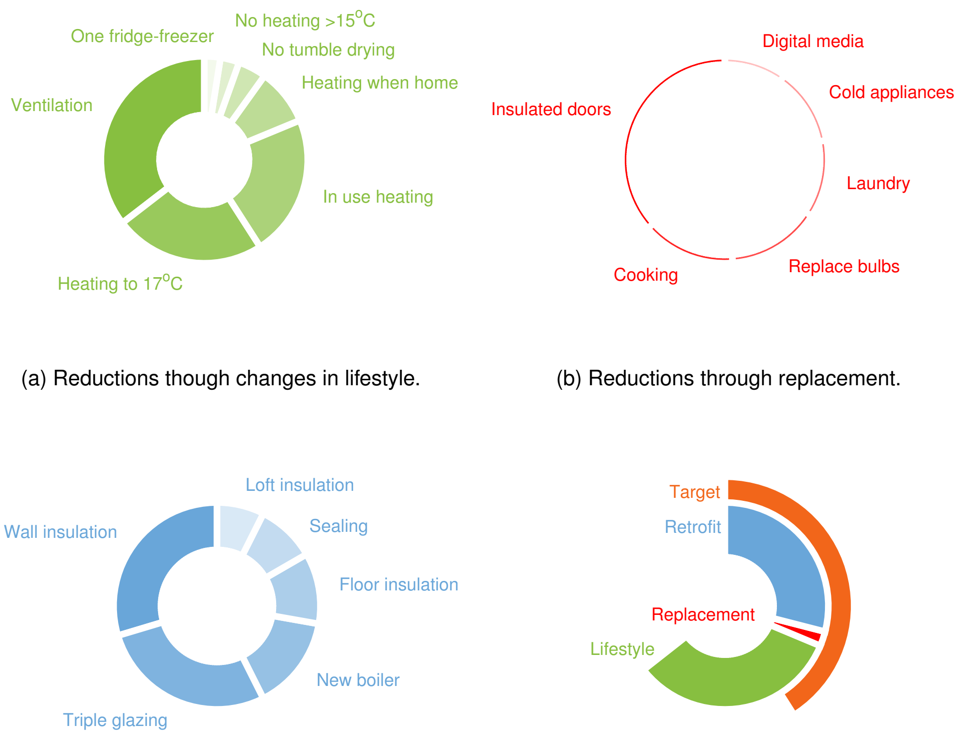
The average reductions in consumption across the studied homes are presented in Figure 1. The plots a - c (green, red and blue) show the proportional reduction in energy consumption from each reduction measure if applied on its own in each of the three categories: Lifestyle, Replacement and Retrofit: the relative weight of impact reductions in that group is indicated by the ring thickness. Reductions less than 1% were not shown in the Lifestyle and Retrofit categories (green and blue).

Figure 1d brings together the total reduction potential if all measures were applied: the circumference represents the annual energy consumption of the (sample average) household today, i.e. 100%. Reductions are shown in a coloured bar rotating in a clockwise fashion, hence the 'white' section between 7 o'clock and 12 o'clock represents the minimum energy consumption that could be expected after applying all the reduction measures. The ocre outer ring indicates the anticipated reduction required in order to achieve the 2050 reduction targets.

Figure 1 depicts average results from the sample, across the 11 homes. The total energy reduction potential ranged between between 50% and 70%. It was, however, the lifestyle category where the reductions *varied* the most. An average of 33% reductions could be made through implementing all the lifestyle measures, which is very similar to the total available through implementation of the retrofit measures. However the level of reductions varied $\pm$15%, three times that of retrofit measures, suggesting that how we choose to live/use energy in homes does vary considerably between families.

Although the prognoses suggested by the results are optimistic, they are in-line with observations published in other studies. For example: lifestyle reductions are close to those reported on a study which published possible savings of 39%, considering inefficient use of space heating and appliances [25]; a study looking at reductions from retrofit measures reported a possible CO_2 reduction between 50% and 80% compared with 1990 average levels [38]; and studies looking at possible savings from electric appliances via feedback and information such as more with informative bills, direct, immediate feedback and smart meters, have shown potential for savings between 5% and 20% [28].

What is also evident from Figure 1, however is that retrofitting measures and replacement combined cannot satisfy the proposed reduction target, meaning that some reduction in comfort and convenience will almost certainly play a role in achieving the reduction targets in the future. This is exacerbated when consideration is given to the application of external wall insulation included



(a) Reductions though changes in lifestyle.

(b) Reductions through replacement.

(c) Reductions through retrofit.

(d) Total reductions against 2050 target.

Figure 1: Breakdown of potential reductions based on the average LEEDR home today.

in the retrofit category which is not only expensive, but also has significant impact on the aesthetics of the property and the disruption of the building works which can be messy and dirty for families to live in; hence its ready application (in the UK at least) is questionable [40].

What the analysis does suggest, however, is that there is the balance point between capital investment and some acceptance of a reduction to comfort and convenience, which the authors term the ‘Reduction Effort Balance’ (REB). The REB is an approach that can be evaluated for each home and is useful in visualising the reduction options available to a specific home. HEMS/ICT can potentially shift the balance helping home owners mitigate the inconvenience that the lifestyle reduction measures entail.

Impact of HEMS/ICT on reduction potential

Basic HEMS enabled by ICT provide householders with feedback on their electricity via an in-home user interface ([12], for example). More advanced HEMS provide individual appliance monitoring and/or remote control over heating. Solutions that also provide zonal heating control are also becoming commercially available. Control automation can result in the reduction of wasted energy that would practically impossible otherwise: optimal starting of heating in response to patterns of occupancy is one such example. ICT potentially gives the user a more intuitive means of accessing critical set-points and parameters, and so makes actioning desired changes more achievable.

Observations from this study suggested that most of the lifestyle reductions were actually achievable without the need for automation or HEMS/ICT over and above traditional domestic control methods. Most, however, require ongoing commitment from householders. The opportunities for HEMS/ICT falls within the lifestyle reduction measures where automation and control can empower and encourage householders to make changes to the way they consume energy and provide convenience. All of the lifestyle reductions listed earlier apart from 'One fridge-freezer' and minimizing use of the tumble dryer can be enabled through HEMS/ICT using technological solutions that are already commercially available or in the process of being commercialised.

Reduction in inconvenience can be minimised through reducing the need for householders to adopt new behaviors (perhaps requiring the breaking of long established habits) as well as enhancing convenience by shifting responsibility for decision making from the household to the smart system. For example HEMS/ICT could be configured to 'power down' any unnecessary stand by loads every night from one bedside switch. Similarly although reductions to thermal comfort can be somewhat minimised though everyday behavior change (e.g. putting a sweater on in response to turning down the heating) HEMS/ICT can also facilitate energy demand reduction whilst helping households maintain desired levels of comfort by for example: responding to a householders preference for fresh air by automatically switching off any radiators in the proximity of the opened window or door [41]; providing convenient but short term boosting of heating via for instance a smartphone app and even encourage adaptation of thermal comfort preferences overtime though gradual reduction of set points which will faciliate acclimatization [42].

The reduction analysis presented suggests that HEMS/ICT could potentially provide savings similar to those likely to be achieved through expensive and disruptive retrofit measures and also have a higher impact on demand reduction than the replacement of appliances. In an attempt to evaluate what proportion of the total reduction potential that might be enabled by HEMS/ICT, the lifestyle categories were revisited in order to select those measures where it might be reasonable to expect a strong role for HEMS/ICT. Table 2 describes how HEMS/ICT might affect the implementation of the lifestyle reduction measures, and whether these are practically achievable without HEMS/ICT.

Table 2: HEMS/ICT energy reduction measures.

Description	**HEMS/ICT relationship**
No standby loads	Appliances can be turned off manually, however, remote access to switching or implementing algorithms that learn behavior using ICT increases the likelihood of unused appliances being turned off, hence reducing unwanted energy consumption.
Heating only when home	Similar to the above comment, can be affected with manual control, but it much more likely to be effectively implemented with a degree of autonomous control automation.
In use heating	Zonal control of rooms is currently practically difficult to implement in rooms except those that are 'always' unoccupied and so ICT enabled control has an obvious advantage.
No heating over 15℃	Automated control scheduling is practically impossible with existing systems. Future ICT enabled systems could automate response to key variables such as outdoor air temperature.
Ventilation	In building that use windows for ventilation (as opposed to HVAC systems) manual control is still the most likely means of operation. However, ICT could enable monitoring of windows controlling or advising when they should be closed, for example when the house is empty or heating is on etc.

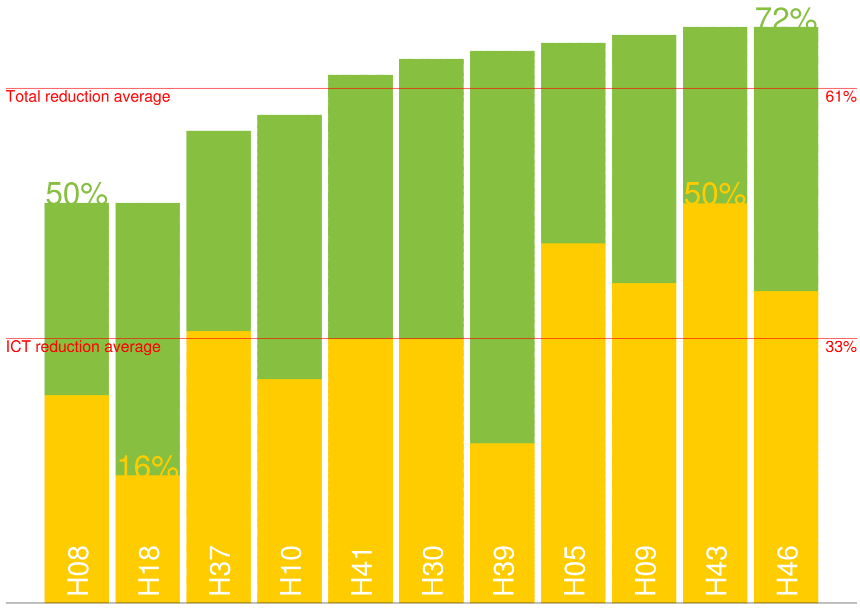


Figure 2: Reductions as a percentage of total energy consumption through ICT (yellow) and through all other measures (green).

Figure 2 compares the reductions that might be achieved through HEMS/ICT, as listed in Table 2. The total reduction potential from the initial investigation (Figure 1) for the 11 homes (which are coded in the horizontal axis of Figure 2) is depicted. The yellow portion of each bar describes the reduction associated with the HEMS/ICT interventions. Average values for the group are shown in red. An average of 61% reduction in current energy consumption is possible across the group, and of that 33% might be enabled, or enhanced by the application of HEMS/ICT systems.

Conclusions

HEMS/ICT is seen as being an important component in realising the energy and CO_2 reduction measures in the UK. This work attempted to quantify the potential opportunities for HEMS/ICT in terms of energy demand reduction in typical, mid-sized family homes in the UK. The analysis was based on detailed longitudinal monitoring and modelling the effects of common energy reduction measures. A number of observations were made:

The impact of lifestyle varies between homes: An average of a 33% reduction could be made through implementing changes in lifestyle, similar to that offered by retrofit measures, but the level of reductions varied $\pm$15%, three times that of the variation in retrofit.

Reduction Effort Balance: The concept was introduced here for the first time to describe the tipping point between benefits gained through capital investment over those gained through the acceptance of lower levels of comfort and convenience.

Opportunities of HEMS/ICT exist over 50% of potential reductions: the prognosis for the usefulness of existing systems and new innovations is strong if HEMS/ICT can help mitigate the loss of comfort and inconvenience that comes with implementing lifestyle changes.

Although the analysis takes an optimistic view of the impact of potential reduction measures, the analysis indicates that the suggested 2050 reduction target contributions are achievable for the type of home studied here. Although the sample studied is small, these homes are very typical of those found throughout the UK, and the authors were encouraged by the results. However, it was also noted that while some homes would find it relatively easy to achieve targets, others would find it very difficult, either due to having already a retrofitted house which still consumes high levels of gas or due to having already applied some lifestyle measures (such as lower room temperatures) but still be over target levels.

Retrofitting alone, it seems, will not generate sufficient reductions in all cases and hence it is extremely likely that some degree of lifestyle change (reduction in comfort and convenience) will be required in the future. It's worth noting that in the study here, both the application of external wall insulation and consideration of ventilation are sensitive components in the model. The application of external wall insulation in the UK it's not an attractive solution currently and without this additional insulation, there is further pressure to decrease comfort and convenience. In addition, minimising ventilation plays a key role in lifestyle reductions, but the actual impact is difficult to quantify, particularly in older properties that maybe damper and require greater ventilation, apart from the challenges associated with drying washing during the winter months and the resulting requirement for increased ventilation.

What the study has demonstrated is that although significant reductions are within reach, the application of HEMS/ICT can play an important role, and this will be against a changing landscape depending on the penetration of retrofit technologies and practicable levels of ventilation in the home.

Acknowledgments

This paper has forms part of the work produced under the 'LEEDR: Low Effort Energy Demand Reduction Project' based at Loughborough University, UK. The work was funded through the Transforming Energy through Digital Information (TEDDI) call managed by the RCUK Digital Economy and Energy programmes (EPSRC Grant Number EP/I000267/1).

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