DETERMINING HEAT USE IN RESIDENTIAL BUILDINGS USING HIGH RESOLUTION GAS AND DOMESTIC HOT WATER MONITORING

R. A. Buswell[1], D. Marini[1], L. H. Webb[1] and M. Thomson[2]
[1]Building Energy Research Group, Loughborough University, UK
[2]Centre for Renewable Energy Technology, Loughborough University, UK

ABSTRACT

Residential buildings consume about a third of the UKs total energy and the need to reduce this as part of achieving the 2050 CO_2 emissions targets driving the interest the modelling and performance simulation of homes. While simulation and modelling tools are in wide spread use, the detailed empirical data with which to understand the effect of systems and operational complexities of households on the consumption of energy is less developed than it is for commercial buildings. This paper reports some early results from a whole house monitoring trial in the UK where high resolution measurements of gas, hot water and power are being used to disaggregate heat use. The study has shown that: equipment used for domestic heat generation varies considerably between households; gas demand is highly variable at the sub-hourly level, far greater than some of the available hourly monitored data would suggest; and that the current information on hot water consumption characteristics is poor and so some new, more comprehensive data is presented.

INTRODUCTION

Space heating and hot water consumption contribute 27% of the CO_2 emissions in the UK (Rajat and Matthew, 2012) and hence a reduction in these levels can make a significant impact on the 2050 energy targets set by the UK government (Natarajana et al., 2011; Environmental Change Institute (ECI), 2007). These targets are driving the development of methods to reduce energy consumption in a number of ways: new build homes are to have increased performance being designed to be closer to zero-carbon operation (Energy Performance of Buildings Directive (EPBD), 2010; Igor et al., 2012); existing buildings will have retrofit insulation (Milorad et al., 2012; Gucyetera and Gunaydinb, 2012) and better heating system controls (Fernandez Seara et al., 2012).

The need for better, higher resolution data to help the modelling and design of domestic energy systems and energy supply has been recognised (Swan and Ugursal, 2009; Widen et al., 2009) and with the development of 'smarter' urban districts as 2020 approaches and beyond, the need to understand existing energy demand to model energy networks will increase (Chaudry et al., 2012; Pillai et al., 2011; Gyamfi and Krumdieck, 2012).

The exploration of domestic heat generation and use is developing rapidly and there have already been a number of studies carried out to date including: annual data based on suppliers data (Baker, K.J and Rylatt, R.M, 2008); monthly data based on utility bills (Majcen et al., 2013); weekly (Westergren et al., 1999), daily (Hamilton et al., 2011) half-hourly (Wright and Brown, 2008; Ferreira, 2009) data; and some that monitored gas consumption at shorter intervals (Stoecklein et al., 2001) and (Branco et al., 2004). Some current UK trials by energy providers are measuring gas flow rate at short intervals (EON, 2012) and Smart meters are being rolled out in the UK, but the data from these is currently limited to a resolution of 30 minutes (DECC, 2010, 2010).

Gas and hot water consumption data is important for validating simulations and detailed data is currently lacking. What hampers the analysis in domestic properties is that heat generation is enabled through a variety of devices, and these vary from home to home. Modelling the existing building stock is therefore difficult as the mix of gas and electric appliances affects the calculated CO_2 in particular.

Hot water consumption is a key input variable that affects the design of low-carbon homes because of its impact on thermal storage, however often we have to rely on simplifications in analysis as these two examples illustrate:

Cockroft et al. (2007) created a model of a hot water storage cylinder with thermostat switching on at 50℃, and off at 60℃. The combi-boiler model assumed a draw-off temperature of 50℃. The draw-off rates were taken to be the Standard European Pattern, comprising 10 draw-offs totalling 122 l/day with average duration 6s and flow rate 0.00855 l/s for 7 draw-offs.

Steijger et al. (2013) assumed that hot water was stored above 60 ℃ and has a temperature of 40 ℃ at the draw-off points. The authors assumed 80l/person/day hot water consumption based on UK BREDEM standard (Anderson, 2001).

This paper presents empirical data from a detailed whole house monitoring study in the UK. Gas and hot water consumption are measured and combined with electrical power and other data so that heat consumption can be attributed to space heating, hot water, cooking and ancillary (i.e. the energy overhead is providing the service). The study reported on here considers 20 homes and detailed gas heat consumption characteristics are presented for two of these with different space heating and hot water systems.

HOMES STUDIED

In this study, 20 homes are being monitored in significant detail. All participating homes are within a 4 mile radius of a market town in the East Midlands of the UK. The homes are typical of their respective years of construction (1900 to 2002) and of those found throughout the UK. All homes are occupied by families that range in number an age, from 3 persons to 6 persons and range from parents with babies to adult children and relatives living together. Most have had some retrofitting of insulation and been living there for more than 4 years, nearly half for more than 10 years.

Two homes are highlighted in this paper, H30 and H41. H30 is a detached home, approximately 100m^2, over two storeys with cavity wall construction built between 1950 and 1965 and an extension built later in the 1970's built with cavity wall. There is some loft insulation and the cavity wall is not insulated. The property is fully double glazed pre 1998. The heating system was refurbished in May 2011, the old tanked hot water system was replaced in 2001 with a combi boiler and this was replaced in 2011 with a 35kW condensing combi-boiler that provides heating and instantaneous hot water. The system distribution pipework was retained and the downstairs radiators have been replaced, but the majority are older than the boiler. The family comprises of Mother and child aged 11.

H41 is a semi-detached home, approximately 100m^2, built over two storeys with cavity wall construction between 1966-1974, including an extension built later in 2000, in addition the house has a conservatory which is heated by the central system. The loft has over 250mm of insulation and the cavity walls are insulated. The property is fully double glazed. The heating system comprises of a tanked hot water storage, radiators and boiler installed in 1993. The 15kW boiler is 20 years old and has simple thermostat controlled on/off operation, with ignition through pilot light. The family comprises of Mother Father 2 children over 18 and 2 children aged 16 and 11.

MONITORING APPROACH

The electrical systems are monitored using a wireless proprietary system that connects CT devices and plug monitors to a central hub which transmits that data from the homes to a centralised database at a sample rate of 1 minute. The power measurements were used to measure energy consumption by electric showers, hobs and ovens. Room temperatures are also monitored with this system at a sample rate of 2 minutes and these were used in this study to determine the internal air temperatures to compare the loads on the boilers. Temperatures on the flow pipe serving the heating systems were also measured to determine when the heating systems were on.

Figure 1: A typical rotating dial on an older UK gas meter.

The hot water flow rate was measured at a sample rate of 1 second to capture the characteristics of the water draw-off volumes and durations. A turbine meter placed on the cold water feed to the boiler, in the case of a combination system, and in the cold water feed to the tank, for tanked storage systems. The surface temperatures of the copper pipes at these inlets and outlets points were used to indicate the water temperature and hence to estimate the heat used by,

$$\dot{Q}_w = \dot{V}_w \rho_w C_w \left(\theta_{w_{in}} - \theta_{w_{out}}\right), \qquad (1)$$

where $\dot{Q}_w$ is the heat supplied to hot water at the point of generation or as it leaves the storage container (kW), $\dot{V}_w$ is the volumetric flow rate of hot water (m^{3}s^{-1}), ρ_w is the density of hot water C_w is the specific heat capacity of hot water (kJkg^{-1}K^{-1}) and $\theta_{w_{in}}$ and $\theta_{w_{out}}$ are the inlet and outlet temperatures respectively (℃).

The energy supplied to the buildings by gas was estimated taking the calorific value of gas to be 39.5 MJm^{-3} and measuring the volumetric flow rate at a sample rate of 1 second. Figure 1 depicts a typical dial found on older gas meters in the UK that measures volume in fractions of a ft^3 . A novel approach was developed to capture images of these dials every second and then interpret the needle position from the image, then convert the dial rotation into an angular displacement over time. The equivalent volumetric flow rate of gas ($\dot{V}_g$) in ft^{3}s^{-1} can then be inferred and then converted to m^{3}s^{-1}.

Determining heat generation and use

The heat generation equipment was surveyed in the 20 homes and the results presented in Table 1, some data was indeterminable and has been noted with '-' . The table gives the approximate installation, or refurbishment date of the central heating system, the capacity of the boiler, and whether the HWS is supplied from combi-boiler or via a hot water cylinder. The shower

Table 1: The heat generation systems in the 20 surveyed homes.

House	Age (yr)	Boiler (kW)	HWS	Shower type	Cap. (kW)	Hob	Oven
H01	13	14.5	Tank	1 Electric	9.5	Electric	Electric
H05	4	29	Combi	1 HWS	29	Electric	Electric
H08	13	-	Tank	2 Electric	7.5, 10.8	Electric	Electric
H09	13	28	Combi	1 Electric,1 HWS	9,28	Gas	Electric
H10	4	28	Combi	2 HWS	28	Gas	Gas
H11	18	24	Combi	1 Electric	9, 9.8	Gas	Electric
H18	4	28	Combi	2 HWS	28	Gas	Gas
H23	13	-	Tank	1 Electric	8.5	Gas	Electric
H28	13	9	Tank	1 Electric	9, 9.8	Gas	Gas
H30	2	35	Combi	1 HWS	35	Gas	Electric
H33	4	28	Combi	1 Electric,1 HWS	9.5, 28	Gas	Electric
H37	4	37	Combi	1 Electric,1 HWS	9.5, 37	Gas	Electric
H38	4	24-39	Combi	1 HWS	39	Gas	Electric
H39	9	30	Combi	1 Electric	8.9, 9.5	Gas	Gas
H40	13	24	Tank	2 HWS	-	Gas	Electric
H41	20	15	Tank	2 Electric	9.5, 10.8	Gas	Gas
H42	4	28	Combi	2 HWS	28	Gas	Electric
H43	9	-	Combi	1 Electric,1 HWS	9.5, -	Gas	Electric
H45	4	35	Combi	2 Electric	8./5, 9.5	Gas	Electric
H46	4	-	Combi	1 HWS	-	Gas	Electric

types and capacities are noted, where the capacity of a combi-boiler supplied shower will be the maximum boiler output; and the hob/oven types are also noted.

What is most striking is the variation in systems, all these homes are very similar in size with gas fired central heating, but the variety of cooking, shower and hot water combinations is significant. Attributing heat use to the four categories, space heating, hot water production, cooking and ancillary, therefore, needs to be carried out for each house individually because the combinations of devices are different. Two examples are given here for the two homes H30 and H41.

H30 has a combi boiler, serving taps and the shower and a gas oven and electric hob. The electrical power can be measured and so the challenge here is to separate the energy supplied by the gas for space heating, hot water production and oven use. A staged approach was used:

- determine when there was water flow and remove the gas flow in this period, attributing this to the production of hot water;
- using the flow temperatures and room air temperatures, determine when the heating is on[1] and then attribute the gas flow to the space heating;
- if the cooking related gas flow can be identified, this can be attributed also; and so
- this leaves the ancillary gas consumption.

H41 has gas space heating, tank storage of hot water heated by gas, electric showers, and gas oven and hob. Because the boiler is an older unit with a single flow rate, the oven and hob use and be identified since the flow rates are different. The challenge here is to estimate the heat lost through storage of hot water so that the energy used for space heating can be more precisely estimated.

[1]Where the boiler controls can be monitored this is trivial, however this needed to be inferred from other measurements in these homes.

For tanked systems there can be significant losses from the tank as it cools, from the surface of the cylinder (usually insulated) and the connected pipework (often uninsulated). Since it was not possible to measure the heat into the cylinder, the ancillary consumption associated with the losses from the tank is estimated using data from testing carried out by Simpson and Castles (1992). There experimental results can be arranged to give the following relationship,

$$Q_l = 2.748\Delta\theta, \qquad (2)$$

where, Q_l are the standing losses for a 120litre cylinder (W) and $\Delta\theta$ is the temperature difference between the ambient air and the hot water, (K). For a copper cylinder insulated with 17.4mm of polyurethane foam insulation, with the water kept close to 55°C in an ambient air temperature of 20°C (as it is in H41) gives $Q_l = 97.3W$. Q_l is considered here as ancillary consumption, the losses are inevitable in order to provide hot water in the right quantity at time to overcome the intermittent nature of hot water demand.

RESULTS

Hot water use

The hot water flow rate and temperatures where sampled every second so that the precise time and duration of the water usage could be characterised. In H30, the turbine flow meter was inserted in the cold water feed into the boiler and temperature measurements made on the water inlet and hot water outlet pipe and were cited close to the boiler. This measures the heat used to raise the temperature of the water delivered by the boilers and does not account for the practical working temperature (i.e. that at the draw-off). On the tanked system in H41, the sensors were cited to measure the heat out of the cylinder, and hence does not account for the heat input and storage losses. Figure 2 depicts the flow rates and temperatures as measured for both

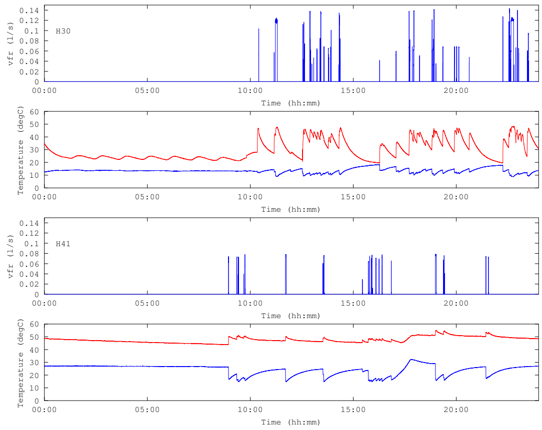

Figure 2: Hot water volumetric flow rates and temperatures.

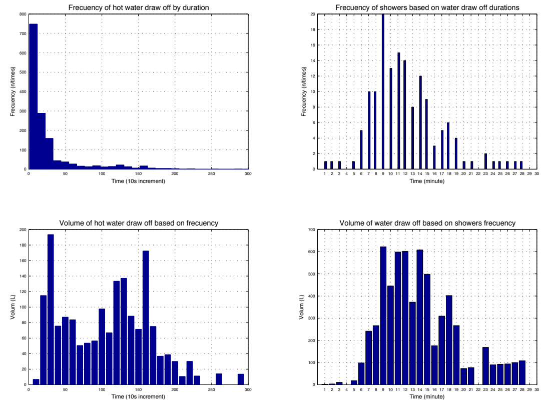

Figure 3: Hot water draw-off duration frequency and volume consumed for H41.

homes: the upper two plots show H30 and the lower two H41 and for each plot pair, the upper plot gives the flow rate and the lower gives the water outlet (upper in red) and inlet (lower in blue) temperatures.

H30 appears to have greater hot water activity, although it should be noted that the shower is connected to the boiler. In H41, there are two electric showers which are not measured with the flow meter. The volume of water consumed by using the electric showers has been estimated by assuming a water temperature rise of 35K and the using the measured power consumption, measured by CT devices in the distribution board.

The inlet temperature of the H30 combi-boiler is lower that H41 since this is mains fed, and in persistent draw offs, this can been seen to dip to about 9℃. In H41 the water is fed from a tank above the cylinder and hence will be closer to room temperature. The flow temperature of the Combi system trends to the ambient temperature when under free cooling and hence larger rises from this to the supply temperature of about 45℃ can be seen. The tanked system is maintained between 50℃ - 60℃.

Note that the hot water for showers is provided by electric shower units and hence Figure 5 shows only gas consumption for cooking and space heating for H41. The regular spikes of gas flow in H30 is the 'ECO' setting which maintains the temperature of the water stored in the boiler. The time between gas flow is related to the time constant associated with the heat loss from the surface of the boiler casing and connected pipe work. It can be seen in Figure 2 that between 00:00 and 10:00 the flow temperature rises and falls in relation to this intermittent gas burning. The sensors are attached to the surface of copper pipes close to the boiler an hence as the boiler warms, this heat travels down the pipework and is picked up by the sensor. Finally the middle left plot of Figure 6 shows the high resolution water flow data as someone is showering.

Figure 3 gives the the hot water consumption for showering in the right hand plots and the water used for domestic, hygiene purposes on the left for H41. Figure 4 gives the draw-off duration frequency and volume for the total hot water consumption in H30. Both figures have been generated from data spanning one month (January, 2013) and what can be clearly seen is the high number of very short draw offs. In fact 28.6% of the hot water volume occurs at draw-off duration of less than 1 minute in H30 and 21.4% in H41.

Table 2 represents hourly hot water use for a typical day (6th January) and for one month (January) averaged day flow. H30 (two people) can consume 199 l/day of hot water (170 l/day on average). In H41 the hot water consumption for typical day (6th January) is 59 l/day, not including hot water for showering. An average day included showering, yields a hot water consumption of 224 l/day; and so 73% of hot water consumed was for showering.

The volumes and fractions of hot water consumption represented here at this table at hourly intervals, and can be used to model hot water consumption in residential buildings. In Table 2 'Frac' refers to the fraction of the volume of hot water draw off in that house, relative to the maximum draw off in any hour. Water flow is the water flow at particular hour to maximum flow (often defined as design flow rate) occurred during 24 hours: so to model hot water consumption, for a given (or assumed) maximum flow rate, we can define the hot water consumed for each hour (or total) as based on hourly fractions.

Variability in gas demand

Figure 5 depicts the gas volume flow rates (top and middle plots) and cumulative gas flow volume (bottom plot) for both properties, for a typical day (00:00:00 to 23:59:59). Although both homes use similar volumes of gas, the pattern of consumption varies significantly. What can be seen in the top plot is the series of flow rates at regular intervals previously discussed that have been attributed to the boiler's internal control settings maintaining the water volume at operating temperature. The gap between these is related to the time con-

Table 2: The hot water use based on typical and averaged day of month.

	One Days Flow (6th January 2013)						One months (January) Averaged Day Flow			
	H30			H41			H30		H41	
Time (hr)	Vol (l)	Draw-off (s)	Frac (-)	Vol (l)	Draw-off (s)	Frac (-)	Vol (l)	Frac (-)	Vol(l)	Frac (-)
1	0	0	0	0	0	0	3.20	0.1	0	0
2	0	0	0	0	0	0	0.53	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1.71	0.1	23.82	0.9
8	0	0	0	0	0	0	8.04	0.3	13.62	0.5
9	0	0	0	1.43	29	0.11	5.80	0.2	9.67	0.4
10	0	0	0	6.58	159	0.52	7.67	0.3	24.67	0.8
11	1.45	17	0.02	0	1	0	5.55	0.2	13.45	0.5
12	42.14	362	0.63	10.42	143	0.83	5.05	0.4	21.77	0.8
13	16.4	213	0.25	0	0	0	11.68	0.5	9.11	0.3
14	14.63	181	0.22	7.14	118	0.57	4.66	0.2	10.81	0.4
15	7.40	84	0.11	0	0	0	5.61	0.2	9.98	0.4
16	0	0	0	7.89	167	0.63	7.83	0.3	3.44	0.1
17	0.11	3	0	8	149	0.64	3.45	0.1	3.72	0.1
18	11	161	0.16	0	0	0	4.99	0.2	6.40	0.2
19	11.60	145	0.17	3.76	52	0.30	5.09	0.2	8.72	0.3
20	7.68	133	0.11	12.57	199	1	24.85	1	26.53	1
21	8.23	161	0.12	0	0	0	15.87	0.6	25.20	0.9
22	0	0	0	2.10	46	0.17	17.18	0.7	7.18	0.3
23	66.90	597	1	0	0	0	14.23	0.6	2.76	0.1
24	11.20	171	0.17	0	0	0	10.72	0.4	1.89	0.1
Total	**198.7**	**2228**	**-**	**58.90**	**1063**	**-**	**169.10**	**-**	**223.8**	**-**

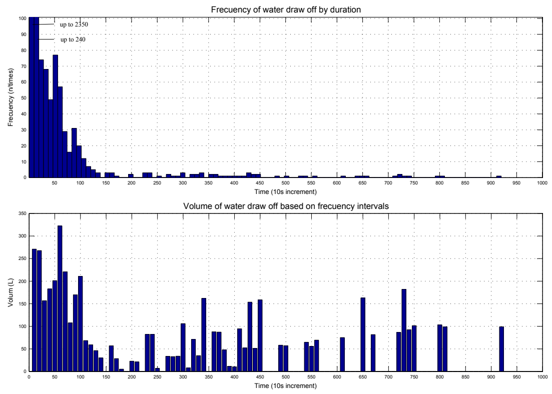

Figure 4: Hot water draw-off duration frequency and volume consumed for H30.

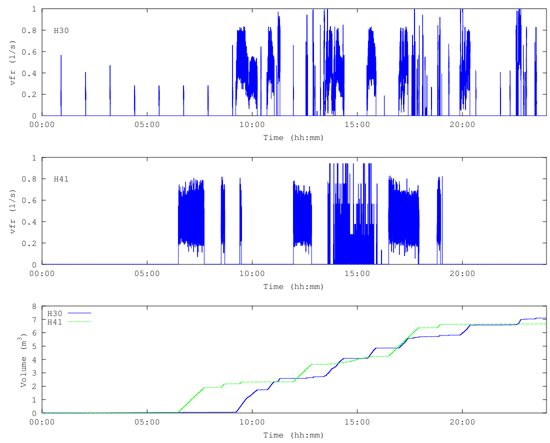

Figure 5: Gas flow characteristics.

stant offered by the rate of heat lost to the surrounding space. The top plot also demonstrates the constant gas firing through the day due to calls for space heating and hot water supply.

The middle plot of Figure 5 shows the boiler in H41 which is an old unit; the gas flow due to the pilot light is only $\approx 0.002 \mathrm{ls}^{-1}$, and so cannot be seen on this scale. The key difference between modern boiler in H30 is that there is a constant gas flow rate and that the main burner is either on, or off. The top two plots in Figure 6 depict the characteristics of these two boilers in more detail. The plot on the left shows the modern boiler in H30 and it can be seen to modulate gas flow, when there is a call for heat the boiler runs at maximum output, which ramps down after a period of time. The unit can modulate its heat input from 6.1kW to 30kW in heating mode (it draws 35kWwhile calling for hot water). The older boiler in H41, depicted in the top right plot is either on or off and hence base one gas flow rate and can draw a maximum of 19.1kW. The flow rates measured approximate quite well to the input specifications of both boilers: the calorific value of natural gas, mains pressure available and commissioning of the gas valves at the meter and in the unit are all unknown variables and will contribute to the observed differences.

In the middle plot of of Figure 5 (H41) at 15:00, the gas flow is not supplying the boiler, the kitchen is equipped with a gas oven and hob. The data was recorded on 6/1/13, which is a Sunday and this is lunch/dinner preparation. The flow rates are shown in more detail in the bottom righthand plot of Figure 6. It is easier to determine the use of gas for cooking in a home with a boiler of this kind since the flow rates are

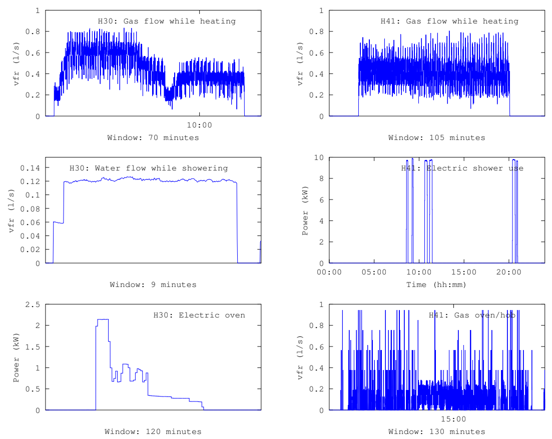

Figure 6: Heat appliance and how water production characteristics.

easily determinable. H30 has a gas hob and an electric oven. The power consumed by the oven is measured by a CT device in the distribution board, and a close up view of the data is given in the bottom left plot of Figure 6. The middle plots of Figure 6 show detailed characteristics of the hot water draw-off during showering in H30 on the left, and the power consumption of the showers for H41 on the right.

This level of detail allows the hot water production efficiency of the combi-boiler in H30 to be measured directly since the gas volumetric flow rate is measured, the heat input can be estimated assuming a calorific value of gas to be 39.5MJm^{-3} . The hot water output from the boiler can be estimated using Equation 1. At a time when the heating is not on, the efficiency was estimated to be 68%, some 15% less than the technical specification suggests.

Attributing in heat use and CO_2 production

Figure 7 depicts the cumulative heat use in four categories; provision of space heating (sh), hot water production (hw), cooking (ck) and ancillary consumption (an). Both homes show similar trends although the heating in H41 comes on earlier than in H30. Separating out the uses of gas in H30 is challenging and hence its likely that gas use at the hob for cooking is likely to be slightly under predicted and the ancillary consumption is probably over estimated as a consequence. The ancillary consumption in H41 is very low, in fact only the pilot light contributes to this in this analysis. However, in reality the system on both homes have hot water storage and both loose heat from here into the surrounding space. The capacity of these is different, in H30 the storage is in the combi-boiler and is about 2litres, in H41 it is a 120litre copper cylinder. If the heat lost from the cylinder was correctly attributed in H41 then the gas consumption for the space heating would be reduced and the ancillary consumption would increase. Table 3 gives details of the overall heat consumption per household, and the proportions attributed by category.

Table 3: Heat consumption and CO_2 production.

Heat Use	H30 (En.)	H30 (CO_2)	H41 (En.)	H41 (CO_2)
Total	275MJ	14.5kg	293MJ	19.2 kg
Heating	74%	71%	72%	56%
HWS	17%	16%	18%	36%
Cooking	7%	10%	7%	6%
Ancillary	3%	3%	3%	2%

The relationship between the waste and useful heat is complicated by operating conditions. Modern comi-boilers often have some 'ECO' function which maintains the temperature of the water stored in the boiler ($\approx$ 2 litres in H30), hence a gas draw at regular intervals is noticeable through the night when the unit is not in use. This gas load contributes to the 'ancillary consumption', i.e. represents the heat not directly used in completing some task in the home and may be regard as waste heat. In addition, part of this heat load will be lost to the space (effectively contributing to space heating) through the hot water cooling in the pipe between the boiler and the the draw-off point.

CONCLUSIONS

The measurement of energy consumption in buildings is becoming more cost effective and more wide spread. The information gathered from these systems is vital to underpin modelling and simulate work, both for validating simulation output and for developing better models and simulation inputs so that performance prediction is improved. Presented in this paper were some early results from a detailed monitoring scheme implemented in family homes in the UK. The high-resolution monitoring of gas and hot water consumption, combined with electrical power measurements allows a close examination of the use of heat in the home. The following findings are highlighted:

Variability in heat generation systems: although all homes use heat for hygiene, cooking and space heating, however, even within the limited sample of homes studied here there were a high number of unique combinations of hot water production, storage and use, showering system (types and numbers) oven and hob fuel type, sizes and combinations and heating system controls and preferences. This variability may hamper the estimation of good predictions from modelling larger scale systems, particularly for refurbishment of existing building stock, or for designing district heating schemes.

Hot water draw off characteristics: Currently the implementation of the inputs for hot water draw off in simulation tools are poor. Table 2 gives the hourly hot water draw-off characteristics for two family homes. In addition, at least 20% of all hot water is consumed through very short draw-offs, which have implications for waste heat as the wa-

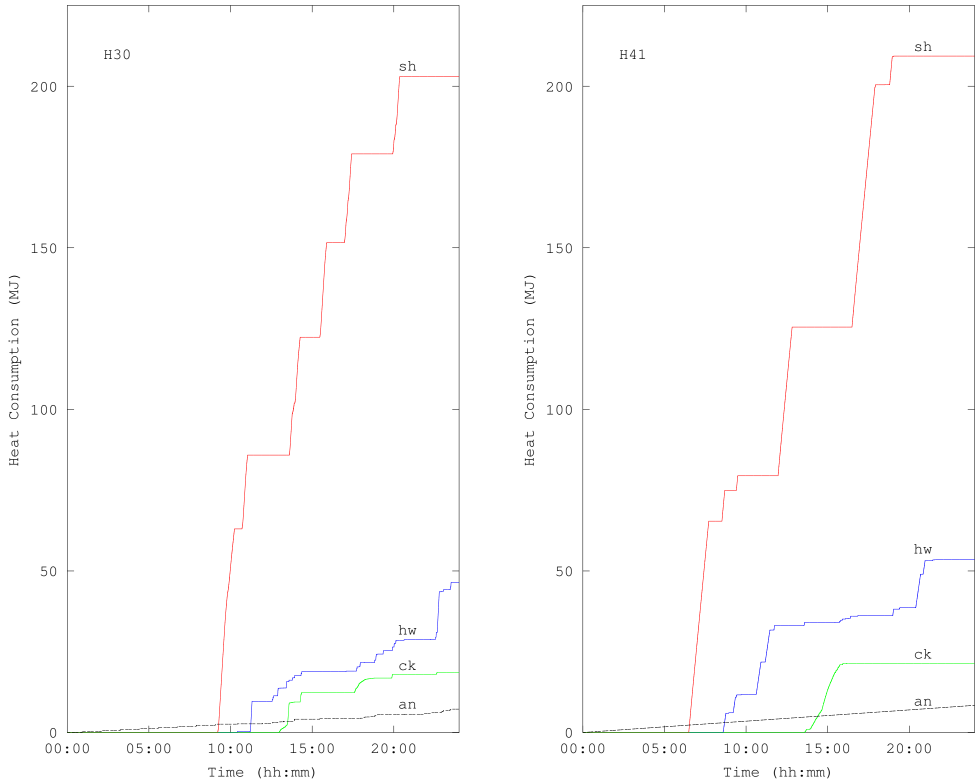

Figure 7: Total heat production and use.

ter will cool in the pipe work that transports the water from the boiler to the tap. Average showering times vary significantly, but have a mean of ≈12minutes in H41.

Sub hourly variability in heat demand: implications for electrification of space heating, also when evaluating a change in energy supply, you need to account for how heat is generated, which is complex and homes have many variations and consumption rates, which may hamper modelling and simulation of larger scale heating schemes.

Installed efficiencies of heat generation equipment: the observed boiler operational efficiency from our test home appear to be lower than manufacturers specify in practice which is significant if this is representative of installations in general. Additionally, comparing an older boiler and tank system with a newer combi-boiler is evident that the ancillary heat load for both is similar in the homes studied and hence the assumption that the 'parasitic' loads are less in more advanced boiler systems might not be correct.

ACKNOWLEDGEMENT

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 TEDDI call managed by the RCUK Digital Economy and Energy programmes (EPSRC Grant Number EP/I000267/1).

REFERENCES

Anderson, B. 2001. *BREDEM-8 model desciption*. Technical report, Building Research Estabilishment BRE.

Baker, K.J and Rylatt, R.M 2008. Improving the prediction of uk domestic energy-demand using annual consumption-data. *Applied Energy*, 85:475–482.

Branco, B., Lachal, B., Gallinelli, P., and Weber, W. 2004. Predicted versus observed heat consumption of a low energy multifamily complex in switzerland based on long-term experimental data. *Energy and Buildings*, 36:543–555.

Chaudry, M., Skea, J., Wang, X., and Jenkins, N. 2012. Modelling UK energy system response to natural gas supply infrastructure failures. *Journal of Power and Energy*, 226(4):501–513.

Cockroft, J., Samuel, A., and Tuohy, P. 2007. Development of a methodology for the evaluation of domestic heating controls. Technical report, University of Strathclyde.

DECC, 2010 2010. GB-wide smart meter roll out for the domestic sector. Technical report, Department of Energy and Climate Change (DECC).

Energy Performance of Buildings Directive (EPBD) 2010. Directive 2010/31/eu of the european parliament and of the council of 19 may 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*.

Environmental Change Institute (ECI) 2007. Home truths: A low carbon strategy to reduce uk housing emission by 80 % by 2050. Research Report 34, Environmental Change Institute.

EON 2012. Thinking Energy - Innovative smart homes tested in Milton Keynes. http://pressreleases.eon-uk.com / blogs / eonukpressreleases / archive / 2012 / 09 / 19 / 1861.aspx. Accesed 28th January 2013.

Fernandez Seara, J., Uhia, F., Pardinas, A., and Bastos, S. 2012. Experimental analysis of an on demand external domestic hot water production system using four control strategies. *Applied Energy*, 103:85–96.

Ferreira, V. 2009. *The analysis of primary metered half-hourly electricity and gas consumption in municipal buildings*. PhD thesis, Institute of Energy and Sustainable Development.

Gucyetera, B. and Gunaydinb, H. 2012. Optimization of an envelope retrofit strategy for an existing office building. *Energy and Buildings*, 55:647–659.

Gyamfi, S. and Krumdieck, S. 2012. Scenario analysis of residential demand response at network peak periods. *Electric Power Systems Research*, 93:32–38.

Hamilton, I., Steadman, P., Lowe, R., Summerfield, A., and Bruhns, H. 2011. Buildings and Energy Data Frameworks - Final Report. Technical report, Uiversity College London (UCL) Energy Institute.

Igor, S., Assunta, N., and Karsten, V. 2012. Net zero energy buildings: A consistent defnition framework. *Energy and Buildings*, 48:220–232.

Majcen, D., Itard, L., and Visscher, H. 2013. Theoretical vs. actual energy consumption of labelled dwellings in the netherlands: Discrepancies and policy implications. *Energy Policy*. http://dx.doi.org/10.1016/j.enpol.2012.11.008.

Milorad, B., Slobodan, D., Andreja, S., Marko, M., and Dragan, C. 2012. Decreasing energy consumption in thermally non-insulated old house via refurbishment. *Energy and Buildings*, 54:503–510.

Natarajana, S., Padgetb, J., and Elliott, L. 2011. Modelling uk domestic energy and carbon emissions: an agent-based approach. *Energy and Buildings*, 43:2602–2612.

Pillai, J., Heussen, K., and stergaard, P. 2011. Comparative analysis of hourly and dynamic power balancing models for validating future energy scenarios. *Energy*, 36:3233–3243.

Rajat, G. and Matthew, G. 2012. Using uk climate change projections to adapt existing english homes for a warming climate. *Building and Environment*, 55:20–42.

Simpson, A. and Castles, G. 1992. Measurements of heat losses from an insulated hot water cylinder. *Building Services Engineering Research and Technology*, 13:43–47.

Steijger, L, A., Buswell, R, A., Smedley, V., Firth, S, K., and Rowley, P. 2013. Establishing the zero-carbon performance of compact urban dwellings. *Journal of Building Performance Simulation*. DOI:10.1080/19401493.2012.724086.

Stoecklein, A., Pollard, A., Camilleri, M., Amitrano, L., Isaacs, N., Pool, F., and Clark, S. 2001. Energy Use in New Zealand Households, Report on the Year 5 Analysis for the Household Energy End-use Project (HEEP). Technical report, -, Judgeford. June 2001.

Swan, L. and Ugursal, V. 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renewable and Sustainable Energy Reviews*, 13:1819–1835.

Westergren, K., Hogberg, H., and Norlen, U. 1999. Monitoring energy consumption in single-family houses. *Energy and Buildings*, 29:247–257.

Widen, J., Lundh, M., Vassileva, I., and Dahlquist, E. 2009. Constructing load profiles for household electricity and hot water from time-use data-modelling approach and validation. *Energy and Buildings*, 41:753–768.

Wright, A. and Brown, N. 2008. The Analysis and Interpretation of Half Hourly Utility Data in UK. Improving Energy Efficiency in Commercial Buildings Conference (IEECBC) Building Performance Congress: Frankfurt, April 2008.