Estimating the potential reductions in energy demand through efficiency, control and lifestyle change in a real home

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ABSTRACT

In order for the UK to generate pathways to help deliver the near and long term CO_2 reduction targets set by the Committee on Climate Change, a number of future scenarios were generated to simulate consumer responses to energy price changes based on economic background, developments in technology, fuel price and other assumptions. The overall carbon reductions anticipated by these scenarios lie between 40% and 90% by 2050, the domestic sector is expected to reduce emissions by 31% by 2020 and 60% by 2050. The question is how the residential sector will respond to the anticipated changes to the supply and demand for energy. There will be potential future CO_2 reductions through the introduction of more efficient appliances and the implementation of more advanced heating controls, enabled through ICT [1]. What is less clear is how far the benefits of efficiency and control will get us to these goals and to what degree people will have to make changes to their chosen way of living in the home. In this paper we ask, whether the answer to significant reduction in energy consumption lies with the acquisition of equipment, or the adaptation of family life. The approach has been to take whole house energy data from a real family home in 2013 and place it in three possible landscapes that look towards 2050. This model simulates energy consumption in 2050 by applying potential interventions to determine the effects of efficiency, control and more sustainable lifestyles.

Keywords

Domestic energy consumption, Whole house simulation, Lifestyle change, Future Technology

1. INTRODUCTION

The UK CO_2 targets require a reduction in emissions of 80% by 2050 [41]. This challenge is of special interest to the domestic sector, which accounted for 25% of the overall UK emissions and just over 40% of the final energy use in 2009 [14]. Future scenarios predict significant decrease in CO_2 emissions for energy production due to implementation of renewable energy systems [37] and increased localised domestic energy production [15]. The introduction of renewable energy systems creates greater intermittence in the supply which is challenging for the energy sector, where demand must be met while balancing generation [28].

Reducing domestic CO_2 emissions is challenging as reduction and shifting demand requires active participation from the user, over and above the capital investment and time for organising refitting, buying new efficient appliances and updating home technologies [8]. Future pathways towards reduced CO_2 emissions assume lifestyle change and anticipate that householders will respond to energy price signals and social sustainable values [41]. However, several studies argue that energy is not visible to users and that they are not always rational in their actions [48] which makes it difficult to predict the real savings from energy efficiency and control interventions. The design of energy demand reduction interventions, therefore, needs to consider lifestyle values related to energy consumption in the home including perceptions of comfort and convenience [35, 39, 34].

The aspects of home dweller's lifestyle that need to change in order to deliver the savings in consumption necessitated by reduction targets is not well defined. Future scenarios such as the lifestyle scenario [41], The UKDCM (UK Domestic Carbon model) developed as part of the model 40% house [7, 23] and other national household scenarios [33, 38, 29, 45, 25, 20, 2, 19, 24, 47, 43, 42, 3, 40, 26, 27, 17, 21, 30] make assumptions about the shifting and reductions in domestic demand, in order to establish the topology of future generation. As we move towards 2020 and beyond, the roll out of smart meters to every dwelling will occur [15, 32, 18] and the hope is that consumption will become more visible, and billing more sophisticated. More advanced Home Energy Management Systems (HEMS) are also entering the market, these allow consumption monitoring at an appliance level as well as increased home automation and control. Such systems should help users to reduce energy consumption, although the effectiveness of such interventions has so far been varied [1, 4, 31, 6, 10, 13].

[1]ICT: Information & Communication Technology

There is a need therefore to consider more explicitly and systemically how the 2050 target can be met taking into consideration retrofit opportunities, smart appliances, systems control and lifestyle change. The approach taken in this paper is to sketch out plausible 2050 landscapes, take a real family living today, and model their consumption under different interventions to predict the effect of these interventions on consumption in a 2050 world. Conclusions can then be drawn about the extent of the changes that may need to take place as well as the challenge of the assumptions on which the current future scenarios are based.

2. LIVING IN 2030/2050

Existing future scenarios that describe possible landscapes towards 2050 CO_2 reductions examine not just public policy measures, fuel prices, economic growth and technical improvements but also important cultural shift [46]; especially in the home, where domestic consumption, dominated by space heating, hot water use and electricity consumption for lighting and appliances purposes, increased by 150 per cent between 1970 and 2008. The main increase in the domestic sector took place from 1970 to 1986 largely as a result of the spread of installed central heating and the increase in the number of energy-consuming goods [18] which resulted in people adopting higher comfort levels in the home. This trend has been the focus of several programmes and studies which aim to decrease domestic energy demand by designing and evaluating information and feedback interventions. Insights from these intervention studies are being used to shape socio-political initiatives towards a low carbon housing stock. Government policies have already been launched to facilitate the implementation of more efficient systems, improved billing, consumption feedback and greener energy production. Programmes such as the Green Deal, ECO, the Renewable Heat Incentive (RHI) and Energy Performance Certificates (EPCs) [5] consider not just technological change but aim to encourage lifestyle change [5], incentivising people, for example through finance schemes and attempting to reduce the 'rebound effect' associated with Retrofit and ICT interventions in existing homes. The lifestyle scenario, The Carbon Plan and the UK White Paper 2007 [18], describe some of the key characteristics of energy production and consumption predicted to impact new and existing households. Published changes in energy consumption for existing dwellings have been analysed here and possible savings have been quantified for a sample house, differentiating between technology, ICT, behaviour and retrofit interventions and evaluating three outcome scenarios.

3. THE HOME TODAY

The data used in this paper is from an ongoing home energy monitoring project in the UK, which explores residential energy use and the interplay with householders lifestyles and routines. 20 homes are monitored in total and a whole house approach has been taken, looking at main electrical appliances and circuits, gas and hot water consumption, room and outside air temperature and room presence signal [11]. This paper uses data from one monitored home, hereafter called H05. H05's energy profile is typical of homes in the UK and is deemed representative, with its estimated annual electricity consumption of 14745 MJ nearing the average figure of 11678 MJ reported by DEFRA [49]. The property is a 1930s semi-detached family home with a floor area of $\approx$100m^{2}over two-storeys.

Taking a snapshot of the property today in 2013, the house wall construction already has post building insulation installed in the cavity and the loft has been insulated with 200 mm of rock-wool. The windows have been refitted with double glazed units through the whole house and more than half the lights are CFL [2]. H05 has been extended and contains a large kitchen diner, a living room, a sitting room used as home office and a utility on the ground floor, and three bedrooms and a bathroom on the first floor. There is a detached garage which contains a tumble dryer, a second fridge and a second freezer.

Most appliances are relatively new, including a A+ rated washing machine, and an electric hob and oven. The main hot water and space heating system is a gas condensing combination boiler which is less than 5 years old. Space heating is supplied by radiators which have TRVs [3] fitted. The space heating is mainly controlled by a programmer which allows multiple time and temperature settings. Hot water for showering is supplied by the main combination boiler.

The family comprises of two parents, a teenage daughter and a dog; The house is generally occupied all day on Fridays, (when the father (H05MA) works from home) and at weekends. H05 therefore, has two main occupancy profiles,

- working days, from Monday to Thursday when the whole family is out of the house during the day; and,
- 'at-home' days, from Friday to Sunday when the house is more permanently occupied.

To describe and apportion the energy consumption in the home, monitored data was taken for two winter days, one working day and one 'at-home' day. Figure 1 shows the energy consumption profile for gas, hot water and electricity during both days of study: the total energy consumption in H05 was 40% lower during the working than the 'at-home' day. During the 'at-home' day the heating system was continuously on, maintaining the indoor air temperature close to 22℃. The heating system led scheduled on/off times which resulted in a fluctuating air temperature between 15℃ to 19℃ during the working day showing different cumulative gas flow, depicted in the top two plots of Figure 1. Gas flow is constant during the 'at-home' day (left hand plot) except between 07:00 and 08:00 when a shower took place, indicating that the boiler modulates gas flow depending on load.

The power profile also differs between both days. Peaks in electric consumption appeared all along the 'at-home' day, whereas during the working day, peaks are mostly concentrated in the evening when people are active in the home. Electricity consumption lies between 7% and 9% of whole energy consumption of the home on both (winter) days. Space heating demand is on average near to 90% of the daily energy consumption. During the monitoring year, H05 space heating was on from September to April, which proportionally accounted for 60% of the annual energy demand, being very similar to UK published figures [16].

To analyse the energy reduction afforded by the implementation of measures which are part of the future landscapes, savings are simulated in H05 based on the data from

[2]CFL: Compact Fluorescent Lights

[3]TRV: Thermostatic Radiator Valve

the two days of study. The simulation modelled improvements in technology for lighting, appliances and for the heating system, ICT interventions for space heating and appliances and retrofit opportunities. Likely savings from each of the categories were quantified and applied to three future household scenarios.

4. INTERVENTIONS 2013 → 2050

Over a span of less than 40 years, substantial technological and cultural changes are expected to shift everyday life in the home. Housing low carbon scenarios describe more smartly controlled houses, more efficient appliances and heating systems, stronger regulations for product design and labelling and higher energy prices [8]. Major potential changes affecting energy demand in households have been identified in the literature and are listed below:

Space and hot water heating controls

Minimum heating controls comprise a time programmer and room thermostat or combined programmable room thermostat plus thermostatic radiator valves (TRVs) and further zone controls to heat required parts of the house [11]. The most likely application of such controls is through 'smart home' technology that is combined with HEMS to provide more efficient management of energy use in the home.

Building fabric and housing stock

New buildings need to achieve close to zero space heating demand by 2020 the latest. Therefore heat loss standards as well as ventilation heat loss through infiltration of cold air will be reduced. Refurbishment of the existing stock to the standard of current Building Regulations for new dwellings is necessary since most of the UK housing stock will still be standing in 2050 [46, 8]. Retrofit opportunities range from easy and cost-effective measures, such as insulation of cavity walls, replacement of old windows with double, triple and other glazing systems and placement of thicker insulation in lofts, to more expensive and disruptive solutions such as insulating solid ground floors, updating already refitted windows or applying surface wall insulation [44]. Infiltration of cold air from the fabric will be reduced by the application of restrictive air pathways such as blocking chimneys, sealing skirting boards and service pipes penetration to achieve the same infiltration rates as in new buildings. [8]

Appliances, lighting and heating systems technology

More efficient domestic appliances are expected to enter the market eventually decreasing energy consumption; standby loads will decrease to 1 Watt and smaller appliances will become trendy. Incandescent bulbs will be replaced by CFLs in the first stage and LEDs[4] after 2020.[41]. New high efficient heating systems will be installed widely, phasing out non condensing boilers and rising up boiler efficiency levels to 95% [8].

Heating and electricity provision

Low carbon heat pumps and zero carbon solar hot water, biomass, geothermal, solar Photovoltaic and wind turbines will generate 30% to 40% of domestic gas and electricity [8] which will impact on carbon emissions and also on energy price and availability.

Lifestyle

Greener lifestyles are expected to become a social norm [41]. In these future lifestyle projections, feedback and information will increase people's awareness of energy to enable savings. These information measures which take several forms ranging from informative bills to direct, immediate feedback as with smart meters, have potential for savings between 5 and 20% [9]. Overheating will become socially unacceptable and maximum peak indoor temperature will be 17℃ from 2025 [41]. Ventilation will need to be reduced not just by avoiding infiltration of cold air but by motivating appropriate natural ventilation, lowering down standard ventilation rates to 0.6 air changes per hour. Practices will be led by personal action against carbon emissions by shifting time of use to satisfy energy availability and by changing shopping, laundry and cooking routines to reduce carbon emissions from electricity production.

5. MODELLING THE HOME 2013

The model described here is based on measured consumption values taken from H05. The object of the model is to describe energy consumption of the home today (2013) and then by systematically applying changes to the model, yield the energy consumption that might be indicative of that in 2050. The approach is staged:

1. develop a steady-state heat balance model that parametrises the high level energy use and supply;
2. estimate the heat losses through the fabric and ventilation/infiltration;
3. review and classify interventions and ways of changing energy consumption; and then,
4. apply these expected reductions through the high level parameters by disaggregation either by consumption classification or time dependency.

The high level heat balance is given by;

$$0 = (Q_g + Q_e + Q_p) - (Q_w + Q_f + Q_v), \tag{1}$$

Where Q_g, Q_e, Q_p, Q_w, Q_f and Q_v are the daily sum of gas consumption, electricity consumption, heat gains through people, heating for hot water, heat losses due to the fabric of the dwelling, cold air infiltration and ventilation [11]. Gas and hot water consumption are measured at a sample rate of 1 second and hence it is possible to determine gas use for cooking, space heating and hot water production. Q_e is measured at the mains circuit at 1 minute intervals, but can also be generated by summing the power from all appliances and lighting circuits since these are monitored. A balance was made comparing the aggregated power with the mains and the difference was negligible compared to the uncertainty in the measurement of the devices. The number of people in the home on the days used in this study was estimated through observation of activity via PIR sensors and working profile knowledge of the families. The fabric losses were estimated based on selected U-values for the construction type. The mean indoor and outdoor temperatures were estimated

[4]LED: Light Emitting Diode

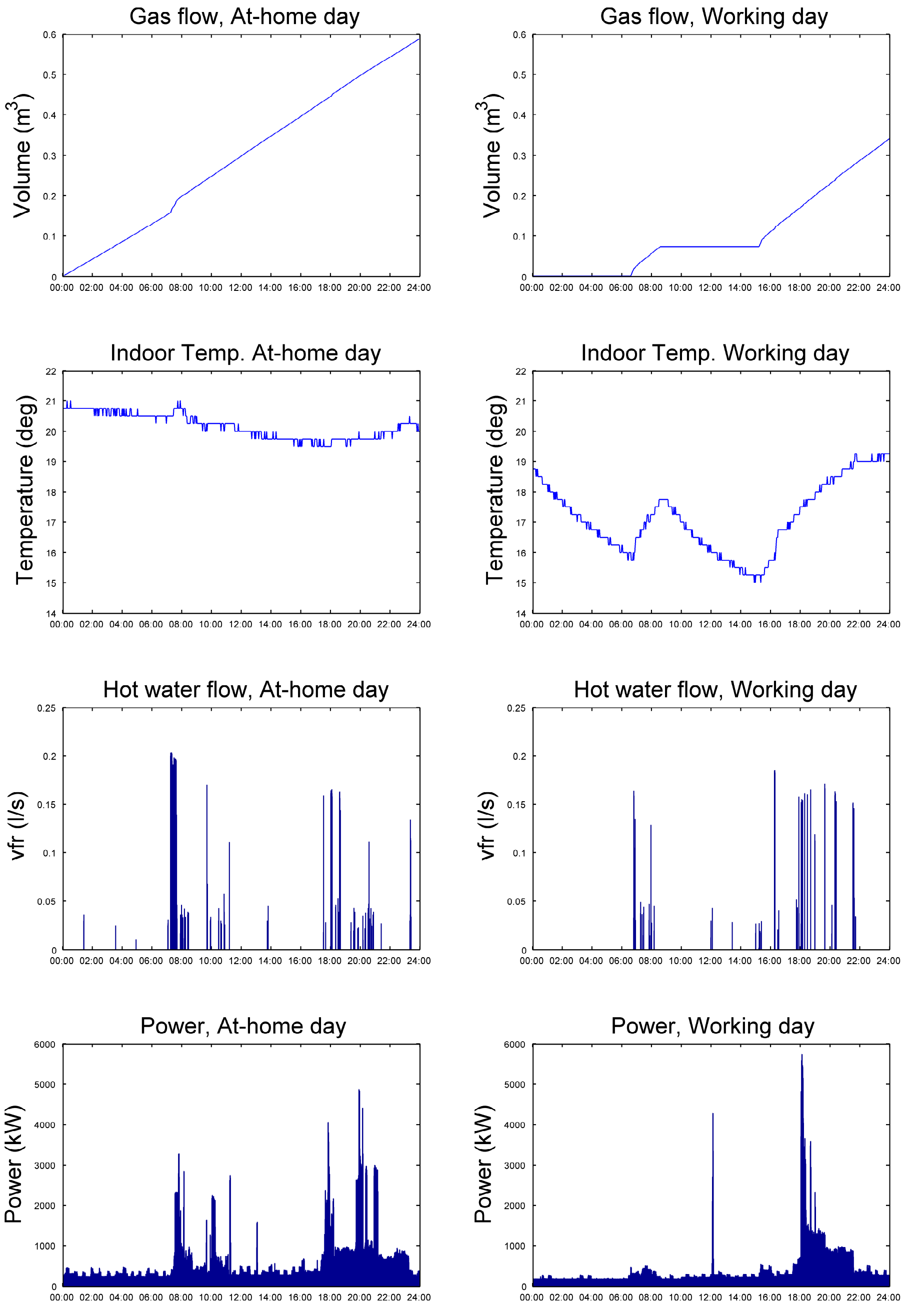

Figure 1: Energy consumption profiles for a working day and a weekend day.

based on the monitoring data. The ventilation/infiltration losses are estimated in Equation 1.

The paper attempts to understand where the line between interventions and behaviour/lifestyle change lies in real homes to ascertain how much change to the day-to-day domestic routines and practices must take place in order to meet the 2050 intended targets. Simplifications are made to make the illustration possible with in the scope of the paper. There is an assumption that the quoted reduction targets will apply to this home, when in reality they are likely to be unevenly distributed, targeting those with higher consumption/CO_2 production. Although the approach is scalable and can be applied to multiple years of data which account for seasonal change, we focus here on a fairly typical week day and an 'at-home' day in January 2013; Since most energy saving are likely to be through reduction of the space heating demand, this study represents a conservative estimate of the saving possibilities, drawing the line between technology and behaviour driven reductions. The key parameters considered on these two sample days are summarised in Table 1. The specified target values are based on predicted changes which will affect households as described in the last section.

Applying changes to the model

A review of interventions has been carried out in the literature and where possible, published reductions from trials have been used as realistic estimates of the savings we might expect our home to make. Some of these changes are easily applied on whole day values: if we know there is one less person in the home (someone has left) then gains (Q_p) will go down proportionally. Where there is a saving on an appliance, i.e. a fridge is replaced with a more efficient device, then this must be applied to the specific device and so the loads need to be disaggregated to do this. This has been carried out for the electrical loads and classified according to the DEFRA categories [49], depicted in Figure 2. Cold appliances include three refrigerators; lighting is measured in the lighting circuits and lamp bulbs; audiovisual equipment and computers are included in the ICE [5] [12]; cooking include all the electric devices used for heating or/and processing food; washing and drying appliances are laundry devices and dishwasher. Electric loads which do not fall neatly into these categories are accounted for as 'others'.

Other changes include modes of operation that are time dependant during the day. A TV, for example, might have a standby load and so a time series model is required to evaluate the reduction generated by switching it off when not in use. The reductions that can be realised by reducing the duration of space heating, or by reducing the set point temperature must be evaluated by estimating the ratio of the effect of reduction on the volume of gas consumed. By way of example, the latter is implemented thus,

$$\frac{Q'_f + Q'_v}{Q_f + Q_v} = \frac{Q'_g - Q'_w}{Q_g - Q_w}, \tag{2}$$

[5]ICE: Information, Communication and Entertainment devices

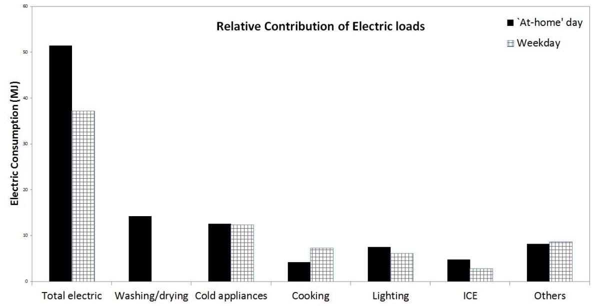

Figure 2: Appliance consumption for a workday and a weekend day.

where $Q'_f + Q'_v$ is the fabric and ventilation losses at the new lower set point and $(Q_f + Q_v)$, Q_g and Q_w are the estimates from the data. The expression then ratios down the gas consumption that might be expected if a lower set point temperature was used. The effects on space heating that have been treated with this and similar approaches in this study are:

- lowering the indoor temperature set point, described above;
- using space heating only when the house is occupied, by applying three different occupancy patterns;
- ensuring the heating is off at night when the family are sleeping; and,
- working from home, when only part of the house is heated.

The appropriate interventions for this family home are applied to the model and the estimated effects on energy consumption calculated. These results are then discussed in context of future targets in the 2050 home.

6. 2050 HOUSEHOLD SCENARIOS

In order to create the future scenarios for H05 energy consumption, the main variables considered have been technology and lifestyle. The reference scenario places H05 where it is now and technology and lifestyle change are applied to move from the house today to three different 2050s' landscapes, which are summarised in Figure 3. For this analysis occupancy patrons remain constant considering 4 working days and 3 'at-home' days.

Reference scenario

The reference scenario describes H05's current picture, illustrating the characteristics of their appliances, space heating controls and building thermal behaviour. H05's central space heating is fired by a combination condensing boiler and it is controlled by TRVs in each radiator and programmer allowing multiple time and temperature settings. Hot water is supplied by the boiler; Indoor temperature is between 18 and 21℃, being very constant on the day 'at-home' but fluctuating on the working day. Natural ventilation is higher during the 'at-home' day when laundry takes place, impacting on the ventilation rate which sharply increases from $0.86h^{-1}$ to 1.86 h^{-1}. The main consuming appliances

Table 1: **Energy balance parameters considered in the model.**

Description	Parameter	Value Weekend	Value Workday	Target Value	Unit	Intervention
Fabric Heat loss	Q_f	315.8	269.54	-	MJ	-
Whole house UA values	UA	174.38	174.38	146	W/K	Retrofit
Ave. indoor temp.	T_i	21.7	18	17	℃	Lifestyle
Ave. outdoor temp.	T_o	0.74	0.11	-	℃	-
Hot water heat loss	Q_w	21.52	7	-	MJ	-
Hot water use	m_w	233	76.5	-	Kg	-
H.water initial temp.	Ti_w	40	40	-	℃	-
H.water final temp.	Tf_w	18	18	-	℃	-
Ventilation heat loss	Q_v	393.72	155.09	-	MJ	-
Ventilation rate	N	1.86	0.86	0.6	h^{-1}	Lifestyle
Electric heat gains	Q_e	55	37	-	MJ	
Cold appliance number		3	3	1	-	Lifestyle
Cold appliances input		12.4	12.4	8.4	MJ	Technology
Lighting input		7.4	6.1	1.95	MJ	Technology
Washing Machine		14.19	0	1	MJ	Lifestyle
Dishwasher		6.75	0	2.89	MJ	Lifestyle
Space heating	Q_h	636	375	-	MJ	-
Boiler efficiency	n_h	80%	80%	95%	-	Technology
Body heat	Q_p	17.28	12.96	-	MJ	-

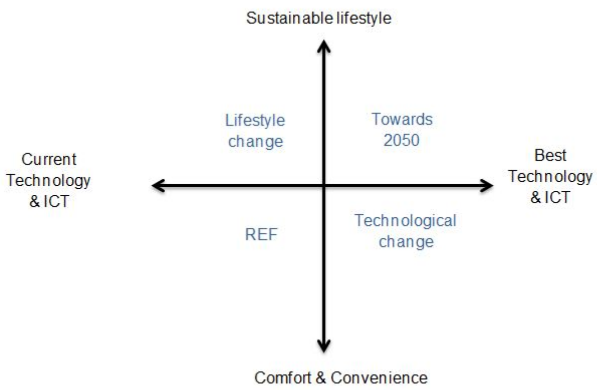

Figure 3: H05 Scenarios.

in the house are the dishwasher, washing machine, a fridge-freezer, a second fridge and a second freezer placed in the garage, three TVs and other ICE devices.The house equipment is considerably new and their building has already been refitted. H05 householders have some interest in the environment even though their lifestyle is not led by sustainable values.

Lifestyle change

In this scenario H05 is placed in a world of energy awareness where sustainability has become a social norm, resulting in an important lifestyle shift. H05's home activities are constrained by householders commitment to the environment. Technology, ICT and building thermal behaviour do not change, the family effort to cut emissions is focused on reducing net consumption rather than purchasing more efficient devices. The indoor air temperature is maintained at 17℃ during the heating season and the family is more conscious of how to program the system to avoid the heating on when no one is using it. The ventilation rate has been reduced to a minimum of $0.6h^{-1}$, assuming that building cold air infiltration is as low as in new buildings and natural ventilation practices are supportive of low heat loss. The assumption here is that the dwelling characteristics avoid cold air infiltration higher than the standard. The family interest for the environment motivate them to look for all sorts of feedback in order to cut consumption and to aim at specific reduction goals in comparison with the neighbourhood and the national average domestic consumption. They also change their shopping routines and the way they store food to reduce their ownership of refrigerators from three to one. The use of the tumble dryer is avoided and the washing machine and the dishwasher are used no more than 3 times a week. The lighting is updated by changing all the old incandescent lights to CFL. In this scenario, carbon emissions are expected to decrease by adjusting appliance time of use to energy availability in the electric grid, considering the integration of smart grids as part of this potential future landscape.

Technological change

H05 Technological change scenario considers best technology possibilities for ICT, main appliances and fabric materials without taking into account the cost effectiveness of the interventions but considering any technological improvement as an investment for cutting energy consumption. In this scenario, the house has been re-refitted with the best windows in the market, better and deeper loft insulation, insulation under the ground floor, surface insulation on the already filled cavity walls and a new insulated principal door; the boiler is replaced by a new best efficient condensing boiler and ICT is installed all through the house to smartly control the heating system and each radiator; only occupied spaces are heated and the 'all off' home mode is used when the house is empty. The rebound effect takes place through increasing householders expectations for ther-

Table 2: Intervention Reduction Percentage

Intervention	% Reduction
Lifestyle	49%
Technology & ICT	25%
Retrofit	8%
Total reductions	82%

mal comfort and considering the average indoor temperature between 18℃ and 21℃. All the appliances are 'best standard' and standby loads accomplish the 1 Watt initiative. The family routines do not change, appliances are used as frequently as currently and the family still owns three refrigerators, although these are new and highly efficient devices. All the lighting is replaced by LEDs. In this scenario the implementation of solar panels for hot water and space heating, PVs and micro generation opportunities needs to be considered for the study of carbon emissions, even though in this case is not analysed since it does not affect energy consumption.

Towards 2050

This is the ideal H05 scenario, where technological and lifestyle change have taken place decreasing energy consumption to the minimum which can be expected from lifestyle and technological change.

7. RESULTS

Energy savings have been quantified in three different categories to differentiate between potential reduction through lifestyle change, technology improvements and retrofitting opportunities. Lifestyle change would have the highest impact reducing energy consumption by 49% of current demand. It would need to integrate several interventions which will impact in household practices and home management especially in heating and ventilation routines. These savings have been defined and applied in the 'Towards 2050' scenario and in the 'Lifestyle change' landscape. Most part of the savings, 36% of whole house consumption, are associated with the air changes in the house, especially during the 'at-home' day, when the ventilation rate was three times the target value. One of the reasons for this high ventilation rate is that during the day, MA was working from home and laundry routines were taking place and since the family do not use the tumble dryer, drying regularly takes place outside. The data suggests that during the 'at-home' day the back and front doors were opened frequently, partly in order to hang out the three laundry cycles that took place along the day and partly to allow the dog in and out the house. It emerged from the ethnographic work that the family considers it valuable to be in the garden and to have frequent fresh air in the home, this being one of the reasons for their preference of air-drying laundry outside instead of using the tumble dryer. The findings here suggests that practices that in principle seems to be more environmentally friendly, such as avoiding the use of the tumble dryer, can result in an increase of the energy loss rate which impact on gas consumption, as the central heating system attempts to maintain an indoor temperature of 21℃ while being frequently in contact with the outdoors. Given that this is the case, the interesting observation is that the family might regard outdoors drying to be a sustainable routine, when at certain time of the year, aspects of their routine could significantly increase their consumption of fuel. The dog is also important when considering the home ventilation since it affects the family's routines of opening and closing doors.

Lifestyle change also considers savings from the decrease in chosen indoor temperatures to 17℃ which would account for 11% of total savings. A reduction in the number of refrigerators currently used in the house is an opportunity for 1% energy reduction, which means getting rid of the chest freezer and the second fridge in the garage to avoid the constant base load in the electric consumption. Since there are just three people in the home, the number of appliances does not lend itself to sustainable practice. Importantly this highlights that changing circumstances and 'hang-overs' from previous living arrangements can have long lasting impact on energy consumption if left unchecked.

From the monitoring data and the ethnographic insights, washing cycles in H05 are assumed to happen during the 'at-home' days, considering 3 cycles per day as the data suggests. To estimate possible savings from lower laundry activity, the number of loads were reduced to 3 cycles a week, which accounted for 0.4% of total energy reduction.

No savings are considered for the dishwasher use since it was used just during the 'at-home' day leading to 3 uses a week. Lighting savings will lead to 0.5% from updating the old incandescent bulbs which were half of the lighting in H05 with CFLs;

Technology savings which account for space and hot water controls and appliances, lighting and heating systems technologies show potential savings of 25% of the energy consumption. In order to achieve these savings, householders would need to become interested in new technologies and be motivated to invest money and time buying and understanding how to use their new technologies efficiently in the home. Technology interventions considered in this analysis have been defined and applied in the 'Towards 2050' scenario and in the 'Technological change' scenario.

Almost all the savings that have been identified from applying new technologies and ICT are based on better heating system controls. These savings were applied to automatic 'switch on' of the radiators in occupied rooms and higher boiler efficiency. Smart ICT for the heating system has high savings potential, especially when there is just one occupied room for over 8 hours in the house, accounting for 22% savings the 'at-home' day but no savings on the working day due to the already implemented time setting program. These savings account for 9% daily reduction including both occupancy profiles. Best boiler efficiency values found in the literature [8] have been considered to calculate savings from a 5 years old 80% efficient boiler, leading to possible reductions of 13% in whole house energy consumption. No savings have been found from 1 Watt stand by loads for new ICE devices since these were not left in stand by. 1% energy reduction could be achieve by changing current incandescent and CFL lights to LEDs, and further 2% savings from changing the three refrigerators to three new A++ rated ones.

Retrofit opportunities have been considered in the 'Technological change' and 'Towards 2050' scenarios since they involve making use of new insulating materials and fabric update. These kinds of interventions in H05 can lead to 8% whole house energy reduction. Energy savings from retrofit measures in H05 are mainly expected from the insulation of the ground floor, which is not just an expensive measure but a disruptive process as well.

The best expectable future picture is the 'Towards 2050' which is hopeful since 82% of the energy can be saved by applying lifestyle and technological interventions. This landscape is especially challenging, since it affects some of the family routines, the way they control their heating and their indoor temperature choice. Furthermore, it requires an important economic investment to update appliances, systems and fabric. The other two scenarios draw half way landscapes. 'Technological change' describes a possible H05 where fabric and systems are best standard but householders choose to have a comfortable and convenient lifestyle which still means reducing their energy consumption by 33%. The lifestyle scenario has more potential savings, requiring a radical shift in home management and in some everyday practices such as laundry and shopping, resulting in 49% energy reduction.

8. DISCUSSION

H05's potential savings are in line with 2050 goals. More than half of the savings that could be achieved in this household affect householders' thermal comfort and family practices. Most of the savings found in the analysis are in reducing energy demand for space heating, which is expected since electricity accounted for 9% of whole energy consumption.

H05 have already applied some sustainable practices such as leaving ICE devices off when not in use or avoiding the use of the tumble dryer. What they might not be aware of is the amount of energy that can be wasted if doors/windows are open frequently and/or for long periods of time, even more so on a cold winter day and when having set the heating programmer to a high indoor temperature. The family efforts towards energy reduction need to be permanently fed back to avoid unexpected rebound effects which can lead to unaware energy consumption like leaving doors open frequently or heating the whole house all day long when working from home.

Household occupancy is determinant of energy consumption [36], therefore occupancy patterns will be most important when targeting domestic energy reduction, questioning the sustainability of teleworking, which leads to space heating, lighting and all sorts of resources that enable an individual working space. On the other hand, some trends such as US size appliances especially in cold appliances and the ownership of more than one refrigerator [49] per household need to be taken into account for sustainable standards; a three member family owning three refrigerators which are permanently on might be prohibitive in a world of rising commodity prices and resource scarcity [22]. The adoption of lower ownership levels for cold appliances will need to go hand in with more frequent shopping which in this case will result in an important lifestyle change.

9. CONCLUSIONS

In this paper possible energy reductions have been quantified and categorised to identify CO_2 savings from expected interventions in household energy consumption towards 2050. This approach needs to be located in the broader picture of future scenarios which predict CO_2 savings from the domestic sector, not just from changes in energy demand but also from changes in energy production and distribution. New technologies, greener lifestyles, best building thermal behaviour and better household controls will be indispensable parts of the savings, but the impact of lower carbon emissions from energy production is a great percentage of the expected reduction. Renewable energy production is targeted to increase in future scenarios depending on economic and technological development. This will result in lower carbon intensive electricity, fuel shift for space heating and hot water, and the implementation of smart grids which will give price signals to adapt appliance time of use to energy availability. Further analysis will look at carbon reduction opportunities based on low carbon technologies and resources. These are described in future scenarios such as the electrification of the heating, the implementation of heat pumps, natural gas networks, and renewable sources making up 15% of the energy production. Other measures considered in the de-carbonisation of the housing stock are the increase of micro generation and local energy production.

The outcomes from this analysis are relative to two days of data, further work is needed in order to confirm conclusions and complete the picture given here. Since both days of study are two winter days, savings from space heating and ventilation loses are magnified, therefore annual savings are expected to be lower. Thus, the application of this model to longer monitoring periods and to a greater number of households will amplify the results, which will make it possible to study hot water usage patterns, showering, cooking and ICE use in more depth.

10. NOMENCLATURE

Q_g	Gas flow rate	MJ
Q_e	Electric flow rate	MJ
Q_p	Personal heat rate	MJ
Q_w	Hot water flow rate	MJ
Q_f	Fabric heat loss	MJ
Q_v	Ventilation heat loss	MJ
Cv_g	Gas Calorific Value	$\mathrm{MJm^{-3}}$
V_g	Gas volume	$\mathrm{m^3}$
m_w	Water mass	kg
Cp_w	specific heat capacity	$\mathrm{Jkg^{-1}K^{-1}}$
n_h	efficiency	–

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