Further Analysis of the Household Electricity Survey

Energy use at home: models, labels and unusual appliances

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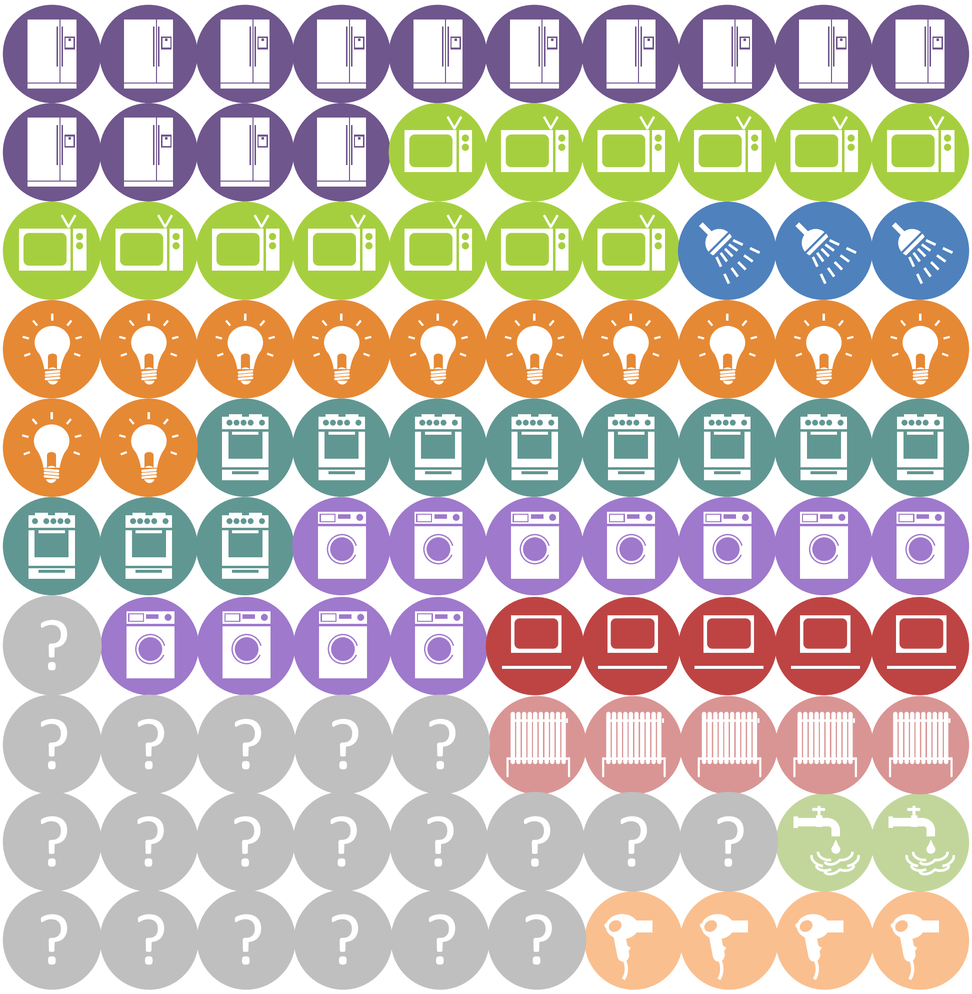
Average electricity breakdown over year



Cold Appliances
13.8% (566 kWh)

Audio/Visual
13.1% (537 kWh)

Showers
2.7% (112 kWh)

Lighting
11.8% (483 kWh)

Cooking
10.9% (448 kWh)

Washing Appliances
10.7% (437 kWh)

ICT
5.1% (207 kWh)

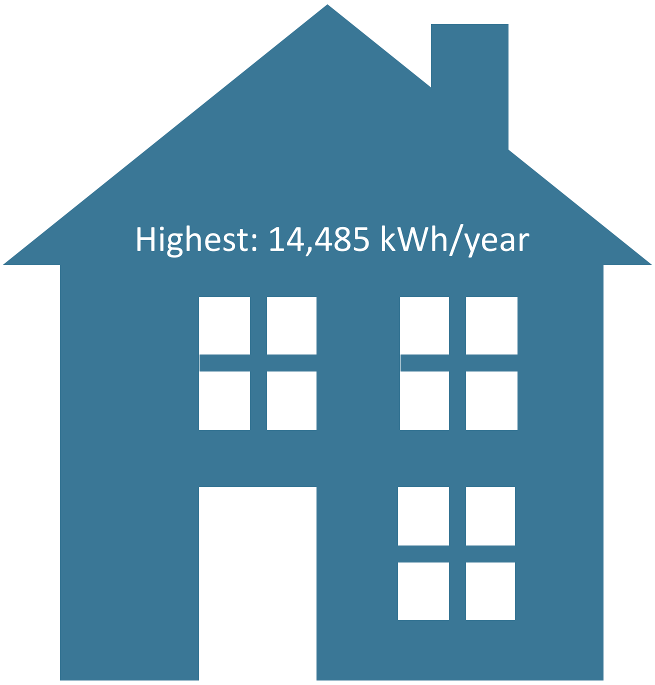
Space Heating
5.5% (227 kWh)

Water Heating
2.1% (85 kWh)

Other
4.2% (173 kWh)

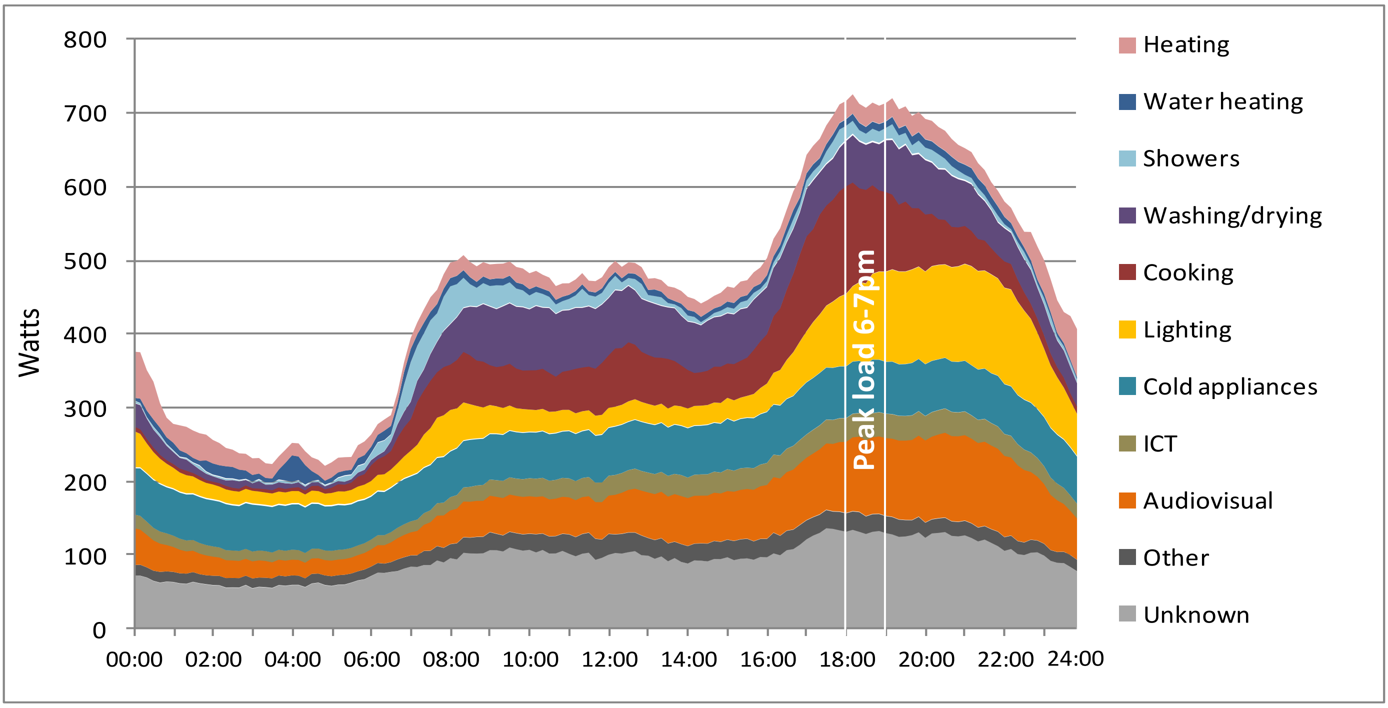
Unknown
20.0% (819 kWh)

Highest and lowest users



Lowest:
562 kWh/year

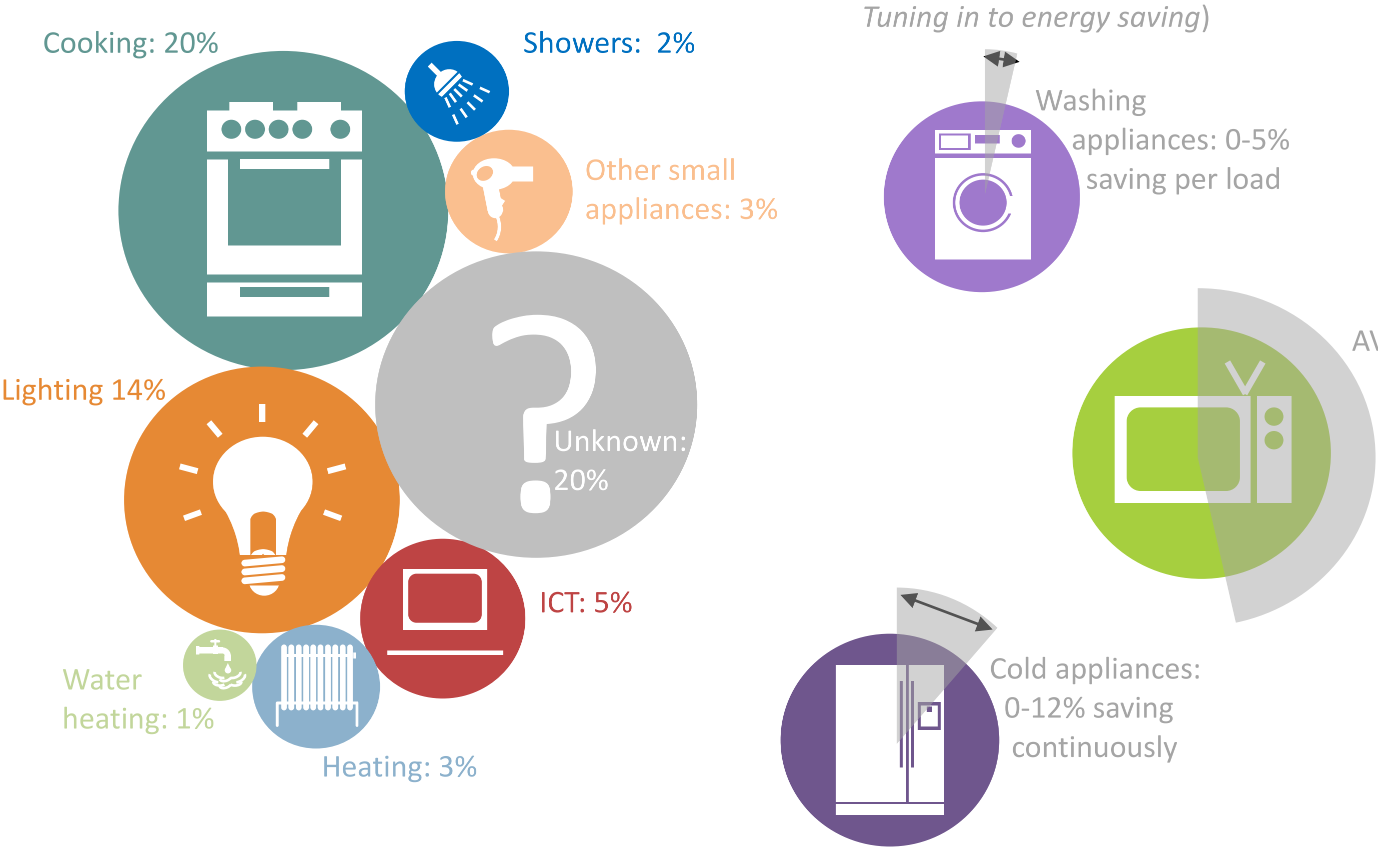
Average 24-hour profile for 250 homes, whole year



Average peak load breakdown

(Area shows proportion)

Savings from smaller appliances
(Slices show proportions, see *Tuning in to energy saving*)



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Executive Summary

Overview

The Household Electricity Survey monitored a total of 250 owner-occupier households across England from 2010 to 2011. It was the most detailed survey of electricity use in English homes ever undertaken. This is the third research report written by Cambridge Architectural Research, Loughborough University and Element Energy presenting further analysis of the Household Electricity Survey (HES)[1].

This report presents our findings comparing actual energy use against modelled and energy label estimates of energy use. It also includes a comparison of the HES homes against National Statistics and another related survey, and looks in detail at unusual appliances, air conditioning and secondary heating. The material builds on the findings of our first two reports, responding to the next set of questions drawn up by DECC and DEFRA. The report covers the following six topics:

1. Comparing actual and modelled electricity and gas use
2. ‘Unusual’ appliances and manufacturers’ data
3. What do HES households tell us about air conditioning?
4. Actual electricity use of major appliances
5. Comparing HES against Energy Consumption in the UK and the Energy Follow-Up Survey
6. Homing in on secondary heating

The methods of analysis were different for each topic, but to give an overview we selected pertinent data from the large HES database. Where necessary, we cleaned the data and put it into a form that could be interrogated using the statistical programming language R and/or Excel. We created tables and graphs so readers can see data for themselves, and where appropriate we carried out statistical tests to look for significant relationships in the data. We also did literature-based work to identify published research connected to each question, summarised in blue boxes in each section.

[1] The first report, *Early Findings*, covers questions related to demand side management. The second report, *Electrical appliances at home: tuning in to energy saving*, covers appliances ownership and use. Both reports are available here: https://www.gov.uk/government/publications/early-findings-demand-side-management

Comparing actual and modelled electricity and gas use

■ We found that the Cambridge Housing Model (used in DECC statistics and policy questions) over-estimates gas use for the HES homes on average, by 20%. Conversely, the Model under-estimates electricity use, but by a much smaller margin: less than 5%.

■ The Cambridge Housing Model estimates that cooking uses about a third less electricity on average than was measured in these homes, while it estimates that appliances and lighting use more electricity than was measured.

■ The actual energy use records show greater variability in electricity use between homes than for gas use – which makes it harder to model effectively. The variability is particularly acute for cooking.

'Unusual' appliances and manufacturer's data

■ Unusual appliances like massage beds, aquariums, pond pumps and dehumidifiers turned out to use considerable energy. However, they are usually advertised and sold without stating typical energy consumption over the year. Instead, they only include rated maximum power. This makes it very hard for purchasers to estimate how much they will cost to run.

■ Only a minority of homes have dehumidifiers, but the three monitored dehumidifiers used up to 22.3 kWh a week, or up to a third of average household electricity use. Aquariums have a wide range of energy consumption depending on the model, and especially whether they heat water. The highest-consuming aquarium used 18.5kWh a week. Two appliances recorded as massage beds turned out to be very different pieces of equipment, with different use profiles and energy consumptions – from 27 W to 1 kW.

■ Although they may reduce peak load, we found that slow cookers do not necessarily save energy compared to ovens. Energy use profiles found that they have similar electricity use to manufacturers' data – where available – but that they tend not to use thermostats to control temperature during cooking. Requiring slow cooker manufacturers to use thermostats would reduce energy use, although the UK could not do this unilaterally.

■ However, by definition there were small numbers of these appliances in the HES homes. It is not possible to extrapolate from this to all households in England or the UK.

What do HES households tell us about air conditioning?

■ Only two households had air conditioning, and both used it only a single room. In both cases, energy use by air conditioning equipment was very loosely correlated to external temperature, and how the households used it was much more significant.

■ Accepting that only a small minority of households now have air conditioning, if it were adopted more widely, peak electricity use could rise by 500 W or more for each household installing it. It is worth considering a mandatory requirement to adopt passive measures to reduce overheating before air conditioning can be installed – this would discourage air conditioning, and help contain the rise in peak power use.

Actual electricity use of major appliances

■ The HES survey monitored the actual energy use of a large number of major appliance types: dishwashers, washing machines, tumble dryers, and fridge-freezers. Comparing the annual energy use of these appliances with Energy Label estimates of energy use suggested that some appliance types use quite a lot *less* energy than expected.

■ On average, we found that washing machines and tumble dryers used around 30% less than the Energy Label estimates. However, on average, dishwashers and cold appliances used very similar amount of electricity to the Energy Label estimates – suggesting that they are being used in a way that is consistent with the assumptions in Energy Labels.

■ We found no clear evidence that major appliances with better Energy Labels actually use less energy – partly because newer appliances with better energy ratings tend to be larger.

Comparing HES against *Energy Consumption in the UK* and the *Energy Follow-Up Survey*

■ Total electricity consumption for lights and appliances was very similar to Energy Consumption in the UK (DECC's annual statistics publication about energy trends since 1970). HES households were recorded as using just 2.6% less, on average, than ECUK. However, the detailed splits of energy use by different appliances suggested that ECUK may under-estimate energy use for cold appliances, and over-estimate for consumer electronics.

■ The distribution of electricity consumption across homes is similar to the Energy Follow-Up Survey (a survey of 2,600 households carried out in 2011, with electricity monitoring of 79 homes). However, high-consuming households in the EFUS use much more electricity than equivalent households in the HES, and the 24-hour profiles are somewhat different. Appliances ownership was similar to the EFUS study, but more HES homes were logged as owning dishwashers (59% of HES homes vs. 41% of EFUS).

Homing-in on secondary electric heating

■ Households with secondary electric heating that was monitored used 610 to 700 kWh a year for secondary heating, on average. This is a very small fraction of total electricity use, but a much larger proportion of the peak load from 6-7pm.

■ This part of the peak load is avoidable, and if all 4.2 million UK households with electric secondary heating switched to a different form of heating it would trim around 2 GW from the peak load (along with a reduction in annual electricity use). However, this would result in increased use of other fuels – at least 3,000 GWh a year.

Introduction

The Household Electricity Survey monitored a total of 250 owner-occupier households across England from 2010 to 2011. Twenty-six of these households were monitored for a full year. The remaining 224 were monitored for one month, on a rolling basis throughout the trial.

The study had four broad objectives at the outset[2]:

1. To identify and catalogue the range and quantity of electrically powered appliances, products and gadgets found in the typical home.
2. To understand their patterns of use - in particular, their impact on peak electricity demand.
3. To monitor total electricity consumption of the home as well as individually monitoring the majority of appliances in the household.
4. To collect 'user habit' data when using a range of appliances through the use of diaries.

Participants kept detailed diaries of how they used certain appliances, which can be matched against actual energy use monitoring for their homes. They had between 13 and 85 appliances in their homes, with about a third of households owning between 30 and 40 appliances.

Seasonal adjustments

Most of the households in the survey were only monitored for a month, and these figures were unduly affected by the time of year when they were monitored. As a result, for some of the Department's questions we had to adjust the data for these homes to account for seasonal differences. For example, fridges and freezers use more energy in the summer, but lighting is used more in the winter.

We used data from the 26 households monitored over a whole year to generate seasonality factors for each appliance type – cold appliances, electric cooking, lighting, washing, AV, ICT, water heating and space heating. (For water heating there was no significant difference between the seasons.)

We calculated the electricity use on each day for each appliance type, averaging over the total usage for the 26 households. Then we normalised this by dividing by the total use over the year, times 365 to get a factor for each day.

The results were very noisy, so we used regression analysis and least squares to find a best fit curve, based on sine and cosine functions. We generated a separate adjustment curve for each of the eight appliance types where there was a link between energy use and the time of year.

[2] DECC/EST/DEFRA (2012) Powering the Nation. London: DECC/EST/DEFRA.

The adjustments result in increased uncertainty, which is hard to quantify, particularly for heating due to the small sample. (None of the households monitored for a year used electricity for their main heating.) For heating we avoid using the adjusted figures where possible.

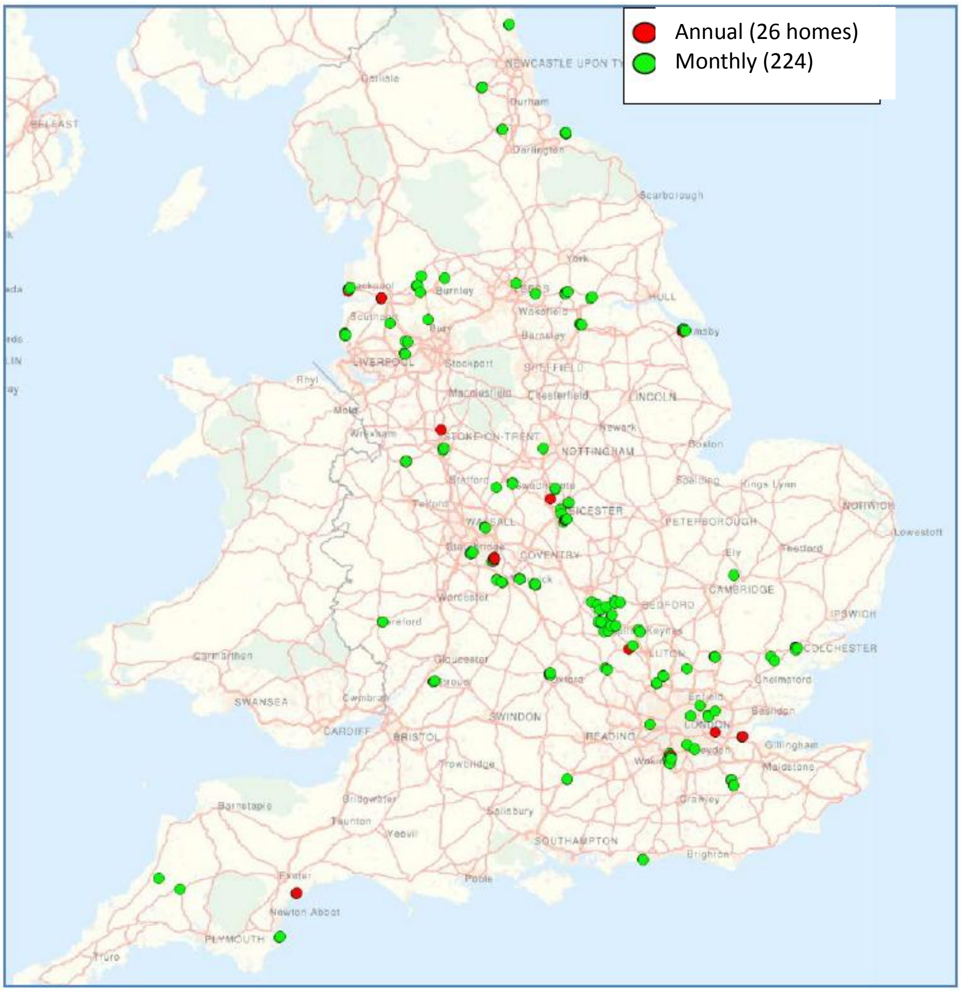
The sample of homes was not perfectly representative – partly because only homeowners were included and partly because they were more energy-conscious than average households. However they were fairly typical in terms of social grade, number of residents, life stage, and property age[3]. There were also fewer than the average number of households with primary electric heating (3.5% against an average across the population of 8%[4]), flats were under-represented (4% against 20% nationally[6]), and the average floor area was 5.5% larger. Average (mean) electricity use across homes in the sample was 4,093 kWh/year, against a mean of 4,154 kWh across all UK homes[5]. The location of households that participated is shown on the map below.

The sample of homes was not perfectly representative – partly because only homeowners were included and partly because questionnaires found them to be more energy-conscious than average households. There were also fewer than the average number of households with primary electric heating (3.5% against an average across the population of 8%[6]), flats were under-represented (4% against 18% nationally[2]), and the average floor area was 5.5% larger. The average (mean) electricity use across homes in the sample was 4,093 kWh/year, against a mean of 4,154 kWh across all UK homes for 2011[7].

This data offers an unparalleled source of very detailed electricity profiles. It has already provided unmatched insights into the way electricity is used in English homes. In our previous reports we examined the scope for demand shifting, baseload electricity demand, changes in the size and efficiency of appliances, and how different socio-economic groups and ages use electricity. We also wrote a report about how smart meters could be used as the starting point for a National Monitoring Survey.

However, there are still other types of analysis and fields of enquiry to examine using the data. This report focuses on modelling, actual energy use and energy labels, and unusual appliances including air conditioning. Our next report will concentrate on social studies and policy questions.

[3] Zimmerman et al (2012) Household Electricity Survey: A study of domestic electrical product usage. Milton Keynes: Intertek/EST/DECC/DEFRA.
[4] Palmer J, Cooper I (2014) UK Housing Energy Fact File 2013. London: DECC. https://www.gov.uk/government/publications/united-kingdom-housing-energy-fact-file-2013
[5] DECC (2012) Energy Consumption in the UK. London: DECC. (Tables 3.1 and 3.3.)
[6] Palmer J, Cooper I (2012) UK Housing Energy Fact File 2012. London: DECC.
[7] DECC (2012) Energy Consumption in the UK. London: DECC. (Tables 3.1 and 3.3.)



Participants came from most parts of England, although they were not perfectly representative – the south-west is under-represented and the north is over-represented. Source: Zimmermann et al, 2012[8].

This report, by Cambridge Architectural Research Ltd, Loughborough University and Element Energy, is the third in a series of five reports that investigate different questions drawn up by DECC and DEFRA. These questions were unexplored, or not explored in full, in the original analysis of the Household Electricity Survey[3] (HES).

Working closely together, we scrutinised and analysed the data in a variety of different ways to explore specific questions. We have established a secure database for the data, and used tools including SPSS, R (both specialist statistics packages), Excel and SQL (structured query language) for analysis. Where necessary we used programming for functions that were not supported in these packages. We carried out standard statistical tests (t-tests and others), and we focused quite explicitly on uncertainty in the data and the analysis.

[8] Zimmerman et al (2012) Household Electricity Survey: A study of domestic electrical product usage. Milton Keynes: Intertek/EST/DECC/DEFRA.

We are writing five detailed reports over the 13 months of this project:

- One on 'Demand side management and grids'[9]
- 'Tuning in to energy saving', on appliances ownership and usage patterns[10]
- This report, on 'Extreme users', 'Updating modelling', and 'Updating electricity use statistics by appliance'
- One report on 'Social studies and Policy', and
- The Final Report – giving an overview of the whole project and summarising the main findings to emerge.

Limitations of the data

Studies like the Household Electricity Survey are unusual because they are complex to organise, and very expensive. Inevitably, there are some compromises in assembling such a rich set of data – largely linked to the modest sample size. Ideally, there would have been thousands, or perhaps tens of thousands of households participating in the study, including both rented and privately-owned homes. Ideally, all homes would have been monitored for the full 12 months rather than having some of them monitored for just one month. Some commentators hold that gender is an important determinant of energy use at home, and ideally we would have data on the gender makeup of households and/or individual participants, but this data was not collected.

It is possible that people living in rented property use electric appliances differently from owner occupiers, although we know of no empirical work in the UK that demonstrates this.

The Departments asked us to draw out policy recommendations from the work where possible. They and we recognise that policy recommendations would be more robust if based on a larger sample – especially for work focused on subsets of the homes in the study (e.g. homes with electric heating, or pensioners). The small sample makes it impossible to extrapolate reliably to all homes, but it is a starting point, and where possible we combine with other sources of empirical data.

In many parts of this work we see associations (or the absence of associations) between demographic profiles and patterns of energy use. We suggest explanations for these patterns where appropriate, with caveats, but we would not claim that our interpretations are categorical or definitive, and it is very seldom possible to infer unambiguous causality from the correlations.

[9] Palmer J, Terry N, Kane T (2013) Further Analysis of the Household Electricity Use Survey: Early findings – demand side management. London: DECC/DEFRA.

[10] Palmer J, et al (2013) Electrical Appliances at Home: Tuning in to energy saving. London: DECC/DEFRA.

Comparing actual and modelled electricity and gas use

The Departments wish to find out how the estimated energy use figures from established models compare to actual energy use in homes (in kWh and cost). The Standard Assessment Procedure (SAP) is used to check compliance against the energy conservation part of the Building Regulations. Along with BREDEM, the BRE's Domestic Energy Model, it is also used in modelling: to estimate the impact of energy efficiency upgrades and to make forecasts of energy use in the whole stock of UK homes.

BREDEM[11] has a longer history than SAP[12], and BREDEM does not put the same emphasis on standardising comparisons between homes. It also allows more flexibility (for example, in the way heating is controlled), and has more detailed calculations of cooking energy. The current algorithms for estimating energy use are very similar (almost identical for lights and appliances), in BREDEM and SAP.

This work is an opportunity to test modelled estimates of energy use for the whole building stock empirically (i.e. with real-world data), and potentially to identify better ways to estimate household energy use.

Approach

We compared modelled estimates of electricity and gas use for the HES households against actual electricity and gas use for the homes. The modelled estimates came from the Cambridge Housing Model[13], which uses SAP and BREDEM as the basis for energy calculations.

We also created an interactive spreadsheet that allows users to select specific house or household types and examine the modelled versus actual energy figures.

Some of the households in the HES were not monitored for a full year, which made it difficult to infer annual energy use reliably (see Early Findings report). Instead, we obtained meter point data matched to the EFUS homes for 2011 – which gave fairly reliable aggregate energy use data. Some of the meter point data are estimated readings (although we do not know which).

The SAP estimate of how many occupants are in each household is needed because developers and designers often need to use SAP before a property is sold – when occupancy is uncertain. This is an important part of the electricity use algorithms. It is also very simple –

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[11] BRE (2013) BREDEM 2012: A technical description of the BRE Domestic Energy Model version 1.0. Watford: BRE. http://www.bre.co.uk/filelibrary/bredem/BREDEM-2012-specification.pdf (last accessed 23.01.14)

[12] Department of Energy & Climate Change (2013) SAP 2012: The Government's Standard Assessment Procedure for Energy Rating of Dwellings. 2012 edition. Watford: Building Research Establishment.

[13] CAR (2012) Cambridge Housing Model and User Guide. London: DECC. https://www.gov.uk/government/publications/cambridge-housing-model-and-user-guide (last accessed 23.10.13)

based solely on floor area. So we examined how reliable this estimate of occupancy is in some detail.

Analysis

We took total 'measured' household gas and electricity consumption figures from the metered energy use data (matched MPAN records for 2011), because this was the most reliable source of annual data. However, we used the HES monitoring data for the detailed breakdown of electricity use (appliances, lighting and cooking). This is the only disaggregated data available, and the period covered varies between households, running from May 2010 to July 2011.

Total 'modelled' energy use came from the Cambridge Housing Model (CHM), DECC's current model for household energy use, used in the Department's statistics publications and for policy questions. Some of the input data was missing to run a full SAP/BREDEM calculation in the model, so we used simple assumptions about window areas, dwelling perimeters, storey height, extensions, and internal and party walls, floors and ceilings. These are described in more detail in the grey box below.

Cambridge Housing Model modelling assumptions

Due to the type and format of HES information, we had to make a number of assumptions and simplifications in processing the raw data into a format appropriate as inputs for energy modelling. These were largely based on the RdSAP methodology, outlined in SAP2009 and not repeated here. Where further treatment of the data was required, the key points are listed here.

- Height: As this data was not available, typical values for each house type were taken from the English Housing Survey data.
- Perimeter: This data was unavailable. Therefore, typical values from EHS were used for each house type.
- Extensions: RdSAP allows for up to four 'extensions' per house to account for elements with different ages & materials. However, the HES data does not include information on the proportion that each 'extension' represents. Consequently, only the one identified as being the 'main' in the data was used.
- Floor Area: The data includes *total* area, but not the breakdown for each storey. Therefore, the area breakdown per storey was assumed constant, except where clear (e.g. areas identified as rooms in roofs, or conservatories)
- Glazing: Households identified as having 'much more than typical' glazing were assumed to have 50% more than the average. Conversely, households recorded as 'much less than typical' were assumed to have 50% less than average. In addition, some 10% of the households were listed as having 'Much more/less than typical' (with no way of knowing whether they had more or less). These households were excluded from the analysis.
- Internal and party walls, floors and ceilings. This data is not available, so the default values were used.

- Flats: The type of flat (purpose built or conversion, which relates to the form) was estimated based on the building age. Pre 1966 flats were assumed to be converted, and post 1966 flats as purpose built.

We used the CHM to compare modelled annual gas and electricity use against the measured MPAN total energy use data. We went on to explore modelling algorithms for appliances, lighting and cooking in more detail, comparing these estimates against the disaggregated HES monitoring data.

Appliances

The CHM uses an equation from SAP (which is very similar to the equivalent equation in BREDEM 2012[14]), based on floor area (m^2) and the number of occupants, to estimate annual appliances electricity use (kWh/year):

$$\text{Appliance Use} = 207.8 \times (\text{Area} \times \text{Occupants})^{0.4714}$$

We compared this against total annualized metered energy figures recorded in the HES for all electrical appliances (ICT, AV, cold appliances, wet appliances, shower (excluding water heating), and 'other').

Lighting

The CHM also uses an equation from SAP/BREDEM based on floor area (m^2) and the number of household occupants to estimate annual lighting electricity use (kWh/year). Adjustments are then applied to account for the proportion of low energy lighting (%), and daylighting:

$$\text{Lighting Use} = \text{Low-energy Lamps} \times \text{Daylighting} \times 59.73 \times (\text{Area} \times \text{Occupants})^{0.4714}$$

$$\text{Low-energy Lamps} = 1 - 0.5 \times \%\text{LowEnergyLight}$$

$$\text{Daylighting} = \frac{\Sigma(0.9 \times \text{WindowArea} \times \text{LightTransmittance} \times \text{FrameFactor} \times \text{LightAccess})}{\text{Area}}$$

We compared this against annualised HES lighting data, excluding households where no lighting distribution boards were monitored, or where lighting was only monitored in summer, consistent with previous work on lighting use. We also excluded households with incomplete window data, because this meant we could not apply the daylighting adjustment.

[14] BREDEM 2012 uses this equation for appliances: Energy = $184.8 \times (\text{Area} \times \text{Occupants})^{0.4714}$. http://www.bre.co.uk/filelibrary/bredem/BREDEM-2012-specification.pdf (accessed 11.02.14)

Cooking

The absence of gas cooking data for HES households means we can only examine electricity use for cooking. The Cambridge Housing Model algorithms for cooking are based on BREDEM 8. (SAP 2009 does not explicitly calculate annual cooking energy use, only emissions and internal gains due to cooking. This means the cooking algorithms are simpler.)

BREDEM and the Cambridge Housing Model make a distinction between households with electric ovens and hobs, and those with electric ovens and gas hobs. The equations for cooking electricity consumption (kWh/yr) in the Cambridge Housing Model are:

Electric oven & hob, Cooking Use = 338.9 + (66.7 x Occupancy)

Electric oven only, Cooking Use = 138.9 + (27.8 x Occupancy)

The HES data includes information on each household's cooking equipment, and those without electric cooking were excluded from this analysis.

Model Tester

We developed a Model Tester spreadsheet that shows the estimated energy use figures compared against the actual ones. Depending what options are chosen, the spreadsheet presents either total energy use using metered (MPAN) data, or disaggregated energy use using the HES data.

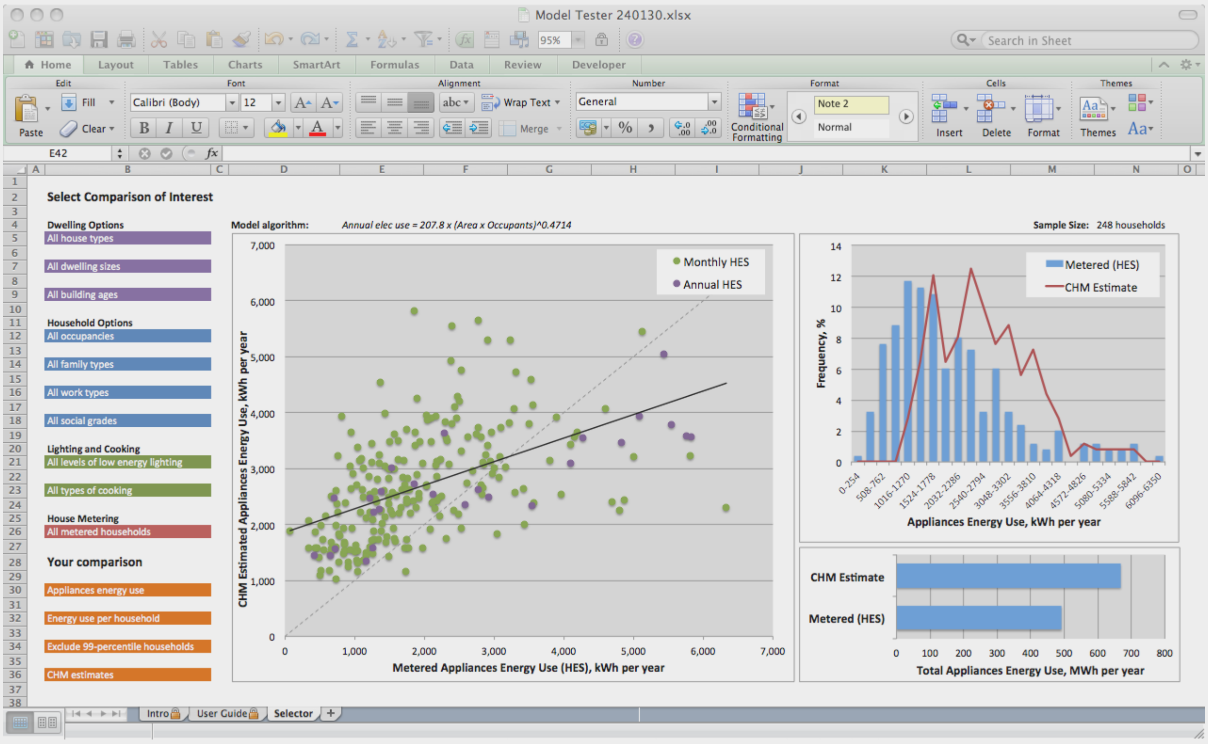
The Model Tester is available here:

www.tiny.cc/HES-Model-Tester

Users can select total electricity use, total gas use, or energy use for lighting, appliances or cooking. The results can be presented for the whole household, per m^2, per occupant or per occupant-m^2. Users may also choose specific house or household types – e.g. just flats, or just single-person households.

The Model Tester generates a scatter graph showing estimated energy use against actual consumption (see screenshot below). A solid black line shows the best-fit line for the data, and a faint dashed line shows a 'perfect fit' (when estimated energy use = measured energy use). Points plotted above the dashed line represent households where a model overestimates actual energy use, and dots below the line are households where a model underestimates actual use.

For HES data, purple points show households that were monitored for the entire year, while green ones show households monitored for just a month (i.e. where HES data had to be annualised). The purple points are more reliable than the green ones.



The histogram to the right of the scatter plot shows the distribution across the stock of actual (blue columns) and modelled (red line) energy uses. Modelled energy estimates can match actual energy in aggregate, even when they do not match for individual households. Therefore, the simple bar chart presents total energy use for the sample (when household energy use is selected) and average energy use across the sample (when energy use per m^2, per occupant or per occupant-m^2 is selected).

In order to make the graphs clearer to view, the Model Tester includes an option to exclude the 99th percentile outliers.

Using the spreadsheet, the results can be examined for different household or dwelling characteristics. However, a few key results are presented here, and the table below summarises the results of the comparison between actual energy use data and the modelling. It shows the total, mean and median energy consumptions from the data and modelling. (In all cases, we used as many data points as possible for the comparisons, so we used all the households with MPAN records and model input data for the total gas and electricity comparisons, and all those with lighting data and minimum data for modelling were included in the 'Lighting' comparisons.)

Result	Total Gas Use (kWh)	Total Elec* Use (kWh)	Appliances Use (kWh)	Lighting Use (kWh)	Elec Cooking Use (kWh)
Whole Sample					
No. of Houses**	128	129	250	184	171
Mean					
Metered (HES)	17,244	4,136	2,031	516	521
Estimate (CHM)	20,767	3,936	2,702	643	353
Median					
Metered (HES)	15,874	3,817	1,728	383	477
Estimate (CHM)	17,446	3,671	2,576	588	306

* Depending on the household, total electricity use may include space heating, water heating, and systems (pumps, fans, etc.) as well as appliances, lighting and cooking. This accounts for most of the variation between the energy use figures.
** Due to variations in the data available, the number of households included varies between energy categories. There are also discrepancies between total electricity use recorded in the HES for each household and the MPAN record of electricity use. Households without MPAN data, or where incomplete building characteristics made CHM calculations impossible, were excluded from the MPAN figures.

The table shows that based on the inputs available and the assumptions we have made, the CHM over-estimates gas use by 20%, on average. It under-estimates electricity use, but by a much smaller margin: just under 5%. However, the breakdown of electricity use between appliances, lighting and cooking attributes too large a share to appliances (33% over) and lighting (25% over), and too small a share to cooking (33% under).

The next table, below, presents the annual energy use costs. These have been calculated assuming households pay 3.8 p/kWh for gas, and 11.4 p/kWh for electricity. (Figures from DECC's Annual Domestic Energy Prices 2013[15] for 2010.)

Result	Total Gas Cost (£)	Total Elec* Cost (£)	Appliances Cost (£)	Lighting Cost (£)	Elec Cooking Cost (£)
Whole Sample					
No. of Houses**	128	129	250	184	171
Mean					
Metered (HES)	656	471	231	59	60
Estimate (CHM)	789	448	308	73	40
Median					
Metered (HES)	603	435	197	44	54
Estimate (CHM)	663	418	293	67	35

This comparison of aggregate results (e.g. mean actual energy vs. mean modelled energy) does not tell the whole story. It provides an idea of the general validity of the calculation for the stock. However, examining individual households gives a better understanding of how the model compares to reality. The scatter graphs below present the actual energy use against the modelled energy use for individual households.

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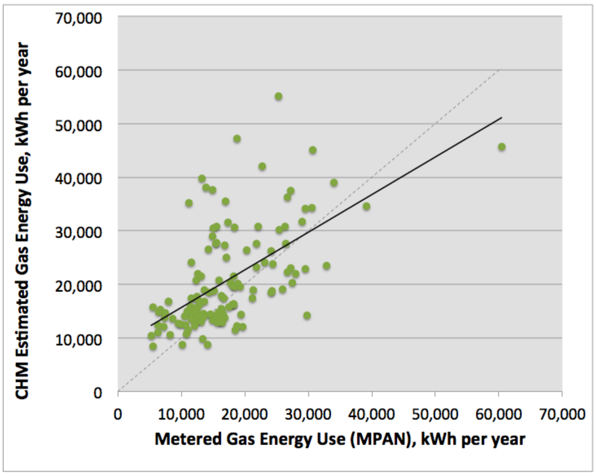
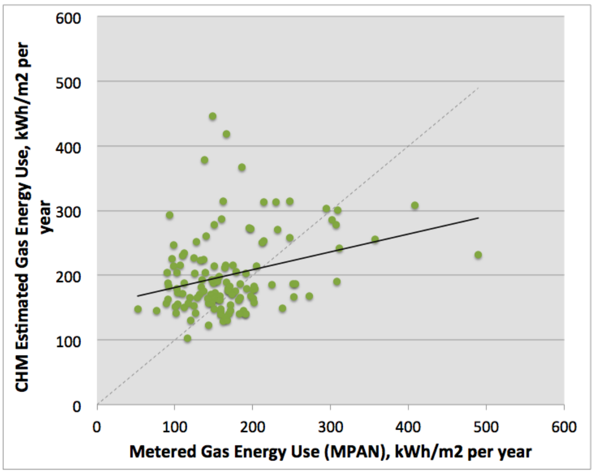
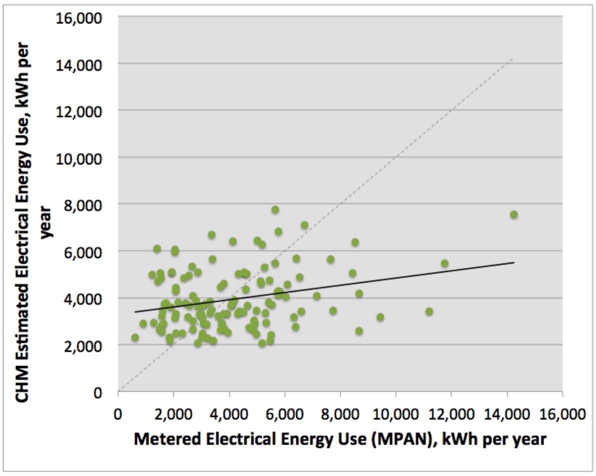
[15] DECC (2013) Average annual domestic electricity and gas bills for UK countries (QEP 2.2.2/QEP 2.3.2). London: DECC
https://www.gov.uk/government/statistical-data-sets/annual-domestic-energy-price-statistics)

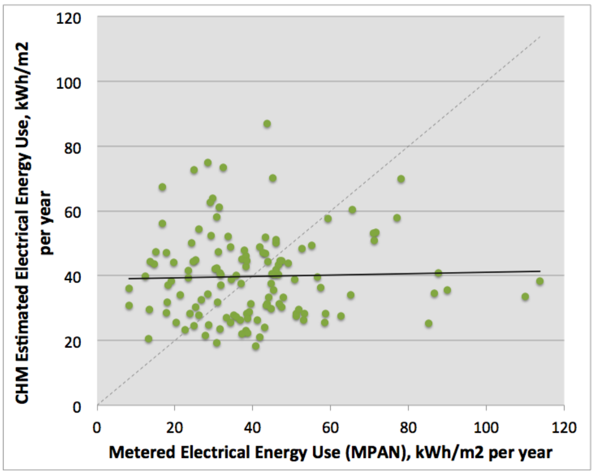
The top and bottom graphs below show total gas and total electricity use, respectively. The left hand graphs show energy per household, and the right hand graphs show energy per square metre (equivalent results for energy per occupant, or energy per occupant-m^2 can be viewed using the Model Tester, but are not presented here for conciseness). Interestingly, the graphs suggest very different results to the aggregated results in the tables above. The tables suggest that the existing modelling provides a better fit for average electricity use than average gas use (differences between actual and modelled mean use of 20% and 5%, respectively). However, the scatter graphs below suggest the reverse: despite the scatter, the gas consumption best fit line broadly follows the 1:1 'parity' line, while the results for electricity are much further away from this line. (The parity line indicates an accurate estimate of actual energy use.)

This is partly a function of the variability in actual energy use: the graphs show that there is much more diversity in electricity use between households than there is in gas use – even when the figures are normalised by floor area. There is a clear dense cluster in gas use (between 10,000 and 17,000 kWh/year, or around 150 kWh/m^2/year), but there is no equivalent cluster in electricity use.









The differences in the accuracy of the gas and electricity consumption estimates may reflect two approaches within the CHM (and SAP/BREDEM). The gas calculation is a complex calculation based on estimating the heating demand, which is largely based upon physical characteristics (heat loss through the envelope, solar gain through glazing, actual weather data for the region each household is located in[16], etc.). The calculation involves scores of variables. However, the electricity calculation is much simpler, made up of the simple equations outlined above, which approximate to behaviour (appliance ownership and usage) based on a very small number of variables.

(We should note here that the CHM was not intended to model the behaviour of individual households – rather it uses standardised assumptions to model 'average' household behaviour. The aggregate energy use for the whole stock is then compared against DUKES, the Digest of UK Energy Statistics, and aligned to match DUKES.)

The range (10^{th} to 90^{th} percentiles) for estimated total electricity, appliances, lighting, and cooking consumptions per m^2 are all considerably lower than the ranges for the actual data (between 30 and 40% lower). In contrast, the estimated gas consumption range is within 3% of the actual figures. This suggests that SAP is less able to account for the extremes in electricity consumption than for gas.

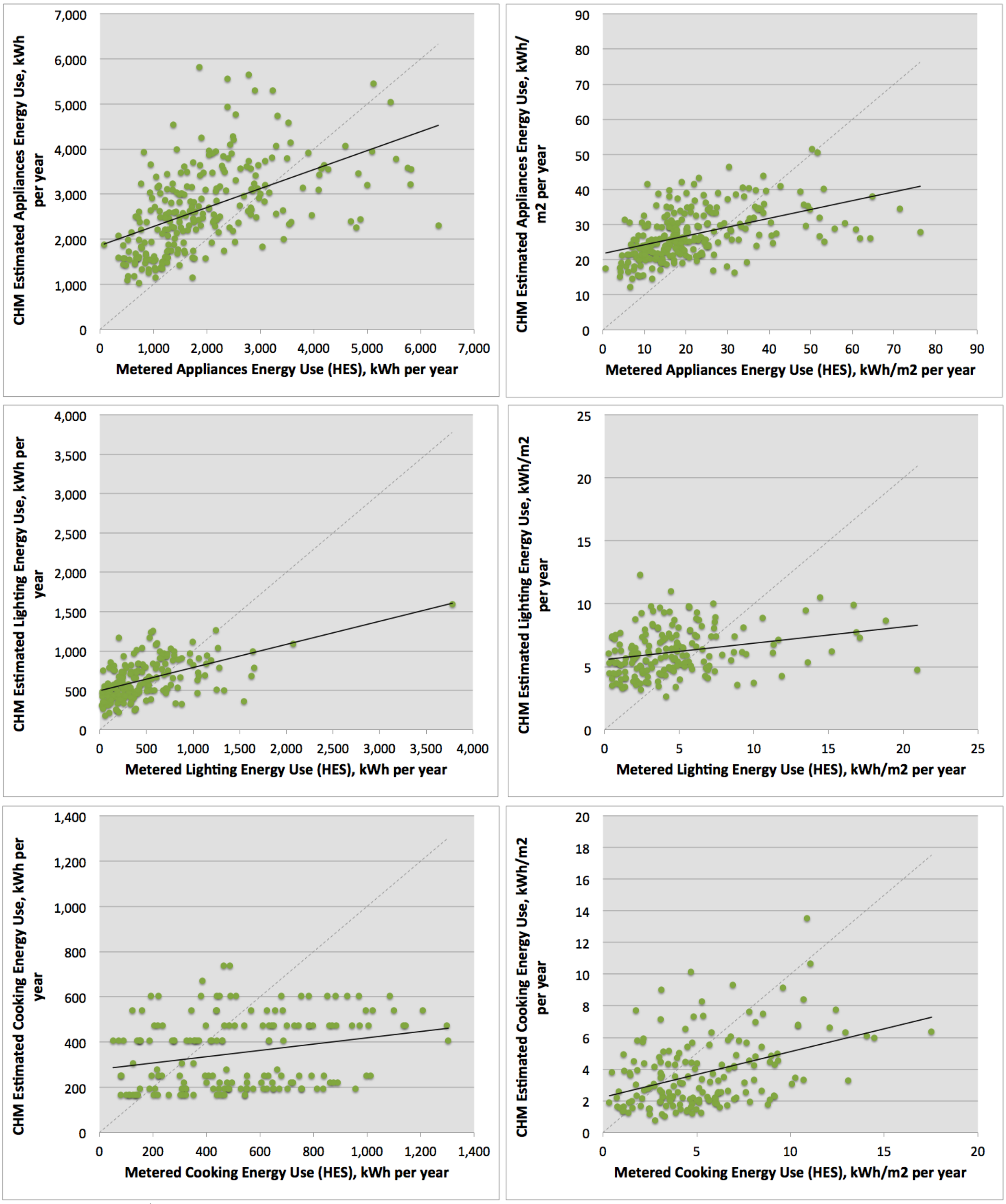
The graphs below present the disaggregated electricity use results for, from top to bottom, appliances, lighting, and electric cooking. As before, the graphs on the left and right are for energy use per household and per m^2, respectively.

(Again, these graphs were generated using the Model Tester, and readers can set up their own comparisons to examine specific subsets of households or dwellings of their own choice.)

Across all three types of electricity use, the model tends to over-estimate low use households, and under-estimate high use households. The actual consumption data shows increasing variability moving from lighting (densely clustered) to appliances (some clustering) and on to cooking (no clustering unless normalised to floor area). The model estimates do not appear to account adequately for the variability. This means that the model's estimate of lighting energy is more reliable than the estimates of appliances or cooking.

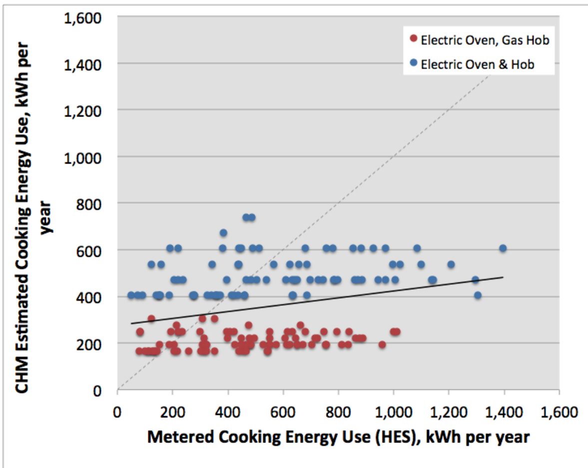
We should not that, like space and water heating, lighting is regulated in the energy conservation part of the Building Regulations. (It is referred to as '*regulated* energy'.) This is in contrast to energy use for appliances and cooking, which are considered to be mainly determined by householder decisions about what appliances to install and how to use them. Consequently, these '*unregulated*' forms of energy use typically receive less attention in building models.

[16] There is no weather adjustment, as such, in the model estimates, but the model includes external temperature data, and the estimates of heating energy take this into account. MPAN gas data includes a weather adjustment applied by the energy suppliers, but how this adjustment is carried out is not in the public domain.



*The extreme (99th percentile) results have been excluded from the lighting graphs to make them clearer to read. The results for the full sample can be viewed in the Model Tester.

The Cambridge Housing Model uses BREDEM algorithms for electric cooking, so we could test these algorithms against actual energy use from HES. The graph below gives a more sophisticated plot of actual against modelled electricity use for cooking, showing households with electric hobs separately from those with gas hobs. The CHM suggests that households with an electric hob use just over twice as much electricity for cooking, on average.



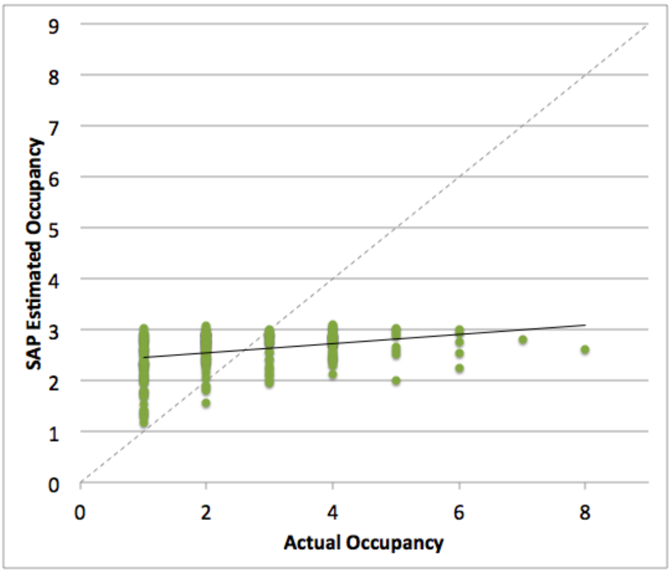
However, the graph shows that there is little link between the model estimate and the actual electricity use for cooking when households with and without electric hobs are plotted separately.

Number of occupants

Occupancy is a key input variable for many of the energy calculations in SAP. (As well as those discussed above, it is also used to estimate hot water use.) In Building Regulations compliance, a simple algorithm from SAP is used to estimate how many people there are in a home – because it is impossible to know how many occupants there will be before a new home is sold by the developer. We did not use the SAP algorithm for this study, because data for the actual number of occupants in HES households was available. However, data from the HES provides an opportunity to compare SAP estimates of occupancy with the *actual* occupancy recorded for HES homes. SAP estimates household numbers based on the total floor area, using this equation:

$$\text{if } Area>13.9,\ = 1 + 1.76 \times [1- \exp(-0.000349 \times (Area - 13.9)^2)] + 0.0013 \times (Area - 13.9)$$
$$\text{if } Area \leq 13.9,\ = 1$$

The graph below shows the SAP estimate of household occupancy against actual occupancy for the HES households. The estimate suggests that no HES households will have more than three occupants. However, in fact a quarter of the HES sample has more than three occupants. Given the importance of occupancy in so many parts of the SAP energy use estimates, this colours all modelling work when the number of occupants is unknown.



Improved algorithms for stock modelling

Part of our brief from the Departments for this work was to develop more reliable electricity use algorithms that could be used in energy models. We carried out regression analysis between the actual energy use figures and all of the dwelling and household data available from the HES study. This was a big task, summarised in the grey box on page 24, but the outcome was that we were unable to identify parameters with a stronger simple correlation to electricity use than floor area and the number of occupants – the parameters currently used in SAP/BREDEM.

One interpretation of this is that that the input data needed for bottom-up estimates of electricity use is not yet available for stock modelling. The types of reliable behavioural data that would be needed are also very difficult to obtain, and non-heating electricity consumption is so dependent on how people e live. It is more closely linked to behaviour than to the form or construction of dwellings.

However, we were able to formulate algorithms similar to the SAP/BREDEM ones, but which more accurately predicted median electricity use for the HES households. (In the jargon, these are 'stochastic' algorithms – based on statistical analysis rather than more complicated bottom-up modelling. Medians are commonly accepted as a better average than means for skewed distributions like energy use.) The table below compares the existing SAP equations for cooking, appliances and lighting energy consumption with the adjusted equations.

Energy Use	Equation	Total (kWh)	Mean (kWh)	Median (kWh)	Median Error (%)
Appliances					
SAP	207.8 x (Area x Occupants) $^{0.4714}$	675,623	2,702	2,576	48
New algorithm	127 x (Area x Known Occupants) $^{0.4881}$	452,403	1,817	1,727	2
HES actual	-	507,772	2,031	1,728	-
Lighting					
SAP	59.73 x (Area x Occupants) $^{0.4714}$	118,231	643	588	59
New algorithm	10.88 x (Area x Known Occupants) $^{0.6849}$	72,511	394	342	-10
HES actual	-	94,983	516	383	-
Cooking					
SAP	Elec cooker: 338.9 + (66.7 x Occupancy) Elec oven: 138.9 + (27.8 x Occupancy)	60,306	353	306	-35
New algorithm	Elec cooker: 88.5 x (Area x Known Occupants) $^{0.3183}$ Elec oven: 81.9 x (Area x Known Occupants) $^{0.2856}$	75,714	434	443	14
HES actual	-	89,072	521	477	-

Unsurprisingly, the table shows that new algorithms to predict appliances, lighting and cooking energy derived from the HES data are better at predicting total or average electricity use *for these households*. Even apart from the discrepancy in the number of occupants, there is scope to improve on the SAP algorithms for stock modelling, and this appears to improve the estimates of both the mean and median electricity use. We would need to compare the algorithms against other households (and especially private rented and social housing) before we could be confident that they serve as better predictors than the SAP/BREDEM algorithms. However, thanks to the similarity with existing calculations, it would be straightforward to replace the algorithms currently used in the Cambridge Housing Model – or the forthcoming National Household Model – for electricity use with these new algorithms.

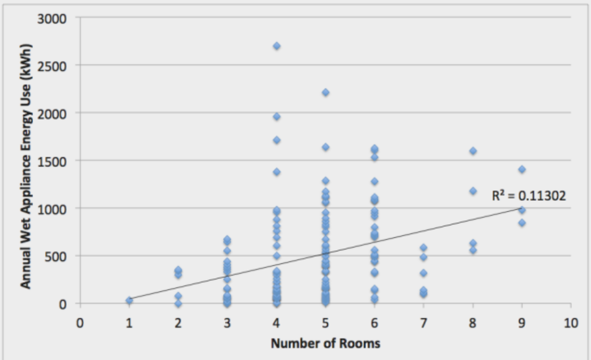
Regression Analysis: Summary

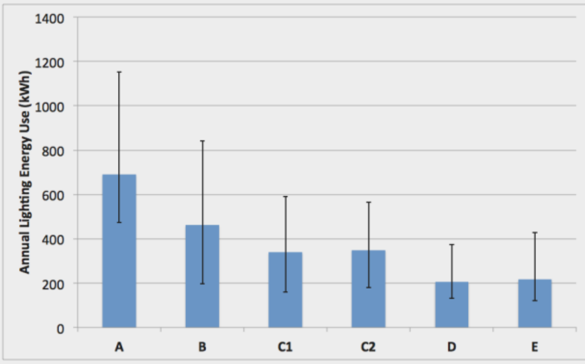
For each of the main uses being investigated, we examined the impact of each of the housing (physical characteristics of the dwellings) and household (social and demographic characteristics of the occupants) variables.

We also explored the different appliance types independently (wet appliances, cold appliances, lighting, etc.). Building characteristics (e.g. floor area, number of rooms, and house type) and occupancy characteristics (e.g. number of occupants, social grade, and employment status) were both considered.

We plotted graphs of each of the variables against energy use for different appliance types, including log graphs and reciprocal graphs, using colour-coding to identify different appliance types (e.g. green for wet appliances and blue for lighting). We plotted categorical variables as column charts, and continuous variables as scatter plots.

Two examples of our graphs are shown below: the scatter graph on the left shows energy use for wet appliances against the number of rooms in the house, while the column graph on the right shows median lighting energy use against social grade.





A number of the building characteristics (beyond floor area and occupancy – the variables currently used in the CHM and SAP) showed some correlation with energy use. However, there is significant scatter for all of these variables (as there is with occupancy and floor area). The inter-quartile range is shown as error bars in the column graph on the right.

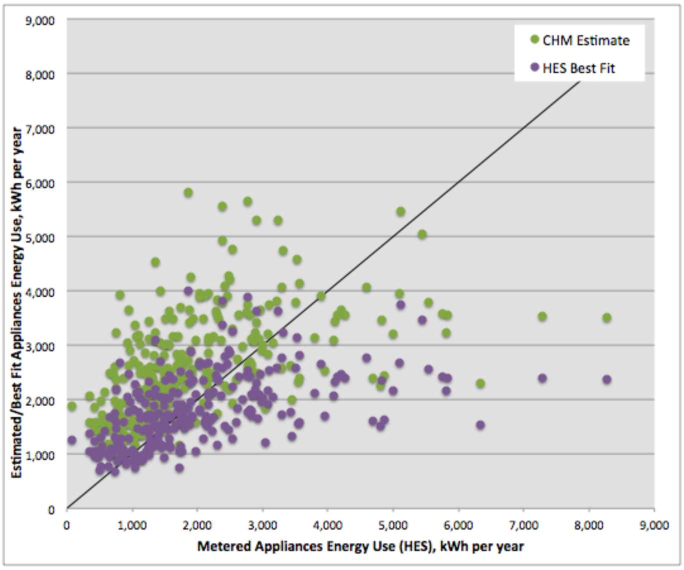
To examine the impact of the different variables on energy use together, we did multiple regression analysis, using the ‘stepwise’ method to determine the key variables. We saw that the end result of this analysis would take the form:

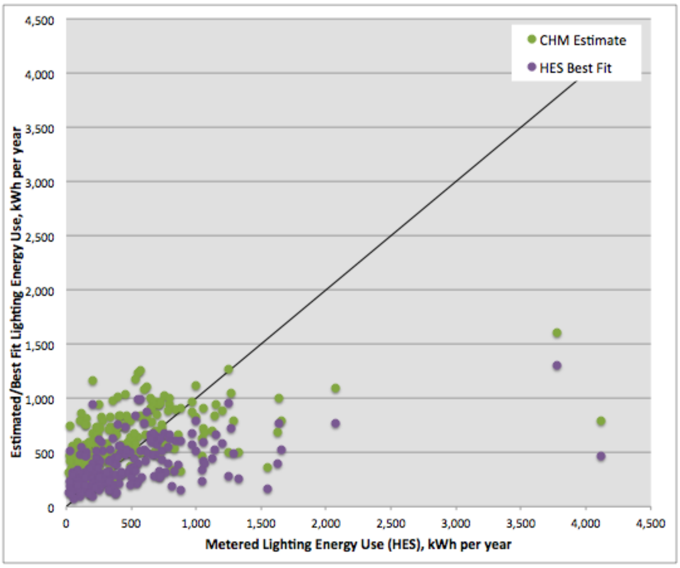
Energy = $A + Bv_1 + Cv_2 + Dv_3$ … (where v_n, are different variables, and A, B C… are constants)

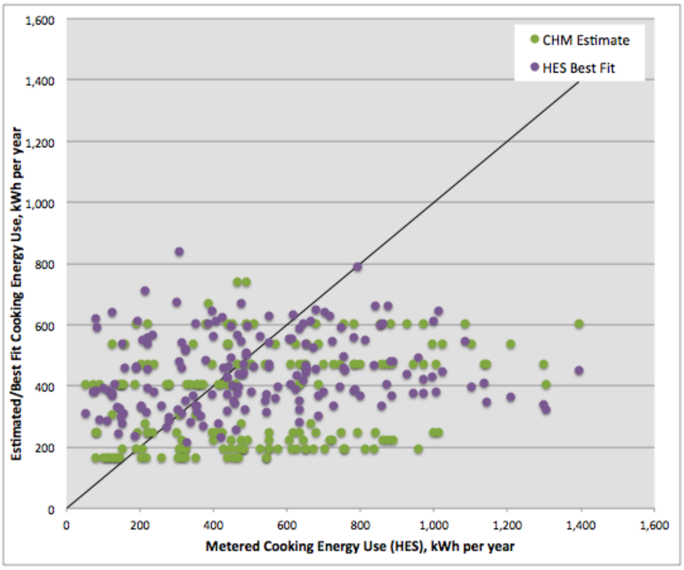
This form of equation could provide a better fit than the current CHM methodology, but the equations would be more complicated, less transparent, and still statistically based (rather than bottom-up/building physics based) so we decided not to continue with this approach.

The plots below show the same household-level comparison of modelled vs. measured electricity use we showed before, overlaid with the new algorithms. Compared to the CHM calculations, the new *Appliances* estimates – based on the HES best-fit algorithm – have a more even split of over- and under-estimates and remove the very high electricity use estimates for some outliers (approaching three times actual electricity use in the original algorithm).

The new *Lighting* estimates also remove some of the very high estimates of the original algorithm, but they share with it the inability to predict high lighting energy use (largely because they do not reflect behavioural determinants – some households leave lots of lights on for much of the time, for their own reasons). While the new *Cooking* estimates eliminate the polarising split between households with and without electric hobs, and have a more even division of over- and under-estimates of actual electricity use, they still fail to predict the very high electricity use in some households.







Because the original CHM estimates over-estimated disaggregated electricity use in HES homes, these new algorithms result in a net decrease in electricity use. We should remember, though, that the MPAN data suggested that total electricity use estimates from the CHM are, in fact, less than the real figures. This disparity could reflect unknown energy use (electricity that was not monitored at the appliance level in the HES, accounting for a third of total electricity use). However, it is almost certainly also affected by the long tail of high electricity-use households, with some high use households using far more (up to 15 times more for lighting, see[17]) than average. These high users are not adequately offset by low use households because low users are much closer to average consumption.

Overall our conclusion from this is that the new HES best-fit algorithms appear to be better for stock modelling than existing algorithms. However, they need to be compared against another sample of households with disaggregated electricity use data to check they are valid more broadly. We also recommend further work on the portion of electricity use that was 'unknown' in the HES survey. Ideally the second sample would have sub-metering on a larger proportion of electricity consumption, and ideally 100% of it.

Again, ideally, if we had data on 'high use' and 'low use' households in advance, it may be possible to construct algorithms or adjustment factors that more accurately reflect electricity usage in extreme cases.

[17] Palmer J, et al (2013) Electrical Appliances at Home: Tuning in to energy saving. London: DECC/DEFRA.
[18] Palmer, J. et al. (2013) Comparing the Cambridge Housing Model against the National Energy Efficiency Data-Framework and Meter Readings. London: DECC.
[19] Hughes M. et al. (2013) Sensitivity and Uncertainty Analysis of England's Housing Energy Model. Building Research & Information 41(2) 156-167.
[20] Johnston, D et al. (2005) An Exploration of the Technical Feasibility of Achieving CO_2 Emission Reductions in Excess of 60% Within the UK Housing Stock by the Year 2050. Energy Policy 33(13) 1643–1659.
[21] Richardson, I et al. (2010) Domestic Energy Use: A High-Resolution Energy Demand Model. Energy and Buildings 42 (10) 1878-1887.

Summary and recommendations

■ We found that the Cambridge Housing Model over-estimates average gas use in the HES homes, but under-estimates average electricity use. Gas use is over-estimated by 20%, while electricity use is under-estimated by 5%. (The forthcoming National Household Model, which has a very similar energy calculation, may exhibit similar modelling gaps.)

■ The CHM also attributes too large a share of electricity use to appliances and lighting and too small a share to cooking. Typically, we found that the HES homes were using one third more electricity for cooking than model estimates suggested.

■ Further, the CHM tends to under-estimate energy use by high-use households – both for gas and electricity. The problem is particularly acute for electricity, which is more variable between households than gas use. This is almost certainly part of the cause of the net under-estimate of electricity use, and linked to the fact that models do not take into account the huge variation in human behaviour. The problem is less apparent for gas and heating because the models over estimate use in many households with non-extreme use.

Comparing actual and modelled energy

Other work has found that the Cambridge Housing Model (based on SAP/BREDEM) matches fairly closely to actual energy data aggregated to whole the UK housing stock.[18] Similar SAP/BREDEM-based stock models have been used to analyse different improvement options for the domestic building stock.

However, research has also shown that considerable inaccuracies in large-scale housing stock models can be caused by uncertain input data and simplifications in the modelling approach.[19,20,21] In a step away from steady-state, monthly/annual approaches, a number of recent studies have modelled residential electricity consumption in more detail.

Considering detailed occupancy behaviour, typically probabilistically, and at a higher resolution (comparable to dynamic simulation of heat demand), these models may enable more detailed consideration of the impact of changes energy use, but also require far more data than the existing approaches. They may be appropriate for stock modelling, but not for checking compliance against Building Regulations.

■ We were unable to improve on the CHM algorithms to estimate electricity use for appliances, lighting or cooking using other parameters available in the Household Electricity Survey. Instead we re-calculated the constants used in the CHM algorithms using the HES data. These should be tested against other samples of homes with measurements of energy use data broken down by final use – especially homes with different tenure.

■ Energy models could be reworked to generate a range of energy use estimates, dependent on how householders behave. At the simplest, they could present ‘high’, ‘medium’, and ‘low’ estimates of energy use for any house assessed. This might be more useful to modellers than a single figure, especially if coupled with other data that can identify households as high, medium or low energy users.

■ Energy models do not generate visibly better (more accurate) estimates of *regulated* energy use (for heating and lighting) than for *unregulated* energy use (for appliances and cooking). However, there is less variability in household gas use than there is in electricity use.

‘Unusual’ appliances and manufacturer’s data

Unusual appliances

A number of families participating in the Household Electricity Survey had some rather unusual electrical appliances – equipment that we would not normally think of in considering energy use in the home. Things like hot tubs, massage beds, aquariums or pond pumps may use considerable energy, but they are not normally included in analyses of household energy use.

In this section we explore some of the highest energy consuming ‘unusual’ appliances, comparing their energy use against manufacturer’s data where possible.

Approach

First we selected the appliances to study based primarily on their energy consumption, using mainly the maximum consumption seen among all the households. Since there were only a few households for each of these appliances, all the data points are potentially interesting, and the maximum from the survey is not necessarily an extreme case for all UK households. Energy use by some of the unusual appliances is affected by seasonal factors, but instead of attempting to make crude seasonal adjustments to energy use, we note kWh/week rather than kWh/year.

The table below summarises the unusual appliances monitored which used more than 2 kWh/week: about 3% of the average household energy consumption, excluding heating. Appliances in bold are explored in more detail below.

Appliance	Number Monitored	Mean kWh/week	Max kWh/week	Notes
Hot tub	1 (Dec/Jan)	50.4	50.4	We do not have the brand/model for this appliance. The energy use is plausible for the type of appliance and the time of year.
Air conditioning	2	20.0	39.0	Explored elsewhere in this report
Dehumidifier	3	11.2	22.3	
Aquarium	15	5.4	18.5	
Decorative fire	2	5.3	9.5	
Pond pump	5	4.2	9.8	
Massage bed	2	2.0	3.9	
Slow cooker	3	1.7	3.1	
Alarm	9	1.4	3.2	Explored in part 1 (24/7 appliances)
Steriliser	4	0.8	2.2	
Fryer	5	0.8	2.2	

Other appliances were excluded because no households used more than 2kWh/week to power them (they were used, but only occasionally, or they drew little power):

- Vivariums (with issues similar to aquariums)
- Food steamers, coffee makers, a yogurt maker, bread makers, a food mixer, and a bottle warmer
- A trouser press and a hair straightener
- A paper shredder, chargers, a clock radio, and a picture frame
- A sunbed, a jacuzzi, and an electric blanket

Although there are interesting use patterns among these appliances, we have not explored them here. This is because the small amount of energy consumed means they do not warrant policy attention.

Dehumidifiers

Dehumidifiers are sometimes used to control moisture in dwellings where the underlying cause is hard to fix. Most dehumidifiers have a humidistat – like a thermostat, but triggered by humidity rather than temperature. However, for two of these appliances the on-mode power did not vary, which could mean the humidity never dropped enough for the unit to switch off.

This table summarises the three dehumidifiers that were monitored. The manufacturers were not required to report typical energy consumption.

Appliance	Manufacturer's rated power (W)	Observed mean power when active (W)	Mean energy use/week (kWh)	Notes
Mitsubishi MJ E16P-E1 (in Lounge)	280	170 (max 240)	1.3	Used occasionally in the evening. Steady on-mode power.
Evantair WDH 610HA (from B&Q)	220	170 (max 191)	22.3	Used for long periods but not all day. Steady on-mode power
Amcor D-250 (in conservatory)	-	177 (max 250)	9.8	On all day, varying with humidistat

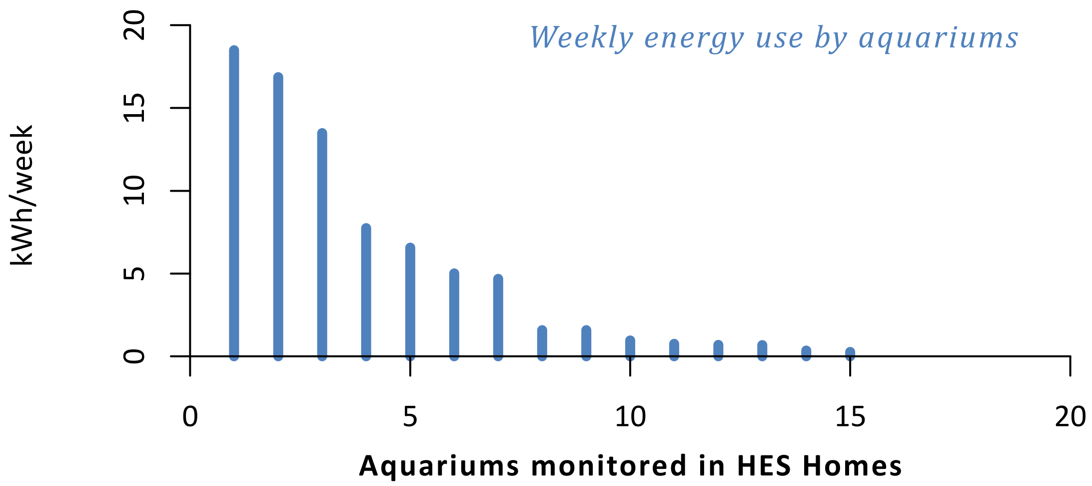
The three appliances had very different energy consumption, due to different patterns of use rather than the nature of the appliances themselves. The use is presumably related to the degree of damp problem, in the householder's perception if not according to the device's humidistat.

Dehumidifiers work as heaters too, and in this respect they have more than 100% efficiency because they run in a similar way to a heat pump (a little like a fridge in reverse) – though in this case the main purpose is to condense the vapour rather than to move heat around. All three of these appliances were monitored in December/January when heat is useful, though the third in the table was in a conservatory and heating a conservatory is not recommended. (The only other appliance monitored in the conservatory with the dehumidifier was a tumble dryer, of the vented type. This suggests the conservatory was probably not occupied during the day and should not need heating.)

All three households with a dehumidifier were bungalows (with no electric heating). However, this is probably pure coincidence and not a significant finding.

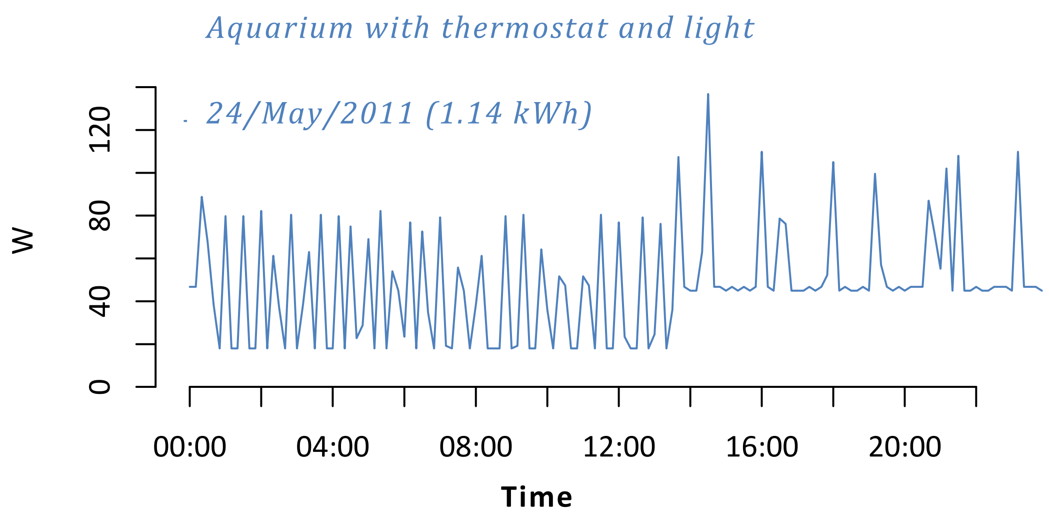
Aquariums

There were 15 aquariums monitored (in 12 households), and six of them used less than 1 kWh/week but three used more than 10 times as much. The highest energy user was 18.5 kWh/week. Brand and model details were only recorded for two of the aquariums, but it seems likely that this information did not cover all the aquarium equipment.



The lowest energy-using aquariums drew a steady current, presumably for a filter and light only. This was never more than 4.5 W.

Some fish need warm water – up to 27°C, or even more depending on the type of fish – and from the consumption profiles the higher using appliances were clearly running a heater with a thermostat. In several cases there was also probably a light on a timer, typically using 20-30 W.



Judging by the profile above, some of the savings from replacing the light with a low energy bulb would be lost because the heater would have to do more work. The heater comes on less often when the light is on. In this particular case, the light is 27 W (difference between minimum energy use in the morning and afternoon) but the increase in average power when it comes on is only 15W.

The top three aquariums were monitored in winter time, but the profile above, from May, shows the heater may be used to a lesser extent for a large part of the year.

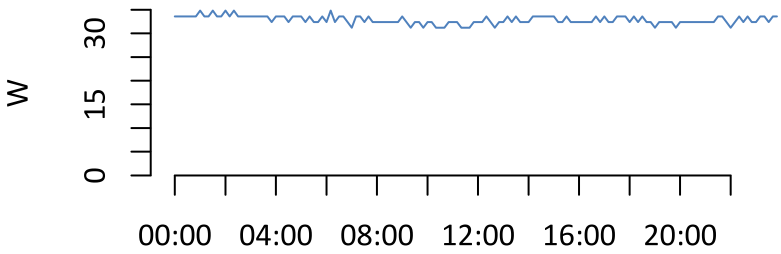
The heating energy used by aquariums depends on the time of year, the size of the tank and the temperature required. Aquarium owners need to be aware of this when choosing which fish to keep and where to locate the aquarium.

Fires

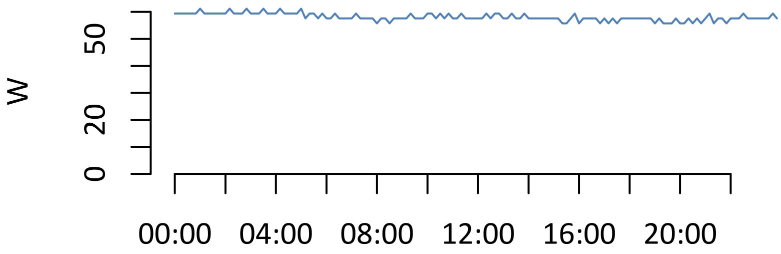
There were two appliances monitored that were recorded as a ‘fire’ rather than a ‘heater’. One of these was clearly an electric fire, consuming 2kW, but it was used only briefly. The other was a ‘Berry Magicoal’ fire fuelled by gas – electricity was used only for a ‘coal effect’ light and this was consuming 120 W. It was used for many hours a day (in November), sometimes continuously from 8am until 9pm, averaging 9.5 kWh/week. As with the dehumidifiers, the heating effect of this lamp could be useful, though it is not the main purpose of the appliance. However, since the coal-effect lighting was used for such long periods, it seems as if it was often on when heating was not needed.

Pond Pumps

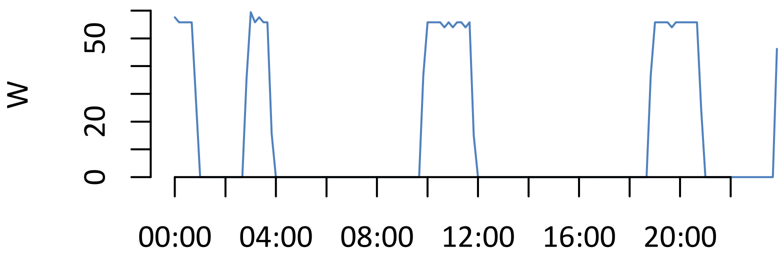
There were five pond pumps monitored and we have no more information about any of these appliances beyond what can be observed from the profiles, shown below. Pond pumps are often used to filter the water and to oxygenate it. They can also power a waterfall or a fountain. The power needed depends on the size of the pond and the stock of fish in it (and hence the rate of filtration needed), as well as the head of water required. The five appliances monitored used between 8 W and 80 W.



Pond pump on all the time 35W

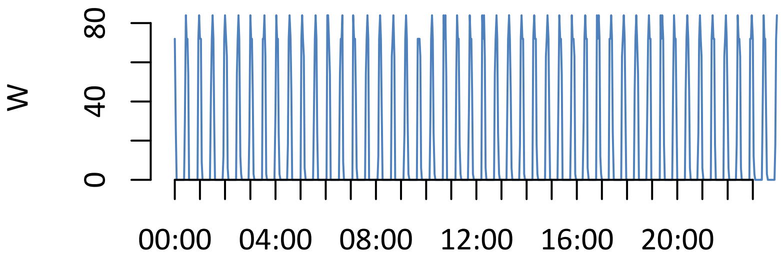


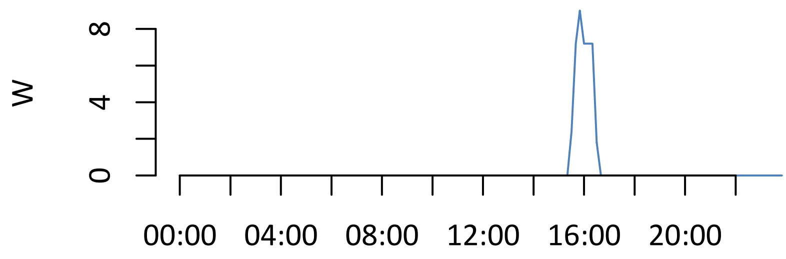
Pond pump on all the time 60 W



Pond pump on a timer, 4 times a day

Pond pump on for 10 minutes in every 30 minutes





Pond pump used occasionally (not every day)

Two of the pumps were in operation 24/7. One of these consumed 60 W, so just over 10 kWh/week. Another two were on a timer: one operated for about 10 minutes every 30 minutes, while the other was on for an hour or two, four times a day. The last one was used only occasionally for brief periods, presumably to drive a water feature.

It was straightforward to find the power ratings for pond pumps advertised on the internet, so householders probably could access the information needed to calculate the running costs for their pump.

The advice we have found on the internet is that ponds containing fish should be filtered and oxygenated continuously. If you run the pump only some of the time it needs to run faster to change the water to the required level. However, a large water feature that needs a bigger pump than is needed for the fish can be run separately.

Massage Beds

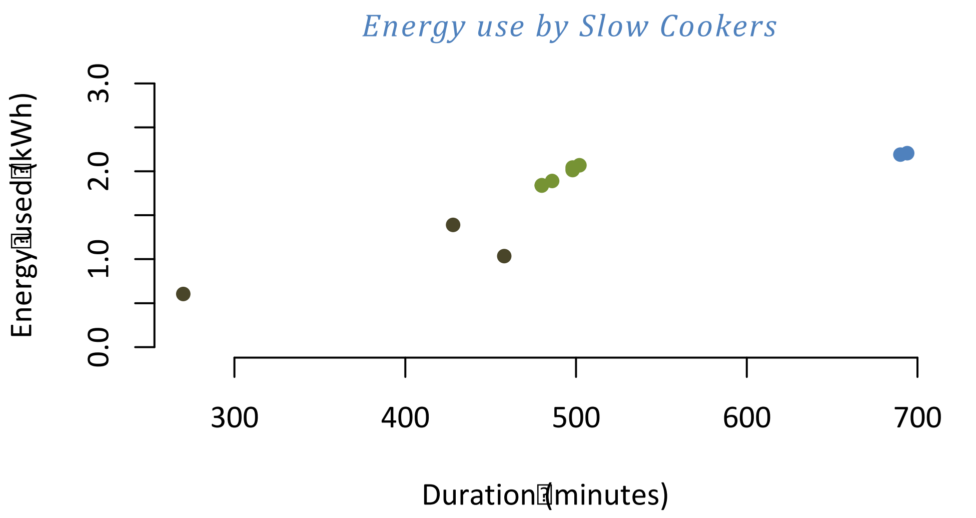
There were two massage appliances monitored, but in fact they were very different appliances. One was a 'circulation booster' for the lower legs and feet. This used 1 kW, but was used for just a few minutes at a time. The other was a bed with built in five-point massage system. This used 27W continuously when on – frequently 24 hours in the day, and averaging 3.9 kWh/week. It is not possible to say with confidence whether the bed was always occupied during that time, or whether the user was awake, but it seems likely that sometimes the bed was left on unnecessarily.

We did not find any specifications for the energy use of either of these appliances. The householder is unlikely to have any idea how much electricity they use.

Depending on the requirements of the householder, it would be possible to save energy by incorporating controls into the massage unit. It could be set on a timer, or to activate only for a set period and then turn off, or it could sense if there was a person in the bed or using the appliance, and deactivate if not.

Slow Cookers

Three households used slow cookers that were monitored. The chart below shows each occasion when these slow cookers were used: one household used the cooker six times, or 1.5 times per week, consuming approximately 2.0 kWh each time; the mean power was approximately 250W. The other households used their slow cookers less frequently.



Slow cookers do not always save energy compared to ordinary ovens: in this study the mean energy consumption for oven use events of 90 to 150 minutes' duration was 2.2 kWh, and two of the three slow cookers used 2 kWh or more on each occasion. However, slow cookers do use less electricity in peak time, because that energy use is spread over many hours, and sometimes all day.

From inspecting the profiles, these slow cookers do not use a thermostat – they consume a steady power depending on the setting, and typically they have three settings to select depending on the expected cooking time.

Appliance	Observed power use	Manufacturer's data
Breville MM14 (2 uses)	190 W	Unknown
Wahl ZX639-1 (6 uses)	270 W for 2-4 hours, then reduces to 200 W	280 W
Asda ESC35 (3 uses)	195 W on one occasion, 135W on two occasions.	unknown

Slow cookers would probably use less energy if they included a thermostat to adjust the power when the contents were the right temperature.

Steriliser

There were four sterilisers (for babies' feeding equipment) monitored, and we had manufacturer and model information for two of them. However, we were unable to find any information about energy use for either, or for any sterilisers currently available.

Sterilisers operate by high temperature steam and the energy used is similar to boiling a kettle. For the four households with sterilisers, the energy used was related to how often they were used and how long on each occasion – the biggest use was five times per day, for 20 minutes each time.

Frequency/week	Average duration (Minutes)	Energy used (Wh/cycle)	Energy used (kWh/week)
35	20	62	2.2
1.5	15	53	0.5
7.6	15	36	0.3
1.5	19	103	0.2

Recommendations

■ Electrical appliances that are not covered by the Energy Labelling Directive are usually advertised without specifying typical electricity consumption over the year. The only information manufacturers must provide is the rated power, which is the maximum used. For appliances such as slow cookers, massage beds, dehumidifiers, 'coal effect' fires, sterilisers and aquariums, it is difficult for purchasers to find out how much they will cost to run. The exception in this group is pond pumps, where the rated power is a good indication of actual usage. Better information in all cases (and ideally broadening the range of appliances covered by the Directive) would help households evaluate the running costs of appliances.

■ Dehumidifiers can be an expensive solution to a damp problem, using 20 kWh/week or more, or more than a quarter of average electricity use for a household. However, they also have a heating effect which can partly offset some other energy use.

■ Large water features in ponds can require powerful pumps of 60W or more. These should be switched separately from filtering and oxygenating equipment that need to be on all the time to keep the pond healthy.

■ Unheated aquariums use little electricity but aquariums heated for tropical fish can use up to 20 kWh/week. It is difficult to predict how much electricity will be used, as it depends on many factors. The heating energy for aquariums is also seasonal, though some heating is often needed for most of the year, since the water temperature needed may be 27°C or more.

■ Massage beds could incorporate controls to avoid leaving them running when no-one is in the bed – ideally a timer to switch off after a certain period and a sensor to detect if there is anyone in the bed.

■ Sterilisers use the same amount of energy regardless of how much equipment is being sterilised, so users should be advised to wait until they have a full load, the same as for washing machines and dishwashers.

■ Slow cookers would save energy if they had thermostats fitted as standard, like a lot of other cooking equipment.

What do HES households tell us about air conditioning?

Air conditioning is a major user of energy and generator of CO_2 emissions in many countries, including the UK. So far air conditioning is not common in UK households, and only around 2% of homes have mechanical cooling.[22] However, adoption of air conditioning in homes is expected to rise – especially as summer temperatures rise as a result of climate change. Globally, energy use for air conditioning is expected to rise faster than energy use for heating.[23]

What can we learn from the HES data about energy use by air conditioning equipment? There were just two air-conditioning units monitored in the HES dataset, one monitored in June/July and the other in August/September. Both operate in a single room of the house – there were no whole-house air conditioning systems. This limits the analysis we can do and how much we can generalise from the HES sample. The Departments asked us to correlate energy use by these appliances with the outside temperature.

Approach

The survey included temperature measurements both inside each home (up to four profiles for room temperatures) and outside. First we identified which of the internal temperature profiles corresponded to the room in which the unit was located. Then we compared the room temperature with the external temperature, and calculated a running mean of the external temperature with the room to allow for the thermal mass of the house. We also computed internal gains in the room from other appliances. Finally, we used linear regression to relate these parameters with the air conditioning power use.

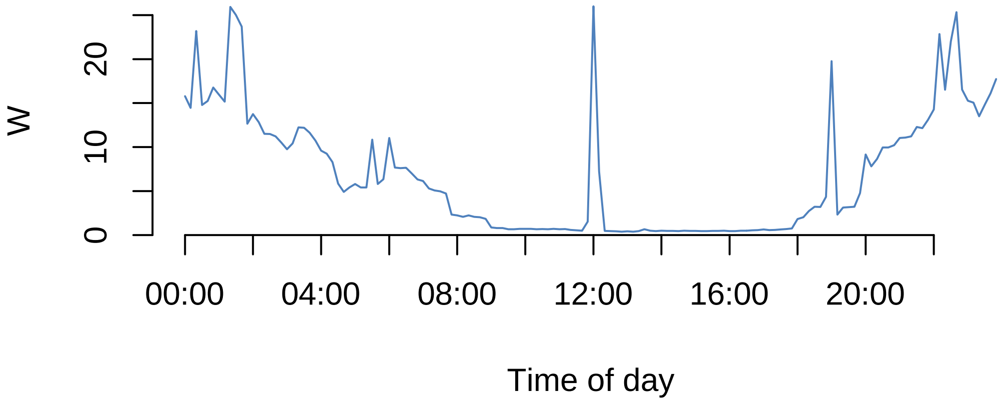
One of the systems we examined was coded in the survey as a 'fan' (the one called 'Study' below). We inferred it was probably an air conditioning unit by its high energy consumption, and this was confirmed in an interview with the householder.

Room	Monitoring period	Daily kWh	Household	Use
Bedroom	Aug/Sep	0.16	Single non-pensioner, mid-terrace house, social grade C2	Mainly overnight. Low power mode 50W, high power up to 1 kW
Study	Jun/Jul	5.57	Two persons, no children, detached house, social grade A	On 24x7, peak energy use in afternoon and evening. Low power mode cycles 30-70 W. High power mode up to 2.5 kW.

[22] Steemers, K. (undated) Human behaviour and energy use in buildings (presentation). Cambridge: Cambridge University Department of Architecture.

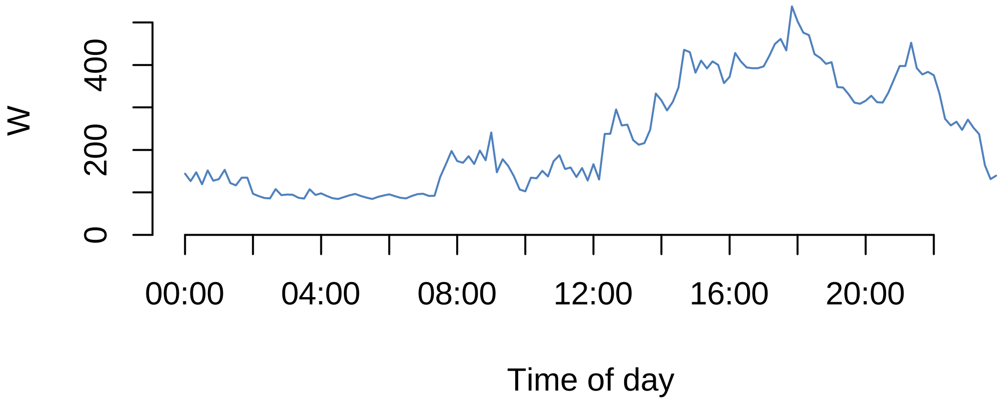
[23] Isaac, M., van Vuuren D. (2009) Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37(2) 507-521.

Bedroom air conditioning unit, average daily use



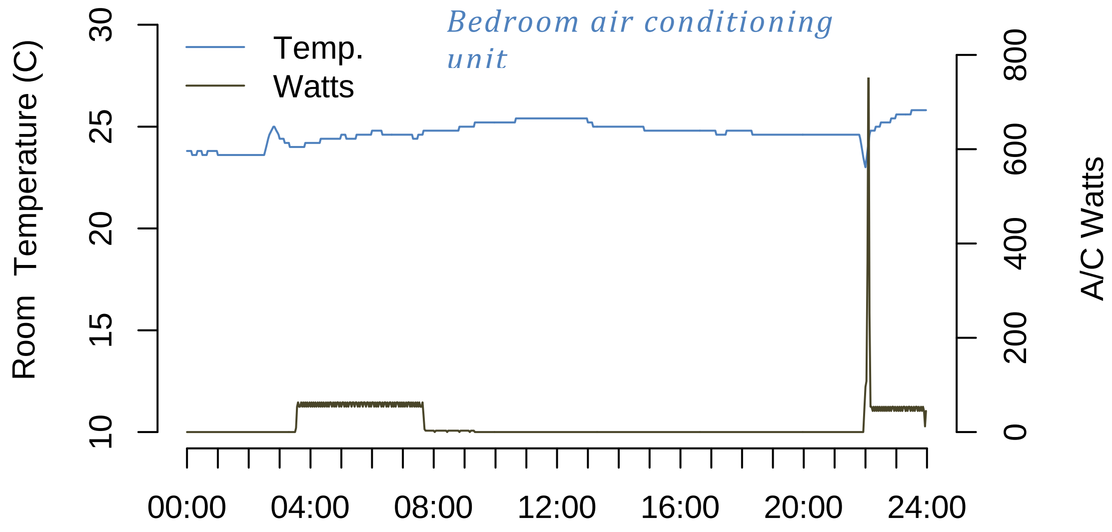
The spike at noon relates to a single day during the monitoring period when the a/c was turned on briefly and used 1 kW.

Study a/c unit, average daily use

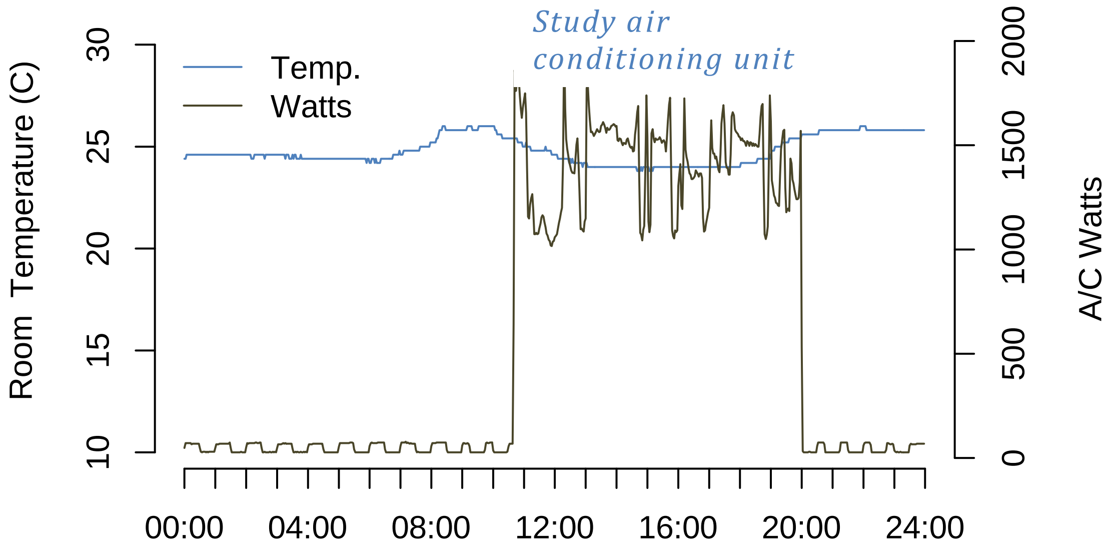


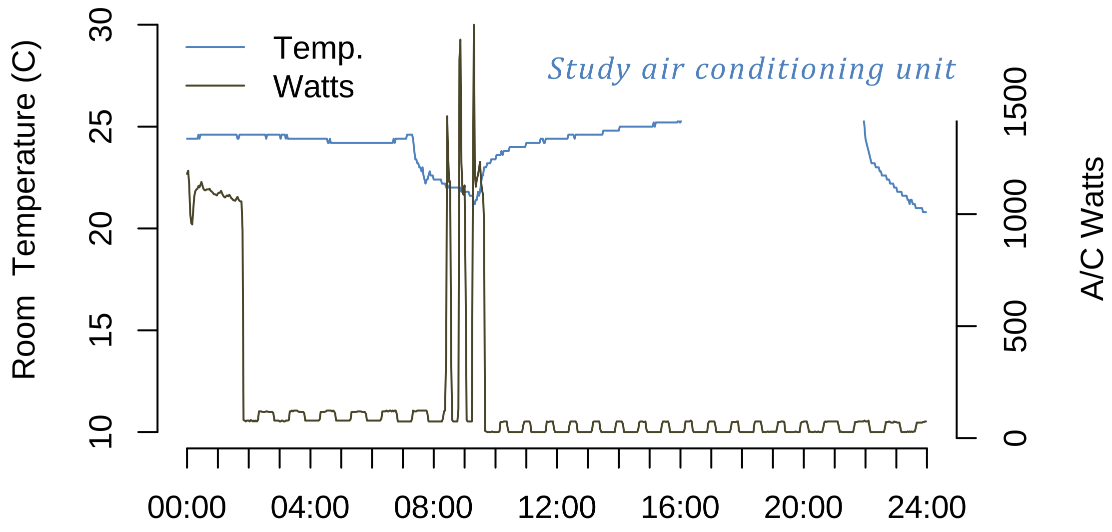
Analysis

For the bedroom unit it was clear which room temperature profile was associated with the air conditioning because there was a distinct drop in temperature when the air conditioning spiked in power use (although there seemed to be some inconsistency between the two profile clocks, since the temperature drop occurred just before the a/c unit activated). Below is a typical profile, showing the power being consumed by the a/c unit and the bedroom temperature at the time, over a day.



For the study unit, we identified a profile that often showed a drop in temperature seemingly associated with the air conditioning, as shown in the sample profiles below.





There appears to be a mis-alignment in the data in that the temperature decreases before the air conditioning comes on. However this is probably due to skewed clocks. We have seen this in other profiles in the data, where the profile of a distribution circuit includes monitored appliances and has corresponding spikes, but with a time slip.

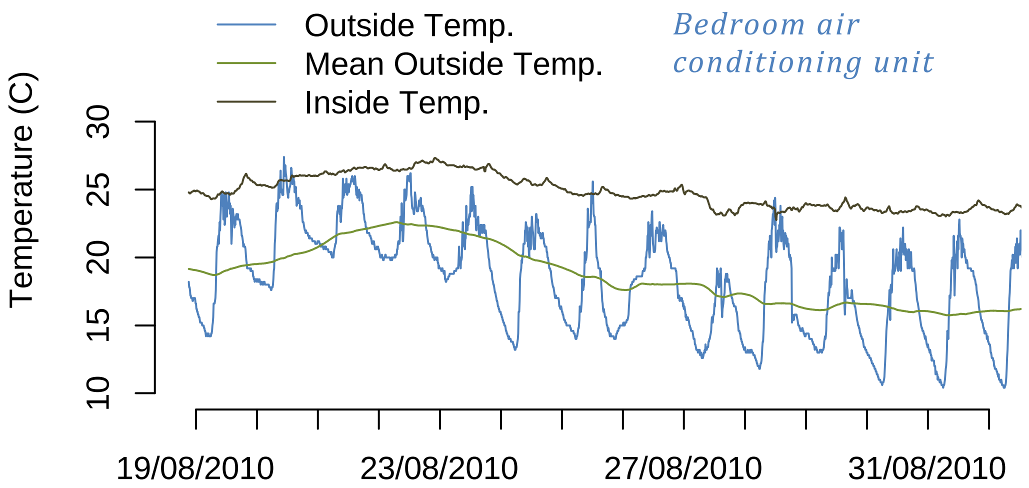
We determined that both air conditioners run in two modes, illustrated in the charts above.

- High power mode: for the bedroom unit this is up to 1 kW and typically only lasts a few minutes, whereas the study unit this spikes up to 2.5 kW but often continues at 1-1.5 kW for an hour or longer.
- Low power mode, averaging around 50 – 70W: for the study unit the power cycles between 30 and 70 W. We believe this is a fan-only mode with no cooling effect.

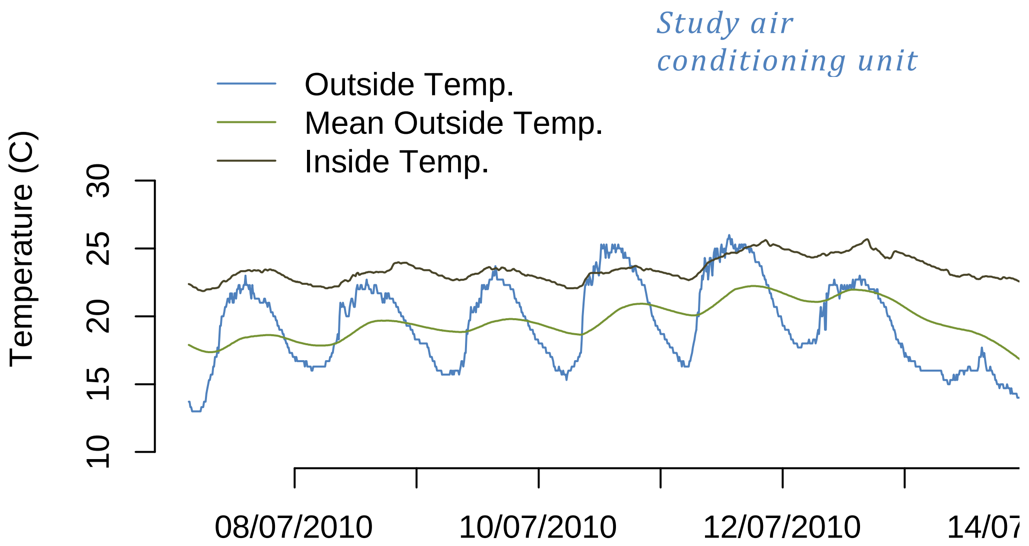
These charts suggest there is only a weak relationship between a/c power use and room temperature. In the bedroom chart above, the a/c unit comes on at about 11pm but then shuts down to low power mode for the rest of the night, even though the room temperature rises slightly. This may be due to discretionary use of the unit – the resident may turn off the a/c mode to reduce noise or to save energy. Similarly, the study unit in the second chart shows no high power a/c activity through the hot afternoon.

Internal temperatures vary much less than external temperatures in most homes due to insulation and the thermal mass of the building – when the weather outside is hot, the walls absorb heat, while when the weather is cooler, the walls give up heat. This means the internal temperature varies slowly and depends on the external temperature averaged over a time window of some hours. We took the average of the other three internal temperature profiles to represent 'base' internal temperature (without a/c) and compared this with the mean external temperature. We optimised the length of this averaging window to get the best correlation between internal and mean external temperatures. For the bedroom case, the window was approximately 48 hours, and for the study case 30 hours. The resulting profiles are shown in the charts below.

It is also noticeable in both cases that the internal temperature is much greater than the mean external temperature. The difference was 6.0°C in the bedroom case, and 4.2°C in the case of the study. We compared average summertime internal and external temperatures for all the houses (removing two outlying cases with implausibly low external temperature) and found the average difference was 4.1°C. There were only 8 out of 82 homes where the internal temperature was 6°C or more warmer than outside. This suggests the bedroom a/c unit is in an unusually warm home.

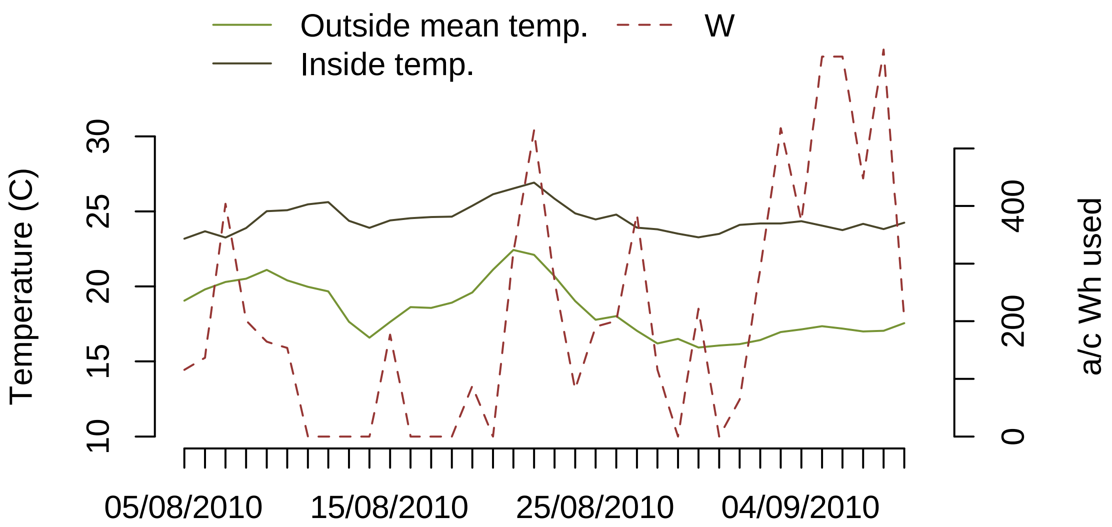


Internal and external temperatures compared with the running mean over 48 hours for the home with a/c in the bedroom.

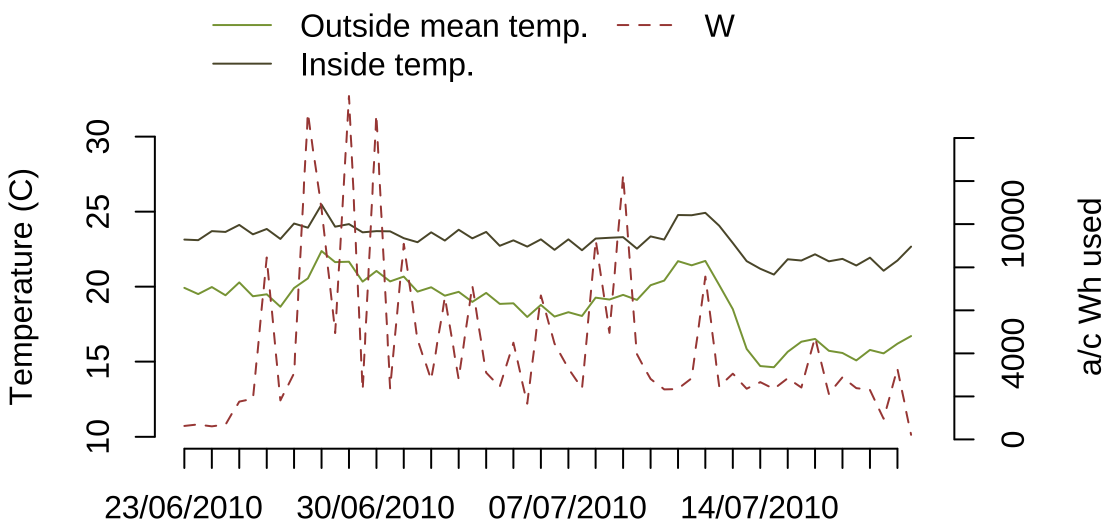


Internal and external temperatures compared with the running mean over 30 hours for the home with a/c in the study.

Finally we compared the running mean external temperature with a/c energy use for both cases. We averaged the mean external temperature and power use over 12 hour intervals. For the bedroom we used only the night time intervals, between 9pm and 9 am, because the a/c unit was usually off during the day. There was little correlation between the a/c power use and the mean outside temperature in either case.



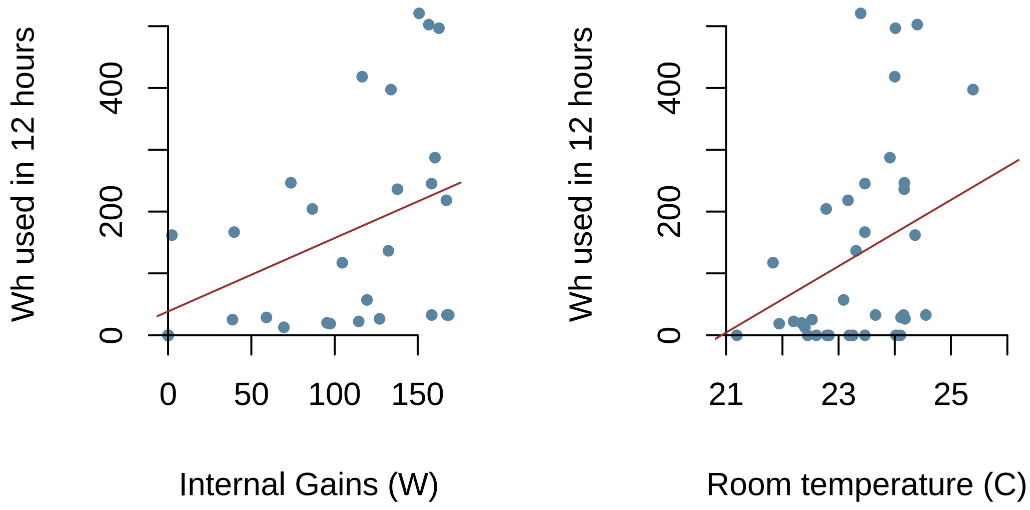
Bedroom a/c
Energy use with temperature (9pm to 9am only)



Study a/c
Energy use with temperature over 12 hour intervals

For the bedroom, linear regression between the mean outside temperature and power use (over the 12-hour intervals) confirmed that a/c use was hardly related to external temperature (R^2=0.005). We also tried regression of power use with internal temperature (R^2=0.001), with the room temperature where the a/c unit was located (R^2=0.2), and with internal gains from other appliances in that room (R^2=0.3). However, the best explanation of the a/c power use we determined was a combination of internal gains from other power use in the room and room temperature ($R^{2=}$0.37).

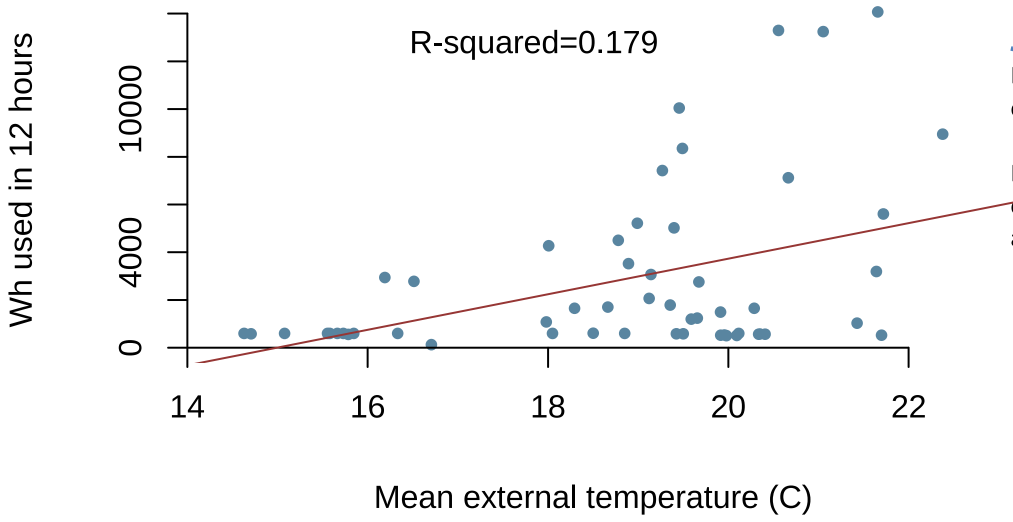
Bedroom a/c energy use with room temperature and internal gains



The only other appliance in the bedroom for which we had information was a set top box, which was often turned off. It is very likely there was also a TV that was not monitored, and when the set top box was on the TV was too, and the residents were awake. It is not possible to say whether they were watching TV (and turned the a/c on) because they could not sleep or if the room was warm because of the TV and so the a/c used more power. In any case, the a/c use was more closely related to internal gains (and hence the occupant's behaviour) than to the external environment.

For the study with an air conditioning unit, linear regression of a/c use against mean external temperature did show a significant relationship, although there was a lot of other variation (R^2=0.18, $p < 0.001$[24]). Internal gains (from a computer, monitor, laptop and TV) were insignificant.

[24] The p-value for linear regression gives the probability that there is no relationship, i.e. the slope of the fitted line is 0.



Study a/c

Energy use with external temperature.

Each 1°C increase in outdoor temperature adds 1.5 kWh/day.

In summary, of the two cases the bedroom a/c unit proved to be low power and little used, with energy use related more to occupant behaviour than to the weather. The home it was installed in was also unusually warm. However, the unit in the study was on most of the time and used much more power, more closely related to external temperature, though still with a great deal of unexplained variation. If domestic a/c becomes more common and this unit is typical then summertime electricity use could increase greatly, in particular during the afternoon/evening peak period (when this unit used an average 0.5 kW).

Other Evidence on Air Conditioning

Monitoring work examining 13 homes with air conditioning in southeast England[25] found that most users turned on their air conditioning equipment at temperatures of 24 or 25°C. Typical running times were five hours in the daytime and seven hours in bedrooms at night. The monitoring identified power consumption of around 700W for a portable cooling system when it was functioning, and around 255W for a single split system with inverter control when running.

Modelling carried out for the 40% House project[26] estimated that climate change could result in 29-42% of homes in the south of England having air conditioning by 2050. Further, the urban heat island effect for London has increased significantly since the 1950s, and is expected to continue to increase into the future, exacerbating the temperature rises already predicted with climate change and further increasing the demand for cooling.[27]

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[25] Pathan, A., Youg, A., Oreszczyn, T. (2008) UK domestic air conditioning: a study of occupant use and energy efficiency. Proceedings of the Air Conditioning and Low Carbon Cooling Challenge Conference, Windsor, 27-29 July 2008.

[26] Boardman, Brenda, et al. (2005) 40% House. Oxford: ECI.

[27] Wilby, RL. (2007) A Review of Climate Change Impacts on the Built Environment. Built Environment 33 (1) 31-45.

Recommendations

■ For the two cases in the sample with air conditioning, energy use for air conditioning was only very loosely correlated to external temperature. How people choose to use air conditioning (and other appliances) seemed to be more significant. This means it is hard to predict with any confidence how electricity use for air conditioning might change over time.

■ Although the findings from the HES homes' use of air conditioning are broadly consistent with other work, more evidence from a larger sample of homes with cooling equipment is needed. Two households with air conditioning does not permit any meaningful generalising to the whole population of households.

Actual electricity use of major appliances

The energy use of many appliances varies according to how they are used. Dishwashers and washing machines, for example, use different amounts of energy according to the temperature setting – as well as the obvious variations according to how often they are used. Manufacturers publish estimates of actual electricity use for many appliances, based on lab experiments and simple assumptions about how (and how often) they will be used.

The HES offers the chance to examine actual energy use of appliances in real life. The Departments wish to calculate the in-situ energy use of each major appliance in the HES as a function of age and energy labelling category. They also wish to compare actual use with the manufacturers' stated electrical usage.

Approach

When the HES started there was an appliance survey in each of the 250 homes that recorded, for each appliance within each home, the type of appliance, the rated energy consumption (if visible on the appliance), the year it was purchased (as reported by the householder, if known) and the energy label rating (if visible on the appliance). Rated energy consumption is the manufacturers' stated energy consumption for the appliance under standard test conditions. In some cases the energy label and rated energy consumption information were sourced at a later stage, during the initial processing of the collected data. (Rated energy use for cycles were not recorded for different settings.)

The energy consumption of each appliance was recorded using sensors at 2- or 10-minute intervals, for periods of one month up to a whole year. For appliances that were recorded for less than a year, the measurements were scaled up to a 12-month period using seasonal adjustment factors, as described in the previous 'Part 2' report[28]. This resulted in 'measured' annual energy consumption values (in kWh/year) for each appliance.

This analysis focuses on the major appliances whose rated energy consumption, year purchased and Energy Label rating were recorded in the appliance survey. This includes six major appliance types: dishwashers, washing machines, tumble dryers, refrigerators, freezers and fridge-freezers.

[28] Palmer J. et al. (2013) Further Analysis of the Household Electricity Use Survey, Part 2: Focus on appliances. London: DECC.

Here the analysis studies the relationships between:

1. *measured annual energy consumption* (in kWh/year, calculated from the electricity readings)

2. rated annual energy consumption (in kWh/year, calculated from the rated energy consumption information recorded in the appliance survey)

3. *measured 'per cycle' energy consumption* (in kWh/cycle, for dishwashers, washing machines and tumble dryers as calculated from the electricity readings)

4. rated 'per cycle' energy consumption (in kWh/cycle, for dishwashers, washing machines and tumble dryers as recorded in the appliance survey)

5. *year purchased* (e.g. '2010', '2011' etc., as reported by the householder and recorded in the appliance survey), and

6. *Energy Label rating* (e.g. 'A++', 'A+', 'A' etc., as recorded in the appliance survey).

Only appliances with non-zero measured annual energy consumption are considered for analysis. The largest sample size is for washing machines (n=203) and the lowest is for tumble dryers (n=95). Many appliances did not record all parameters, so the sample size falls when we analyse multiple parameters together, see table below.

Number of appliances for each appliance type and variable combination studied in this analysis

	Number of appliances in HES sample with measured energy consumption			
Appliance type	Record of energy use	Energy use AND rated energy consumption	Energy use AND year purchased	Energy use AND Energy Label rating
Dishwasher	107	48	89	47
Washing machine	203	125	183	134
Tumble dryer	95	32	84	55
Refrigerator	105	41	87	43
Freezer	115	33	97	41
Fridge-freezer	149	75	125	76

The rated energy consumption was recorded on a 'per cycle' basis for dishwashers, washing machines and tumble dryers, and an 'annual' basis for fridges, freezers and fridge-freezers. The rated energy consumptions are stated by manufacturers, estimated from measurements under standard test conditions as specified by EU Energy Label regulations[29,30,31,32].

[29] COMMISSION REGULATION (EU) No 1016/2010, 10 November 2010, Ecodesign requirements for household dishwashers.

[30] COMMISSION DELEGATED REGULATION (EU) No 1061/2010, 28 September 2010, Energy labelling of household washing machines.

[31] COMMISSION DELEGATED REGULATION (EU) No 392/2012, 1 March 2012, Energy labelling of household tumble driers.

[32] COMMISSION DELEGATED REGULATION (EU) No 1060/2010, 28 September 2010, Energy labelling of household refrigerating appliances.

To compare with the measured annual energy consumption, the 'per cycle' rated energy consumption figures need to be scaled up to annual totals. This is done based on the methodology as laid out in EU Energy Label legislation. In each case the 'per cycle' rated energy consumption E_t is multiplied by an assumed number of cycles per year. The additional 'f' term in each equation is assumed to be zero, as the rated standby power was not reported and, as it is likely to be small, was assumed to have only a minimal effect on the annual totals[33].

To compare rated and measured 'per cycle' energy consumptions, we estimated the measured 'per cycle' energy consumption from the 2-minute electricity measurements using simple heuristics to determine when a cycle starts and stops. Individual cycle energy consumption was calculated as the energy consumption occurring between the identified start and stop times. This automated method of spotting cycles was largely successful, although there are occasional instances of long pauses during cycles, or two cycles running in quick succession, which made cycle identification more challenging.

Rated energy consumption as recorded in the appliance survey

Appliance type	Variable name in the appliance survey data	Description (from EU Energy Label regulations)
Dishwasher	'Dishwasher_Energy_consumption_kWh'	Energy consumption per cycle (kWh/cycle) for a 'standard cycle' defined as 'the standard cleaning cycle … that it is suitable to clean normally soiled tableware and that it is the most efficient programme in terms of its combined energy and water consumption for that type of tableware'
Washing machine	'Washing_machine_per_cycle_kWh'	Energy consumption per cycle (kWh/cycle) for a 'standard cycle' defined as 'the standard 60°C cotton programme at full load'[34]
Tumble dryer	'Tumble_drier_consumption_kWh'	Energy consumption per cycle (kWh/cycle) for a 'standard cycle' defined as 'the standard cotton programme at full load'
Fridge, Freezer, Fridge-freezer	'Refrigeration_Annual_consumption_kWh'	Energy consumption per year (kWh/year) based on 'standard test results for 24 hours'

[33] In the previous report 'Further Analysis of the Household Electricity Use Survey, Early Findings: Demand side Management' washing machines were shown to have a standby power of around 1 W. This would add around 9 kWh/year to the annual energy consumption.

[34] Up to 2010, the EU Label 'standard cycle' for washing machines was 'the standard 60°C cotton programme at full load' and we assume it is the energy consumption of this cycle that was recorded during the HES survey phase.

Rated annual energy use calculation used here for dishwashers, washing machines and tumble dryers

Appliance type	Equation used to calculate rated annual energy consumption	Description
Dishwasher	$AE_C = E_t \times 280 + f$	AE_C is the annual energy consumption (kWh/year) E_t is the energy consumption for the standard cycle (kWh/cycle) There are 280 cycles per year (as per EU Energy Label assumptions) f is an additional term based on the standby power of the appliance
Washing machine	$AE_C = E_t \times 220 + f$	AE_C is the annual energy consumption (kWh/year) E_t is the energy consumption for the standard cycle (kWh/cycle)[35] There are 220 cycles per year (as per EU Energy Label assumptions) f is an additional term based on the standby power of the appliance
Tumble dryer	$AE_C = E_t \times 160 + f$	AE_C is the annual energy consumption (kWh/year) E E_t is the energy consumption of the standard cycle (kWh/cycle)[36] There are 160 cycles per year (as per EU Energy Label assumptions) f is an additional term based on the standby power of the appliance

Findings

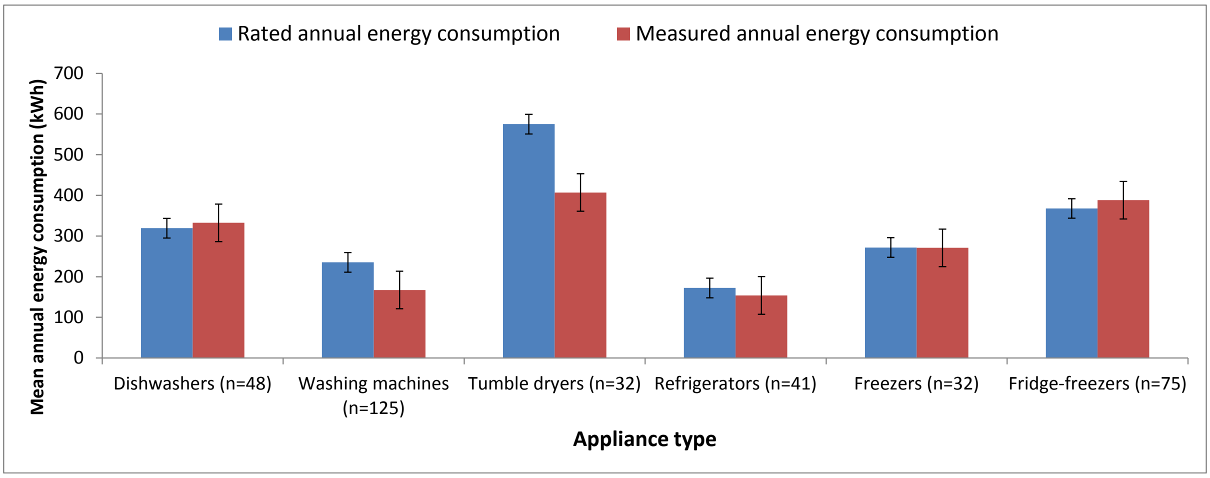
We start this section by comparing rated energy use and measured energy use for appliance types, then we focus on individual appliances, then we consider rated energy use per cycle against the measured electricity. Finally, we turn to the year of purchase, and comparisons against energy label estimates of energy use.

Rated energy use vs. measured use

We calculated mean rated and mean measured annual energy consumption of each appliance type. For example, we take the mean of the 48 dishwashers with its own rated annual energy consumption. We also calculated the 95% confidence interval for the mean, which represents the range expected for the mean value, for 95% of the time, if the survey was carried out again and the population was re-sampled. The 95% confidence interval is a function of the number of appliances in the sample and the standard deviation of the mean values in each sample.

[35] In the current EU Energy Label regulations E_t is calculated for washing machines as a weighted average of three different programme cycles: the standard 60°C cotton programme at full load, the standard 60°C cotton programme at partial load and the standard 40°C cotton programme at partial load. Only the standard 60°C cotton programme at full load was recorded in the HES survey and is used in the calculation here. This is likely to result in rated annual energy consumptions higher than expected by using the current EU Energy Label method.

[36] In the current EU Energy Label regulations E_t is calculated for tumble dryers as a weighted average of two different programme cycles: the standard cotton programme at full load, and the standard cotton programme at partial load. Only the standard cotton programme at full load was recorded in the HES survey and is used in the calculation here. This is likely to result in rated annual energy consumptions higher than expected by using the current EU Energy Label method.



Comparison of rated and measured annual energy consumption of the six major appliance types – columns show the overall mean value and error bars indicate the 95% confidence interval range of the mean. [Base: All appliances with both measured energy use and manufacturers' rated energy consumption.]

For dishwashers, refrigerators, freezers and fridge-freezers the mean rated annual energy use (319, 172, 272 and 368 kWh/year, respectively) is closely matched to the mean measured annual energy use (332, 154, 271 and 388 kWh/year). This suggests that, overall, these appliances, in homes, are operating as expected based on the manufacturers' stated performance and EU Energy Label annual consumption calculations. The 95% confidence interval ranges suggest that there is no significant difference between rated and measured annual energy consumption for these appliances.

However, for washing machines and tumble dryers, the mean measured annual energy consumption (167 and 407 kWh/year) is *lower* than the mean rated annual energy consumption (235 and 575 kWh/year, respectively). This suggests that, overall, these appliances are using *less* energy consumption than expected, based on manufacturers' stated performance and the annual energy calculation method used in this analysis. This could be because lower energy washing programmes are being used (for example, a 40°C wash rather than a 60°C wash) and/or because there are fewer washing cycles per year in study homes than the assumed values (220 cycles per year for washing machines and 160 for tumble dryers).

Care is needed in interpreting the washing machine and tumble dryer results, as the rated annual energy consumptions are based on the single rated 'per cycle' energy consumption value, which is likely to be higher than the weighted 'per-cycle' value as used in EU Energy Label calculations (as discussed in the footnotes on the previous page). This may mean the rated annual energy consumptions given here are higher than calculated using the EU Energy Label method.

Individual appliances

We also compared the rated energy consumption and measured energy consumption values for each individual appliance directly. We plotted rated versus measured annual energy consumption on a scatter plot for each appliance type.

In contrast to the overall mean results, on an appliance-by-appliance basis there is great variation between the rated annual energy consumption and the measured annual energy consumption. This is to be expected as the rated annual energy consumptions are based on test results (and assumed number of cycles per year for dishwashers, washing machines and tumble dryers), whereas the measured annual energy consumptions are based on how appliances are actually used in the home.

For dishwashers, washing machines and tumble dryers, measured energy consumption varies based on several factors including:

- the number of times the appliance is used by the occupants
- the variety of programmes used (i.e. high temperature vs. low temperature programmes, short vs. long cycle times)
- the amount of dishes or clothes washed/dried in each cycle (higher loads increases energy consumption), and
- any faults leading to higher or lower energy consumption.

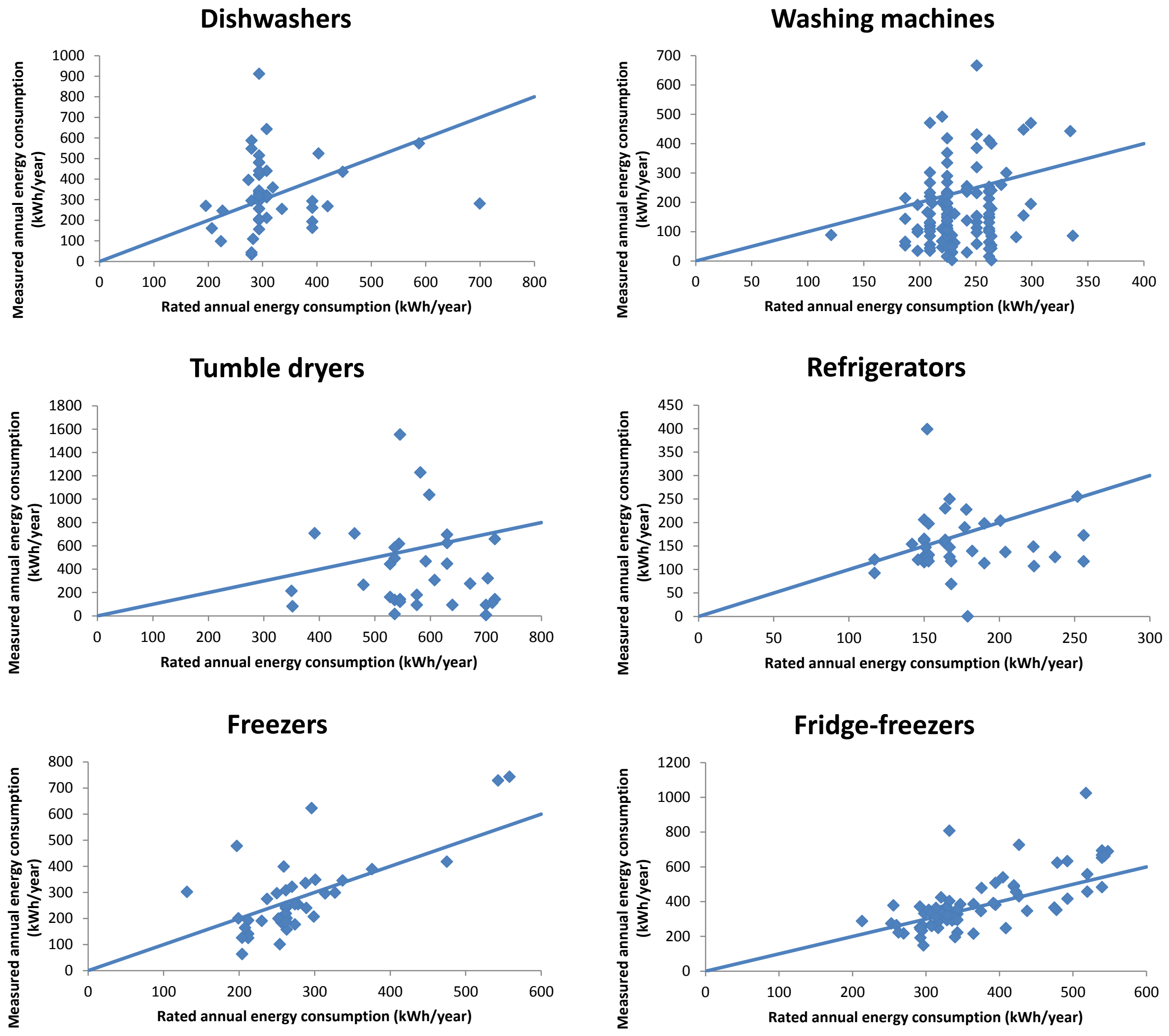
The dominant factor is likely to be the number of cycles per year. Low measured energy consumption may reflect appliances that are rarely used, whereas high measured annual energy consumptions are likely to reflect high usage.

For refrigerators, freezers and fridge-freezers the measured annual energy consumption varies based on several factors including:

- the duration of use of the appliance (the amount of time it is plugged in)
- the frequency of door opening (which increases the cooling load)
- the throughput of food put in and taken out of the appliance (which needs to be cooled)
- the external air temperature (higher external temperatures increases the cooling load), and
- any faults leading to higher or lower energy consumption[37].

A low measured annual energy consumption might be caused by an appliance only being plugged in for a short interval (such as a freezer used over the Christmas period only), while a high measured energy consumption might be caused by a faulty appliance (for example, faulty controls, leading to the compressor running continuously).

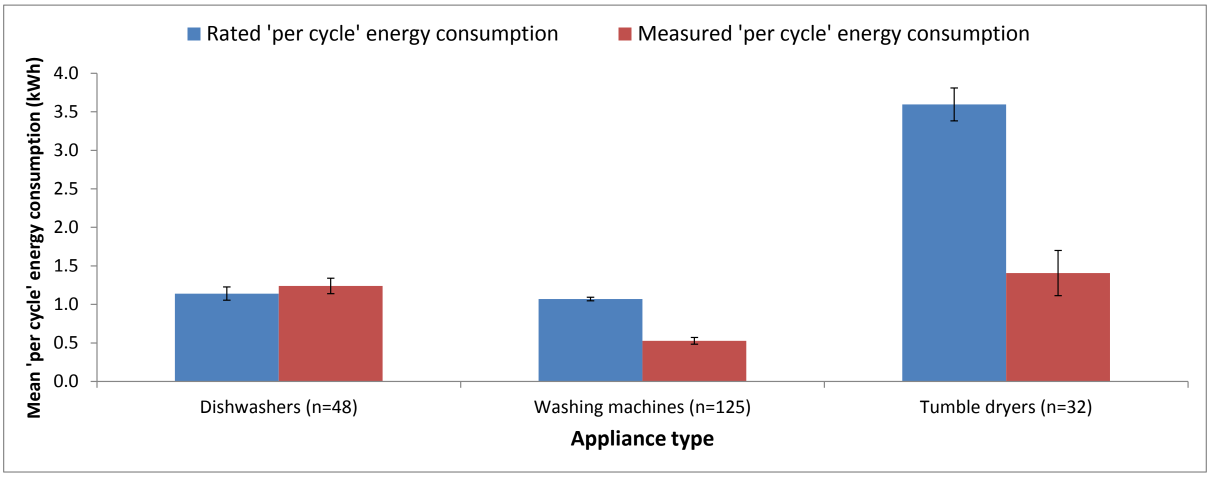
[37] Further evidence on the wide variation in refrigerator actual energy consumption can be found in this reference: ‘Are test procedures passing the test? Ensuring that measured results are representative of energy use in the field’ Proceedings of the 7th Energy Efficiency in Domestic Appliances and Lighting conference, 2013, Portugal.



Comparison of rated energy consumption (x-axis) and measured energy consumption (y-axis) for six major appliance types – each dot shows a single appliance. The blue lines show the 'line of parity': when rated=measured energy use. Note that these graphs show measured consumption on the y-axis, whereas those in the modelling section from p18 show this on the x-axis. [Base: All appliances with both measured energy use and manufacturers' rated energy consumption values.]

Rated vs. measured 'per cycle' energy use

We calculated mean values for the rated and measured 'per-cycle' energy consumption of dishwashers, washing machines and tumble dryers. For example, we recorded the rated 'per cycle' energy consumption for each of the 48 dishwashers, and worked out the mean value for all 48 dishwashers, see chart below. We also calculated the 95% confidence interval range of the mean.



Comparison of rated and measured 'per cycle' energy consumption of dishwashers, washing machines and tumble dryers – bars show overall mean value and error bars indicate the 95% confidence interval range. [Base: All appliances with both measured energy use and manufacturers' rated energy consumption values.]

For dishwashers the mean rated 'per cycle' energy consumption (1.14 kWh/cycle) is similar to the mean measured 'per cycle' energy consumption (1.22 kWh/cycle), and the 95% confidence interval ranges suggest that the difference observed is not significant. This suggests that, on average, these appliances are operating, in homes, as would be expected from manufacturers' stated performance values. The standard cycle used in the rated 'per cycle' energy consumption values is the 'most efficient' programme, often called the 'ECO' programme. The EU Energy Label is based solely on this standard cycle, and dishwashers are designed with the energy consumption of this cycle in mind. However, it appears that using other programmes (such as 'normal', 'intensive', 'quick', etc) results in a mean 'per cycle' energy consumption that is similar to the 'ECO' cycle.

For washing machines and tumble dryers, the mean rated 'per cycle' energy use (1.07 and 3.60 kWh/year respectively) is higher than the mean measured annual energy consumption (0.54 and 1.41 kWh/year). This suggests that household occupants are using other, less energy consuming programmes than the standard cycle recorded in the appliance survey. The standard cycle for washing machines is defined as 'the standard 60°C cotton programme at full load' and for tumble dryers as 'the standard cotton programme at full load'. The lower measured 'per cycle' energy consumption values observed here are likely due to lower temperature washes and less than full load programmes being used by household occupants. (Indeed, our analysis of the HES diary data reported in the Part 2 report[38] found that most washes were at 40°C or less.)

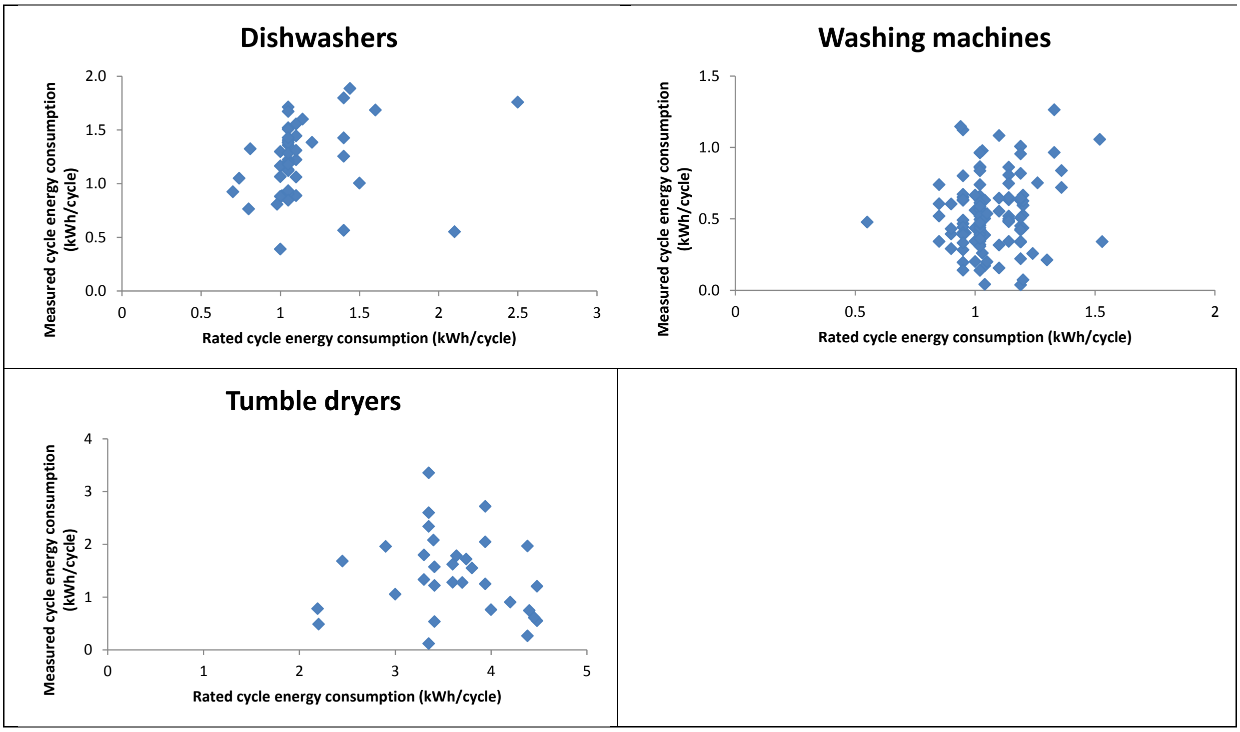
We also compared the rated cycle energy use and mean measured cycle energy use, for each individual appliance directly, for dishwashers, washing machines and tumble dryers. We plotted rated versus measured cycle energy consumption on a scatter plot for each appliance type. For each individual appliance the mean measured cycle energy consumption was calculated as the mean of the total energy consumption for each individual cycle

[38] Palmer J, et al (2013) Electrical Appliances at Home: Tuning in to energy saving. London: DECC/DEFRA.

throughout the monitoring period. For example, if a dishwasher was used 40 times in a monitoring period, then we calculated the energy consumption of each of the 40 cycles and used the mean of these 40 energy consumption values.

Similar to the results for rated and measured annual energy consumptions for individual appliances given above, there is a wide variation at the individual appliance level between the rated cycle energy consumptions and the mean of the measured cycle energy consumptions. The reasons for this are similar to the reasons given for the variation observed for the annual results (except the number of times the appliance is used by the occupants is no longer a factor for this 'per cycle' analysis). These include:

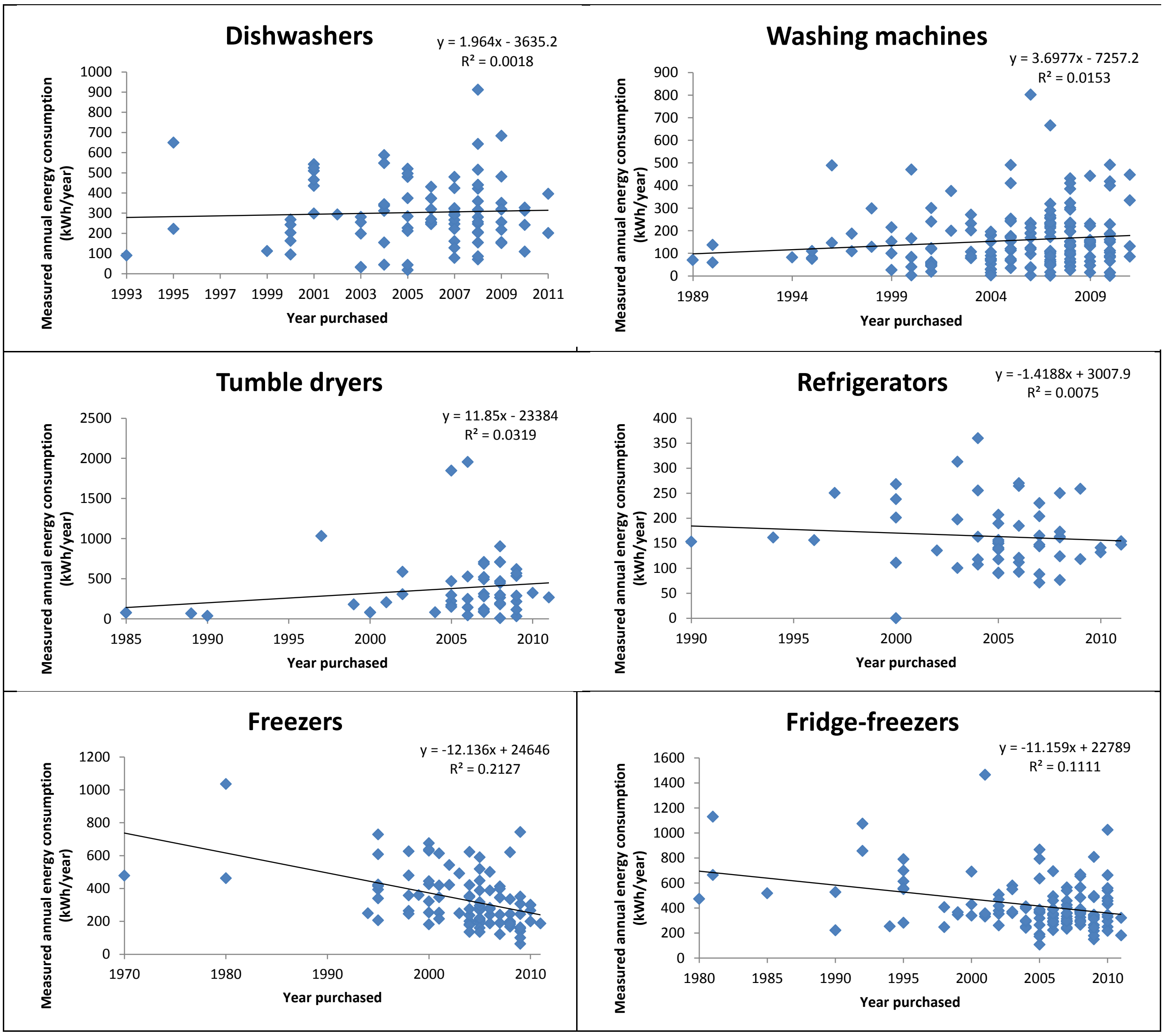
- the variety of programmes used (i.e. high temperature vs. low temperature programmes, short vs. long cycle times)
- the amount of dishes or clothes washed or dried in each cycle (higher loads increase energy consumption), and
- any faults leading to higher or lower energy consumption.



Comparison of rated cycle energy consumption (x-axis) and measured cycle energy consumption (y-axis) for dishwasher, washing machines and tumble dryers – each dot shows the mean cycle energy for a single appliance. [Base: All appliances with both measured energy use and manufacturers' rated energy consumption values.]

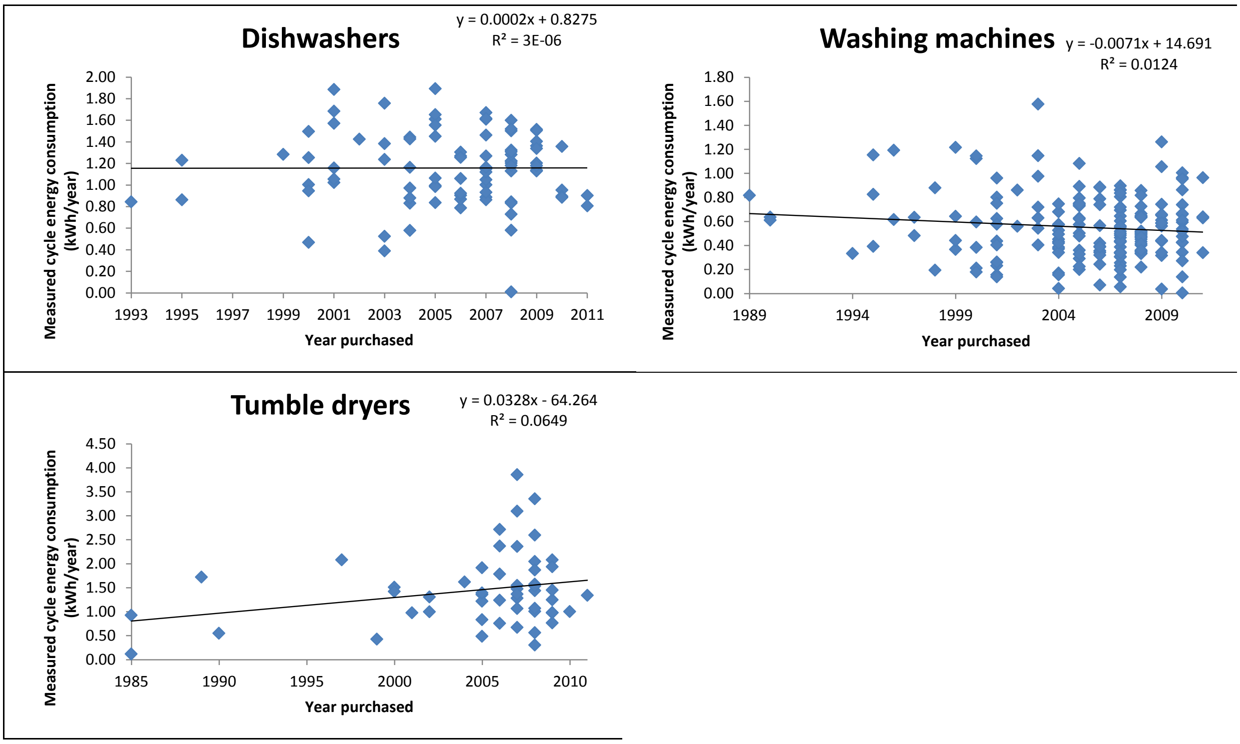
Year purchased vs. measured energy use

We compared the year each appliance was purchased against measured annual energy consumption to see whether the energy consumption of appliances is changing over time. We plotted year purchased vs. measured annual energy consumption on a scatter plot for each appliance type, see charts below.



Comparison of year purchased (x-axis) and measured annual energy use (y-axis) of the six major appliance types – each dot shows a single appliance. A linear regression line is shown for all data points, with the regression equation and R^2 value given. [R^2 is an index of correlation, with zero indicating no correlation, and 1 indicating perfect correlation. Base: All appliances with measured energy use and year of purchase.]

We also compared the year each appliance was purchased against mean measured cycle energy consumption values, for each individual appliance directly, for dishwashers, washing machines and tumble dryers, see charts below.



Comparison of year purchased (x-axis) and mean measured cycle energy use (y-axis) for dishwashers, washing machines and tumble dyers – each dot shows a single appliance. A linear regression line is shown for all data points, with the regression equation and R^2 value given. [Base: All appliances with measured energy use and year of purchase.]

For dishwashers, washing machines and tumble dryers the linear regression lines show that the measured annual energy consumption tends to increase with year purchased. The overall energy consumption of these appliances has increased somewhat over time, on average, although many appliances do not follow this general trend. Further, the comparison with measured cycle energy use shows that only the 'per cycle' energy consumption of tumble dryers has increased with year purchased. This may suggest that more recently purchased tumble dryers have higher 'per cycle' energy consumption when used in the home than older appliances. The energy efficiency and Energy Labels of more recently purchased tumble dryers are likely to be better than older appliances, so it might be expected that 'per cycle' energy consumption would be lower. However a number of factors may contribute to increased energy use, including:

- increased size of recent appliances, so the improved Energy Label does not necessarily result in a decrease in actual consumption
- homes with recently purchased appliances may be choosing more energy-consuming programme cycles, such as high temperature or intensive programmes.

Across the EU the average energy consumption of new washing machines has tended to increase over recent years, as manufacturers have developed larger machines. The effect of this increased size is not observed in EU Energy Label ratings because the calculation normalises for the capacity or size of the machine.[39]

For refrigerators, freezers and fridge-freezers the linear regression lines suggest that the measured annual energy consumption decreases with year purchased. This would mean that more recently purchased appliances tend to have lower energy consumption when used in the home than older appliances. This result matches findings from across the EU, where the average energy consumption of new cold appliances has steadily decreased over recent years.[40] This is consistent with the improvement over time of energy labelled cold appliances.

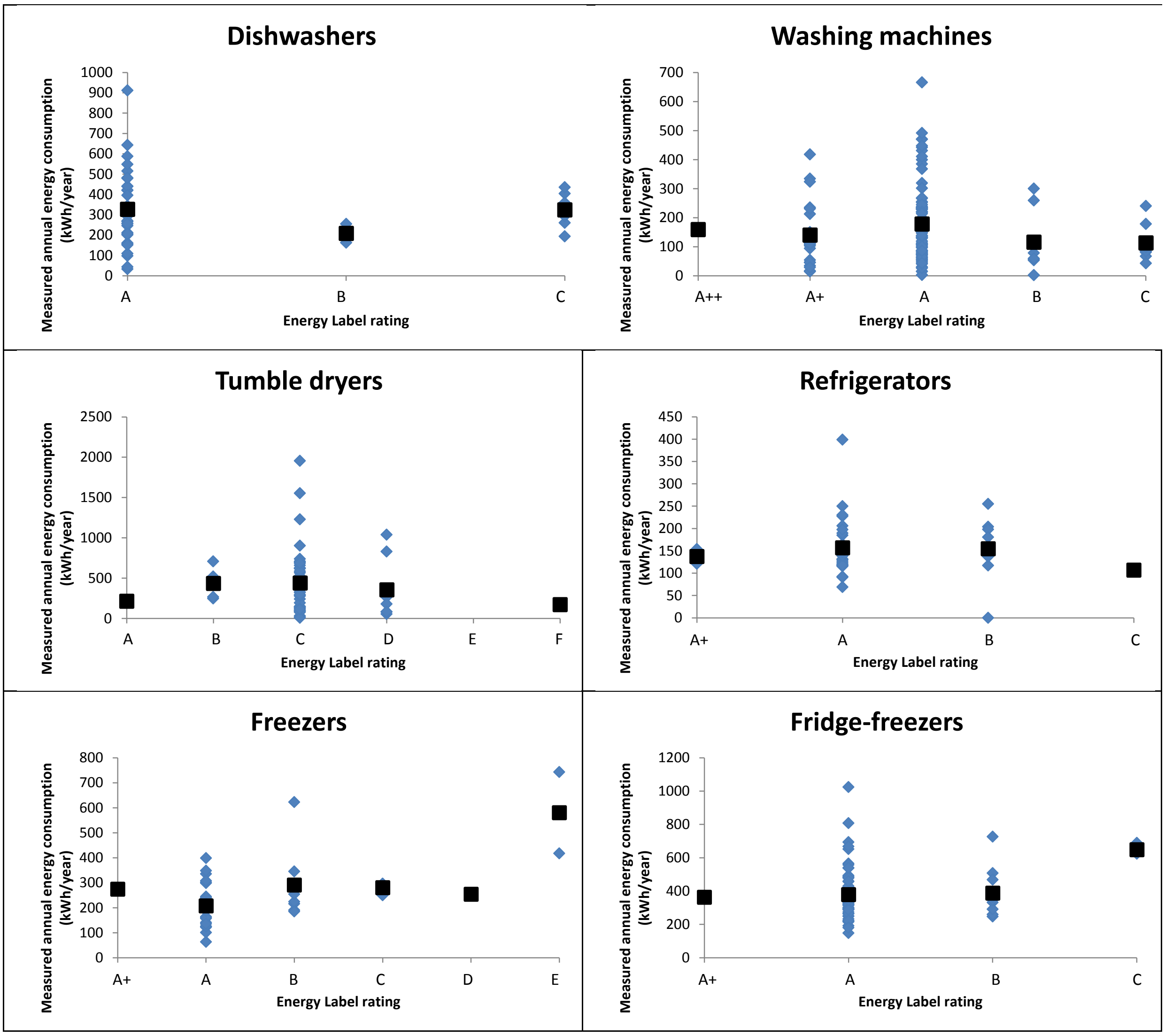
Energy Label rating vs. measured energy use

We also compared measured energy consumption against the Energy Label rating for each appliance type, both means and individual appliance values. This gave an indication of the range of measured energy consumption values within a given Energy Label rating, and allowed us to compare across Energy Label ratings for a given appliance type.

For all appliances, we found no clearly discernible trends between measured energy consumption and Energy Label rating. We expected that measured annual energy consumption would be lower among the better Energy Label ratings (A++, A+ and A) but this was not true. One explanation for this is that Energy Label rating is only one factor affecting measured annual energy consumption. Other factors, including the amount of use of the appliance and the appliance size, may increase measured annual energy consumption values. (Our previous work[41] also found a strong trend of increasing appliance size for cold appliances, and a weaker trend towards larger appliances for other types of equipment.)

Another possible explanation is the small sample size that occurs in many of the Energy Label rating categories. It is difficult to draw conclusions about the differences across Energy Label rating categories when some categories contain only a few measured energy consumption values, and therefore may not be representative of typical consumption of an appliance in that category.

[39] Bertoldi et al., Energy Efficiency Status Report 2012, JRC Scientific and Policy Reports, EUR 25405 EN
[40] Bertoldi et al., Energy Efficiency Status Report 2012, JRC Scientific and Policy Reports, EUR 25405 EN
[41] Palmer J. et al. (2013) Further Analysis of the Household Electricity Use Survey, Part 2: Focus on appliances. London: DECC.



Comparison of Energy Label rating (x-axis) and measured energy consumption (y-axis) of the six major appliance types - each blue dot represents a single appliance and the black squares represent the means for each Energy Label rating. [Base: All appliances with both measured energy consumption and Energy Label ratings.]

For example, for dishwashers the mean measured annual energy consumption of ‘A-rated’ dishwashers (327 kWh/year) was higher than the mean value for ‘B-rated’ dishwashers (208 kWh/year). However there were only two ‘B-rated’ dishwashers measured in the HES survey. It would be unreasonable to conclude that ‘A-rated’ dishwashers have higher energy use because of the risk of sampling error (a sample with, say, 50 ‘B-rated’ dishwashers might show a much higher measured energy consumption). It is possible that ‘A-rated’ dishwashers (and other appliances) do indeed use more energy (perhaps due to larger size appliances or more frequent usage), and this merits further research.

The findings also highlight the wide range of measured annual energy consumptions within each Energy Label rating. For example, for dishwashers, the individual appliance measured energy use for ‘A-rated’ dishwashers vary between a minimum of 33 kWh/year and a maximum of 911 kWh/year. For all appliance types this variation is caused by many factors including the size of the appliance, how it is used (i.e. programme selections, door opening frequency, location), how often it is used (i.e. number of cycles per year), and any faults which have developed during operation.

Recommendations

■ Policy makers can continue to assume that, on average, dishwashers, refrigerators, freezers and fridge-freezers actually have similar electricity use to that suggested by EU Energy Labels. However, for washing machines and tumble dryers further work is required before a similar conclusion can be drawn (such as a survey that collects the parameters required for full Energy Label calculations).

■ Consumers purchasing new appliances may see significantly different energy consumption compared to the EU Energy Label energy estimate given at the point of sale. The Energy Labels could be enhanced to reflect the variation in use by household occupants, for dishwashers, for example, by combining the rated 'per cycle' energy use for different programmes with how often each programme type is used by different households. Consumers could be informed of the expected annual energy consumption according to whether their use is 'low', 'medium' or 'high'.

■ Policy makers can continue to assume that, on average, dishwasher measured 'per cycle' energy consumption is similar to the stated value in EU Energy Label regulations. For washing machines and tumble dryers further work is required to determine if the weighted average 'per cycle' energy consumption value used in EU Energy Labels is similar to results recorded in actual homes.

■ Further work is needed to understand the apparent trend of increasing energy use for recently purchased dishwashers, washing machines and tumble dryers. Based on our findings, policy makers may recommend further changes (particularly accounting for the size of appliances) to the Energy Label regulations, and minimum energy performance standards,

Other evidence on energy labels and energy use

Several large-scale comparisons between appliance energy labels and in-situ consumption have been published to date. An early review paper[42] summarised a number of studies looking at different appliance types, including cold appliances, for which laboratory tests were found to correlate well with actual energy use.

Regarding user behaviour, several studies[43, 44] reveal significant variations from country to country, suggesting that comparing EU energy labels to typical actual use within Europe will require consideration of each country's typical habits. For instance, a recent large survey found typical washing machine temperature in the UK to be several degrees below that for Denmark and Belgium, and another found large differences in the fullness of dishwashers in use across Europe.

[42] de Almeida, A., et al. (2008) REMODECE-Residential monitoring to decrease energy use and carbon emissions in Europe: Final Report. Coimbra (Portugal): ISR-University of Coimbra.
[43] Meier, AK. (1997) Observed Energy Savings from Appliance Efficiency Standards. Energy and Buildings 26 (1) 111–117.
[44] AISE (2013) The Case for the AISE Low Temperature Washing Initiative. Brussels: AISE/I Prefer 30°.

to ensure that new dishwashers, washing machines and tumble dryers have lower energy consumption when used in the home.

■ There is limited data indicating that appliances with Label ratings (A++, A+, A) sometimes consume less energy, when used in the home, than appliances with low Energy Label ratings (B, C, D, E, F). However, there is insufficient evidence to say whether this can be generalised, or if it results from sampling errors. In order to understand whether Energy Labels are truly leading to lower energy consumption, a sampling strategy that captures appliances in sufficient numbers across all Energy Label rating categories is required.

Comparing HES Against *Energy Consumption in the UK* and the *Energy Follow-up Survey*

Context

The Department of Energy and Climate Change produces statistics for Energy Consumption in the UK every year. These statistics cover energy use in homes, as well as energy use in other sectors.

The Departments wish to find out how reliable the Energy Consumption in the UK (ECUK) estimates of energy use by specific appliance types are. They also wish to compare the Household Electricity Study with the English Housing Survey's Energy Follow-Up Survey (the EFUS).

These comparisons are relatively involved tasks, but they help to assess the current evidence base for electricity use in homes. Potentially, both tasks could help to guide future energy statistics published by the Departments.

The EFUS data does not currently provide a breakdown of energy use by different appliances. (Only total electricity use data is available for the households in the survey.) However, it does include a breakdown of appliance ownership, which we can compare against HES appliance ownership.

Approach

In order to explore the breakdown of domestic energy consumption for different appliances, we processed the data to identify instances where monitoring did not cover all of a household's appliances. We should reiterate that the HES is not a perfectly representative sample of UK homes, which affects the comparison. Notably it includes only owner-occupied homes (omitting private rented and social housing). It is also a self-selecting sample (only those who agreed to take part), who may differ from typical appliance use and ownership across all homes.

Separate approaches were taken for appliances and lighting, due to differences in the data available. The two approaches taken are outlined below.

For appliances:

1 Each of the HES monitored appliances was matched to those defined in Table 3.10 of the ECUK statistics[45] (published 25 July 2013). Where HES appliances did not match those identified in ECUK, these were separated (e.g. as 'other wet appliances' or 'other cold

[45] ECUK 2013 is available here: https://www.gov.uk/government/organisations/department-of-energy-climate-change/series/energy-consumption-in-the-uk (last accessed 18.09.13).

appliances'). Monitored data that could not be attributed to any of the ECUK categories (e.g. those defined as 'other' or 'unknown') were excluded from the analysis.

2 The monitored appliances were compared with those identified in the Ipsos Mori survey. For each appliance, households were excluded if the number of appliances in the Ipsos Mori survey exceeded the number monitored. Each appliance type was considered independently. For instance, if HES monitoring covered all of a household's washing machines, but not all of its refrigerators, then this household was included in the washing machine analysis, but excluded from the fridge analysis.

3 The test outlined in Step 2 has an inevitable bias towards households without appliances. For example, households with no games consoles will definitely have 'all games consoles' monitored and consequently be 'accepted', whereas those with multiple consoles may not. To adjust for this, for each appliance, we adjusted the number of households without the appliance to reflect the actual ownership percentage from the overall HES data.

4 More generally, this analysis inevitably has a bias against households with large numbers of appliances (e.g. a household with three televisions is less likely to have had all of them monitored than a household with only one). The result is that, for instance, while over 90% of households with one television were included, this value drops to 50% and 42% for households with two or three televisions, respectively.

We considered more detailed adjustments for different household appliance ownership (similar to that described in Step 3), but not included in the analysis.

5 The average electricity consumption per appliance was calculated for all households included in the analysis.

For lighting:

The HES data includes information on the number of different lamp types per household. However, the monitored electricity data does not include this level of detail, so we cannot say how much energy was used by different lamp types. This means we cannot compare the monitored lamps directly against lamp ownership to work out whether lighting monitoring was incomplete.

Two checks were carried out on the data. These are the same as those carried out for the Lighting Study report. First, we excluded from the analysis households with no lighting distribution boards monitored. Second, households with lighting use only monitored in the summer were excluded, due to difficulties in extrapolating this data to the entire year. These checks resulted in approximately 15% of the households being excluded from the lighting analysis.

The results of this analysis are presented in the tables and graphs below.

Findings

The table below presents the results, comparing the mean HES electricity consumption for lighting and different appliances with the mean 2010-2011 ECUK estimates. For all the main appliance groups except cold appliances and consumer electronics, there is a good match between the HES and ECUK.

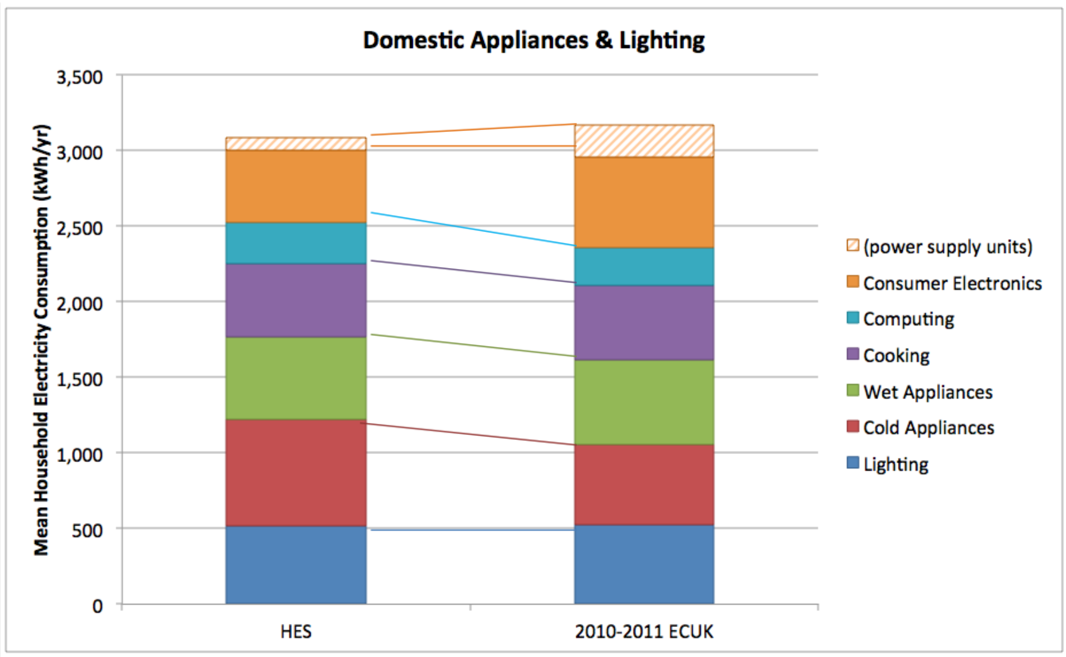
However, ECUK appears to underestimate cold appliances by around one third – assuming that the HES homes are representative of all UK homes for cold appliances use. The breakdown of energy use for the different appliances shows that this is caused by large variations for both refrigerators and freezers, where the HES data is 40-70% higher than the ECUK estimates. The results for fridge-freezers –which make up more than half of the cold appliance energy use in the ECUK– shows close results, with the HES mean within 10% of the ECUK. In contrast to the cold appliances, the disparity for consumer electronics suggests that ECUK is *over*-estimating electricity use for TVs, consoles and DVDs. Power supply units are domestic appliances with external power supply from small appliances, such as mobile phones, to larger rated appliances like vacuum cleaners or hair-straighteners.

Appliances	HES Households w/Appliance		Mean Annual Electricity Use		
	Number	% Accepted	HES (kWh/yr)	ECUK (kWh/yr) *	% Diff
Cold Appliances			704	532	32.4
Refrigerator	134	69.4	106	75	40.0
Fridge-freezer	188	77.7	336	308	9.0
Upright Freezer	111	87.4	157	97	61.4
Chest Freezer	57	71.9	87	51	69.2
Other Cold Appliances	10	90.0	19	N/A	N/A
Wet Appliances			541	556	-2.6
Washing Machine	231	88.7	146	169	-13.7
Washer-dryer	33	66.7	34	90	-62.6
Tumble Dryer	139	80.6	190	172	10.8
Dishwasher	148	75.7	171	124	37.5
Other Wet Appliances	8	25.0	0	N/A	N/A
Cooking			489	495	-1.3
Electric Cookers/ Ovens/ Hobs **	199	56.8	243	234	4.0
Microwave	233	91.0	51	94	-45.6
Kettle	246	93.9	165	167	-1.3
Other Cooking Appliances	244	25.0	29	N/A	N/A
Computing			271	253	7.2
Desktops	151	58.9	101	137	-26.6
Laptops	169	60.9	23	41	-43.8
Monitors	148	59.5	25	61	-59.0
Printers/MFDs	193	56.0	27	14	90.3
Other Computing Appliances	207	70.5	52	N/A	N/A
General Computing Site ***	131	96.9	43	N/A	N/A

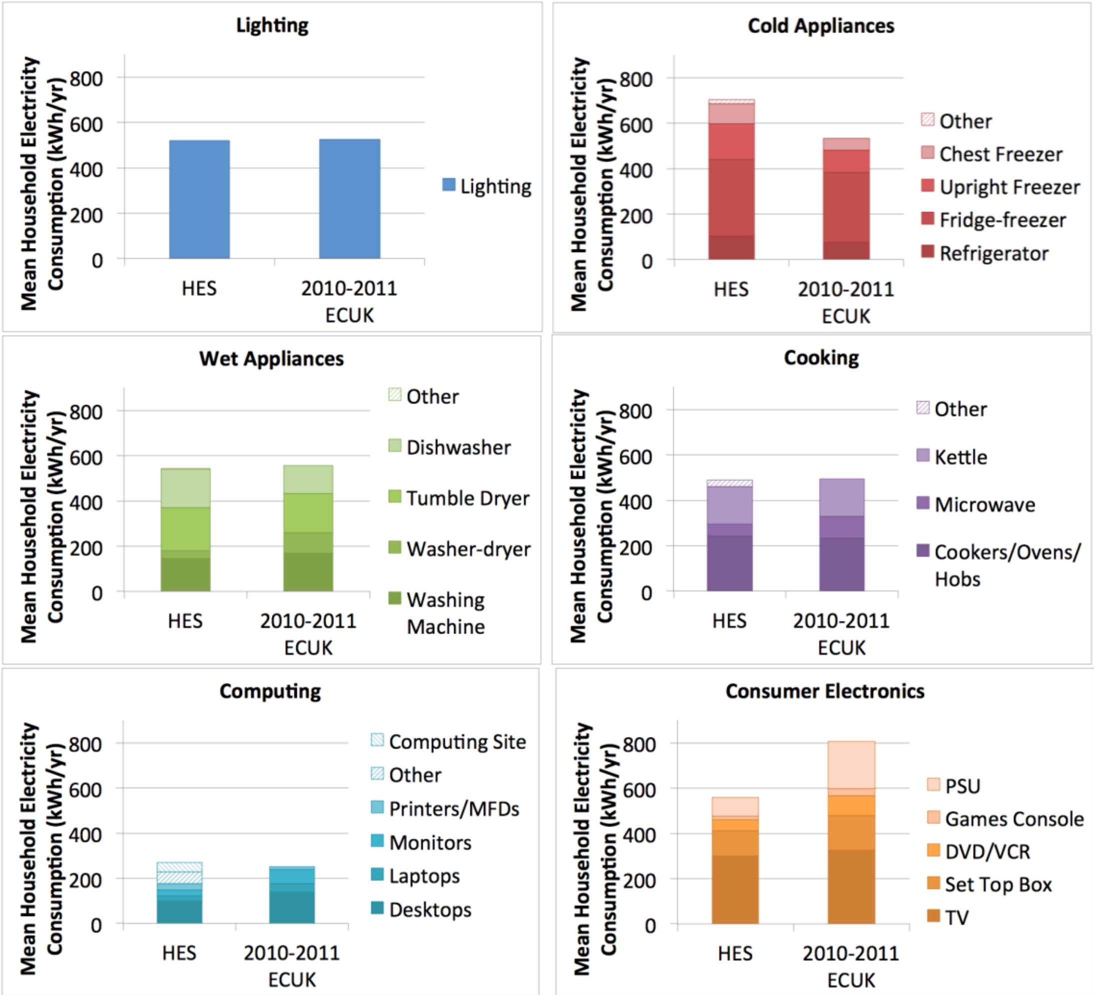
Appliances	HES Households w/Appliance		Mean Annual Electricity Use		
	Number	% Accepted	HES (kWh/yr)	ECUK (kWh/yr) *	% Diff
Consumer Electronics ****			560	807	-30.7
TV	250	57.6	300	327	-8.1
Set Top Box	207	69.6	110	152	-27.3
DVD/VCR	223	49.3	49	89	-44.6
Games Console	100	53.0	16	31	-49.7
Power Supply Units	251	0.4	84	208	-59.7
Lighting	251	85.3	521	527	-1.1

* The ECUK data is presented in thousands of tonnes of oil equivalent. This was converted into average household kWh/yr using 1GWh = 86toe, and the UK household number (ECUK Table 3.07).
** These cooking appliances are separated in the ECUK data, but this level of disaggregation was not possible with the HES data.
*** A number of households' computing systems were monitored as general computer sites, rather than as a separate desktop, monitor etc.
**** Because so few households have reliable electricity consumption for all power supply units, the PSU result should be treated with caution.

Graphs showing the HES appliance and lighting electricity consumption against the ECUK data are included below. The first graph shows the overall appliance categories (with power supply unit results separated due to the poor match, as described in note 4 above).



The six graphs below present the breakdown for each of the appliance groups in turn. Hashed bars represent appliance types that are not included explicitly in the ECUK estimates, such as 'Other Wet Appliances'.



Comparing the monitored appliances against the appliances identified in the Ipsos Mori survey suggests that for most appliance types, the monitoring covered all items for a good proportion of the households. The table above shows that, for instance, for cold appliances, the acceptance ranges from 69.4% for refrigerators to 87.4% for upright freezers. This provides some confidence in the results found.

The one exception is power supply units, where only one household was found to have all appliances directly monitored. This does *not* mean that these appliances were not monitored for the study. Rather, these appliances were often monitored centrally (i.e. monitored at a distribution board or multi-socket cable), or were unclearly labelled. In these instances it was not possible to identify energy use accurately.

Overall, the total domestic appliance energy consumption from the HES study matches well with the ECUK table estimates. HES average total electricity consumption for appliances and lighting was 3,086 kWh/yr, which is 2.6% lower than the ECUK estimate of 3,170 kWh/yr. (The ECUK figures come from the Market Transformation Model – a bottom-up model based partly on sales of energy-using equipment[46] – which undergoes a top-down adjustment to match DUKES, the Digest of UK Energy Statistics.)

However, there is greater variation within the separate appliance groups. While HES energy use for wet appliances, cooking, computing and lighting are within 10% of ECUK estimates, HES consumption is approximately one third higher than ECUK for cold appliances, and a third lower for consumer electronics. Energy consumption varies even more at the level of individual appliances. Most notably freezers, washer-dryers and monitors, which show variations of 60% or more between the ECUK and HES results. For printers and MFDs the HES result is 90% higher than the ECUK estimate.

It is possible that the gaps between ECUK estimates and HES monitoring represents inaccuracies in the ECUK calculation process, as well as the sampling frame that excludes rented homes. Households living in social housing are more likely to be claiming benefits and less likely to be working full-time. Both factors mean they are at home for longer, on average, than owner-occupier households – which is likely to increase electricity use.

Existing studies (see 'Other Studies on Energy Use by Different Tenors' blue box, below) typically suggest higher electricity use in owner-occupied buildings than in rental/social housing. This trend – if it holds true at the scale of the appliance categories – prompts questions we cannot answer about why the HES households have lower energy use for consumer electronics than the ECUK estimates.

Energy Use per Appliance

We tried to work out whether the differences between the HES and ECUK energy uses are likely to be due to ownership or use, by examining appliance ownership in more detail. The tables that follow compare the HES appliance ownership figures with similar information from two sources:

1. ECUK (Table 3.12, Number of appliances owned by households in the UK), and
2. data from the Energy Follow-Up Study (EFUS).

The appliance data available from these two sources is subtly different, and therefore each is examined separately. Table 3.12 of ECUK data provides information on the average number of appliances owned per household across the UK housing stock. However, data on multiple-appliance ownership is not available, a factor which is known to affect energy consumption (e.g. a household's second TV is typically used less than their first TV). In contrast, the tables in the EFUS report present information on the number of households that own the different appliances (i.e. taking into consideration multiple-appliance ownership).

[46] Cambridge Econometrics (2012) A Peer Review of the Market Transformation Programme Model. London: DEFRA.

Both ECUK and EFUS cover all tenure types, not just owner-occupied homes. Although differences in ownership may account for some of the variation in electricity consumption, this is also greatly affected by the type of appliances (efficiency, volume, etc.) as well as by household behavior. These topics have been explored for the HES study in detail in our *Part 2: Focus on Appliances* report, and are not repeated here.

The first table below shows how the HES data on ownership and energy use compares to the ECUK statistics. Broadly, appliance ownership among HES homes matches the ECUK estimates quite well. The mean appliance ownership for fridges, fridge-freezers, freezers, washing machines and dryers, microwaves, kettles, laptop computers, and DVDs is broadly similar among HES households as it is in the ECUK estimates.

However, there are big differences in ownership for some appliances: dishwashers, desktop computers, printers and multi-function IT devices (MFDs) all show higher ownership in HES households than in the ECUK estimates; whereas TVs, set top boxes and games consoles have higher ownership in ECUK households than in the HES estimates. These differences appear to be larger than you would expect from sampling differences alone (even accepting that owner-occupied homes have different patterns of appliance ownership).

(Cookers, ovens and hobs were very difficult to compare, so we have limited confidence in the comparison of these appliances.)

Turning to the energy use comparison, there were more widespread differences between HES and ECUK data. Average energy use was recorded similarly for fridge-freezers, tumble-dryers, dishwashers, kettles, TVs and set top boxes. But there were big differences (30-90%) for other cold appliances, washing machines, microwaves, all computing devices, and games consoles. This may point to flaws in the ECUK estimates of energy use for these appliances. Microwaves, desktop computers and printers/MFDs show very big discrepancies – all around 90% out – suggesting that the ECUK figures need to be checked.

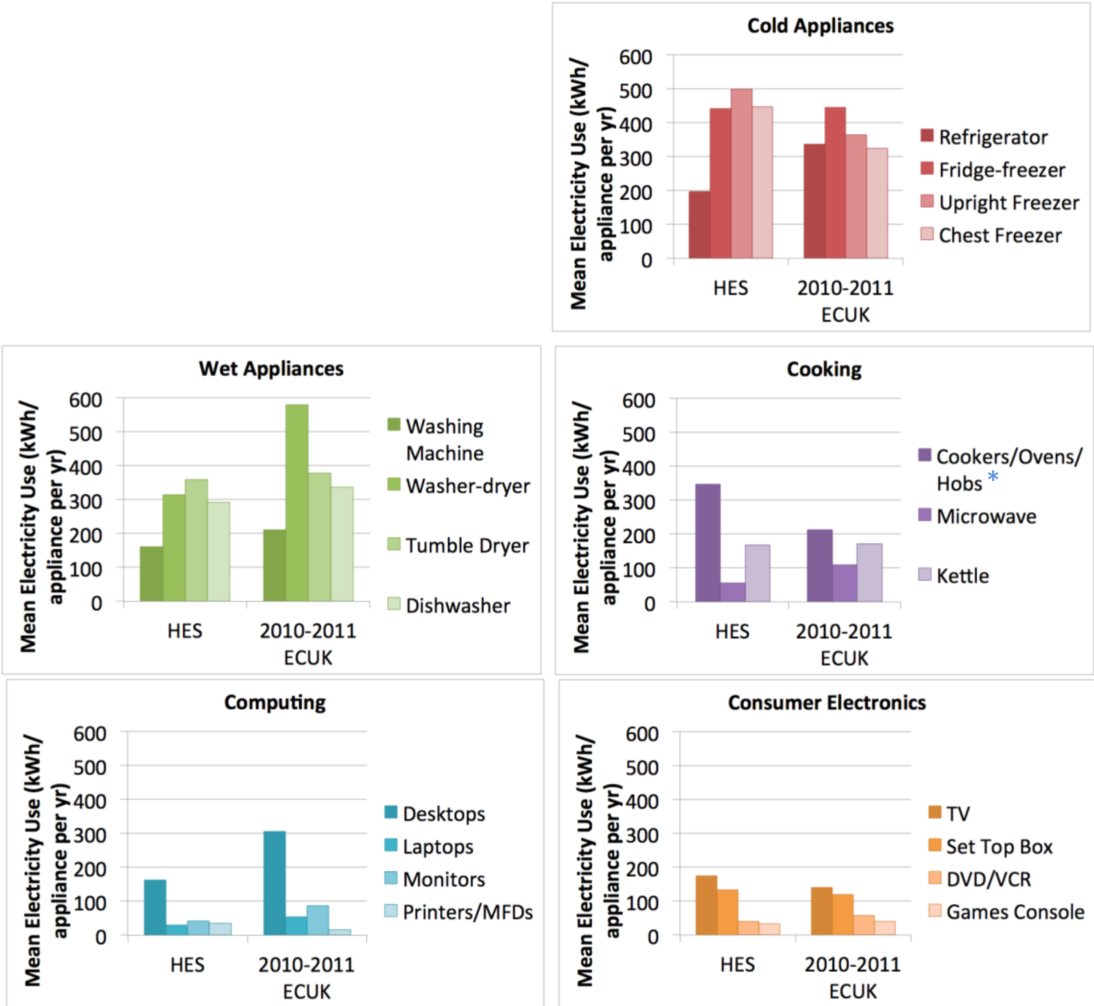
Appliances	Mean Appliances per Household			Mean Annual Appliance Elec Use	
	HES	HES Included	ECUK	HES Included (kWh/app)	ECUK (kWh/app)*
Cold Appliances					
Refrigerator	0.58	0.53	0.38	198	336
Fridge-freezer	0.78	0.76	0.69	442	444
Upright Freezer	0.34	0.31	0.31	498	363
Chest Freezer	0.21	0.19	0.16	447	324
Wet Appliances					
Washing Machine	0.91	0.91	0.80	161	211
Washer-dryer	0.12	0.11	0.16	315	579
Tumble Dryer	0.53	0.53	0.45	359	378
Dishwasher	0.59	0.58	0.37	292	336
Cooking					
Electric Cookers/ Ovens/ Hobs**	1.15	0.70	1.10	347	212
Microwave	0.93	0.92	0.87	56	109
Kettle	0.99	0.98	0.98	168	171
Computing					
Desktops	0.69	0.62	0.45	163	305
Laptops	0.97	0.76	0.74	30	55
Monitors	0.65	0.58	0.70	43	87
Printers/MFDs	0.91	0.80	0.34	34	16
Consumer Electronics					
TV	2.17	1.72	2.32	175	141
Set Top Box	1.05	0.83	1.27	133	120
DVD/VCR	1.31	1.23	1.55	40	57
Games Console	0.59	0.47	0.77	33	41

* The ECUK data is presented in thousands of tonnes of oil equivalent. This was converted using 1 GWh = 86 toe.
** Direct comparison between the number of cookers/ovens and hobs from the HES with the ECUK table was very difficult, so this comparison should be treated with caution.

The graphs below show the HES and ECUK mean appliance energy consumption on a per-appliance basis (i.e. electricity use divided by number of appliances). For some appliances, the differences in total household energy consumption for specific appliances between the HES and ECUK data are partly explained by the difference in ownership. For instance, for refrigerators, although total electricity use is higher in the HES homes, when this is adjusted for appliance ownership, energy consumption per appliance is actually lower.

This may suggest that the weakness in ECUK estimates is linked to assumptions about appliance ownership rather than about energy use per appliance.

Unfortunately, information about multiple-appliance ownership is not available in the ECUK table. Consequently, it is important to bear in mind that the distribution of household appliances may be very different between the ECUK and HES homes, even where average appliance ownership is similar.



* The data for cookers, ovens and hobs were difficult to compare, and we have less confidence in these comparisons.

The ECUK monitor and desktop ownership estimates appear to be inconsistent. It seems very unlikely that there are really 1.7 monitors per desktop computer, even allowing for some desktop computers having two screens. It seems likely that ownership estimates based on product sales have been affected by the adoption of flat screens, with households purchasing flat screens to replace old cathode ray tube screens. Seemingly, the old screens are still recorded as owned.

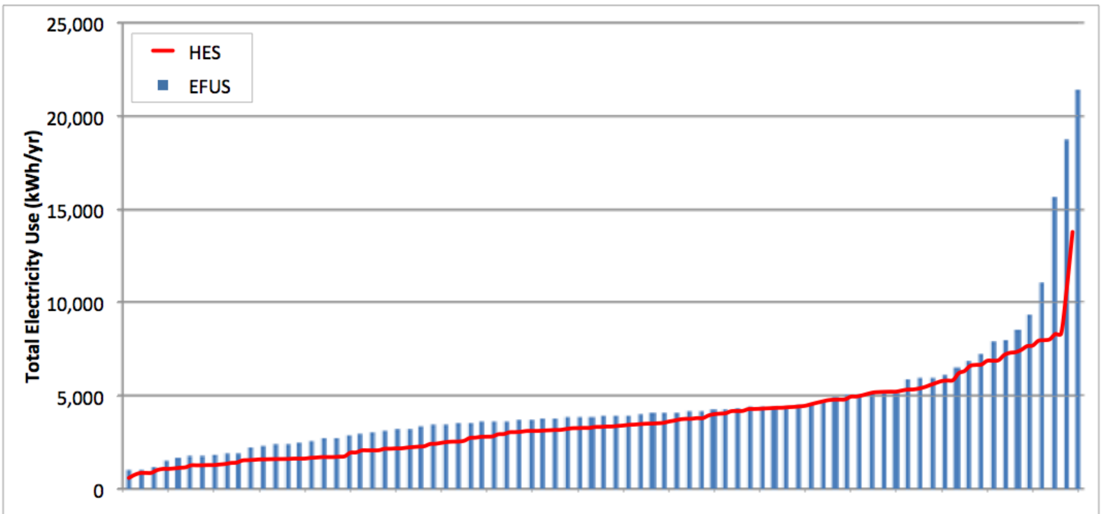
EFUS Data

Unfortunately we were not able to compare HES electricity use at the appliance level against the Energy Follow Up Survey of the English Housing Survey, because only total electricity use data was available, and this was not disaggregated. However, a comparison of a number of the key EFUS study results with the equivalent data from the HES is presented below.

The graphs below compare the EFUS results with the HES results for:

1. total annual electricity consumption per household
2. average base load per household, and
3. the overall energy profile for the stock.

Households with electrical space or water heating have been excluded from the HES results, for consistency with the EFUS. The differences are outlined in the next four paragraphs.

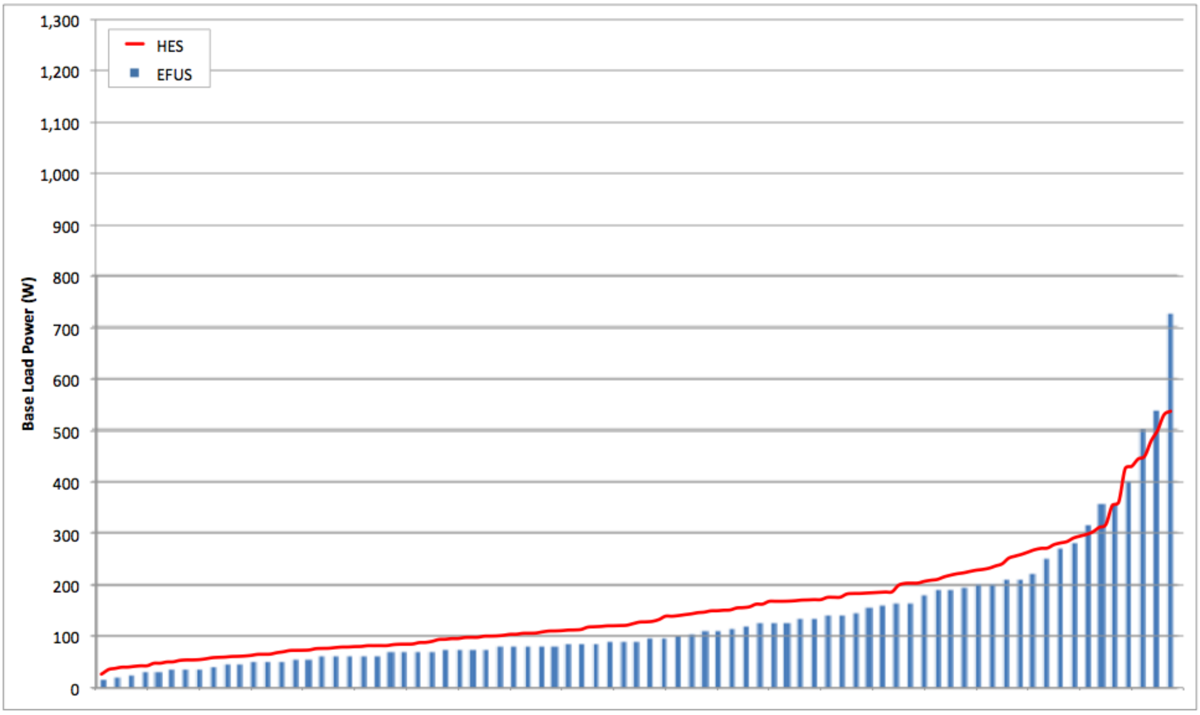


Comparing the total electricity distributions above reveals similar trends in electricity consumption between the studies. However, the 10% highest consuming households in the EFUS are a lot higher than the equivalents in the HES.

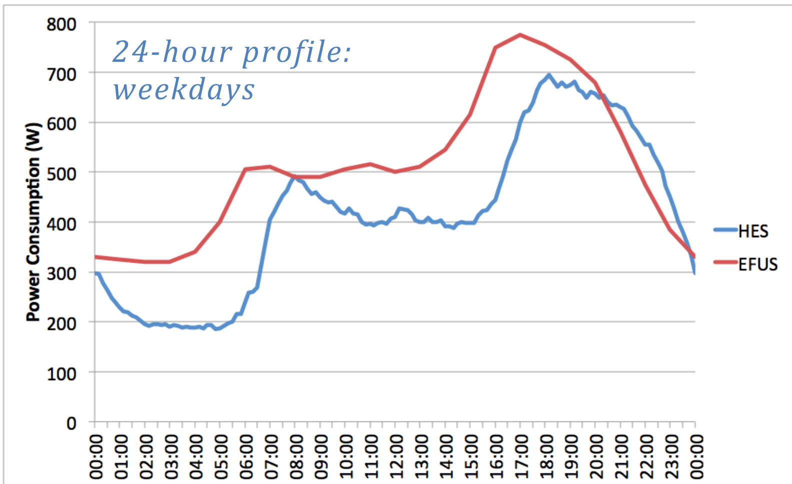
The graph below, comparing the average base loads between the studies also reveals similar general trends between the two studies. Although the graph suggests that the HES sample households have higher base loads than EFUS sample – this may be an artefact of the method by which base load was calculated (the HES assumed the lowest hour of power, while the EFUS used the 10th percentile) and the monitoring process. Full information for each can be found in our first report[47], and the *EFUS Domestic Appliances and Cooking*[48] report respectively.

[47] Palmer J, Terry N, Kane T (2013) Further Analysis of the Household Electricity Use Survey: Early findings – demand side management. London: DECC/DEFRA.

[48] BRE (2014) Domestic Appliances, Cooking & Cooling Equipment. London: BRE/DECC.

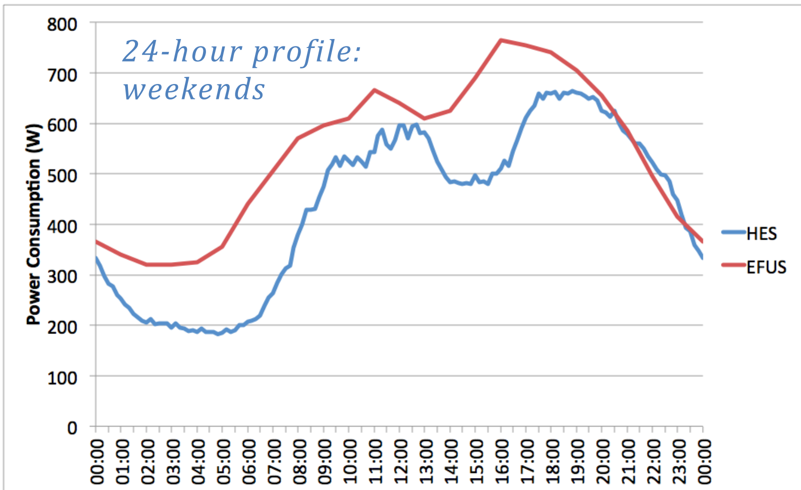


The graph below presents the EFUS electricity profile for weekdays, with the equivalent HES profile (all homes, excluding electric water/space heating) generated in the 24-Hour Profile Chooser. The graph suggests that the general trends are similar between the two studies. However, two key differences are seen. First, the magnitude of the power consumption varies between the studies (surprisingly, while the HES base loads are typically higher than the EFUS base loads, the lowest power overnight is the opposite); and second, the power profile through the day in the HES households seems to lag behind the EFUS sample.



We examined whether the time-lag could be explained by different conventions for recording British Summer Time and Greenwich Mean Time. The EFUS dataloggers were installed between March and July and recorded until January, with the result that they recorded in summer and winter periods. However, the EFUS reports do not explain whether there was any adjustment for clocks being re-set, or how the 24-profile curves were generated. Given that the morning time-lag is two hours anyway, it seems very unlikely that changing from BST to GMT explains the difference. It is more likely that the smaller sample for detailed EFUS electricity monitoring (just 79 households), and resulting sampling errors, explains the discrepancy.

The next graph shows the same comparison between EFUS and HES profiles for weekends. Once again, the morning peak appears to come earlier in EFUS households, and rises to a higher peak load. However, the decline in electricity use late in the evening is recorded with a very similar profile.



The differences in energy consumption between the EFUS and HES shown in the previous three graphs may reflect a variation in the behaviour of owner-occupied households (in the HES) compared with the overall housing stock (represented in the EFUS). However, it is also possible that variations in the way that the calculation or monitoring procedures could account for some of the variation. For instance, from the profile graph it is clear that the resolution for the EFUS is lower than the HES survey, which may reflect smoothing of the data (the HES data is shown in the graph at a 10-minute resolution).

Appliance Ownership Across Different Household Types

The EFUS includes some information on the variation in appliance ownership across different household types. Appliance ownership (the percentage of households that own the appliance) is distinct from the 'mean appliances per household' explored previously, as this considers multiple-appliance ownership. The table below compares the HES appliance ownership against the results of the Energy Follow-Up Study. Some HES appliance types have been grouped together in the table to match the EFUS data.

The HES and overall EFUS ownership figures are similar (within 20%) for almost all appliance types. The only major discrepancy is for dishwasher ownership, where a much higher proportion of HES homes are recorded as owning dishwashers (59% against 41%). However, the EFUS report notes that higher ownership was found for this appliance in owner-occupied homes than in rented, local authority or Registered Social Landlord homes. The dishwasher ownership for owner-occupied buildings alone was 54% in the EFUS sample, which is within 10% of the HES result.

Appliances	Household Appliance Ownership		
	HES (%)	EFUS (%)	EFUS Notes
Cold Appliances			
Refrigerator	53	47	Uniform ownership across household groups
Fridge-freezer	75	65	
Upright/Chest Freezer	56	46	Higher ownership in owner-occupied than rental/social housing
Wet Appliances			
Washing Machine	92	83	Higher ownership in owner-occupied than rented, local authority or RSL
Washer-dryer	13	14	
Tumble Dryer	55	49	Higher ownership in owner-occupied than rented, local authority or RSL
Dishwasher	59	41	Higher ownership in owner-occupied (54%) than rented, local authority or RSL
Cooking			
Electric Cookers/ Ovens/ Hobs	79	65*	
Microwave	93	83	Uniform ownership across household groups
Consumer Electronics			
TV	93	83	Uniform ownership across household groups

* Estimated from EFUS 2011 cooker fuel type and ownership tables.
RSL = Registered Social Landlord
There is insufficient data in ECUK to calculate equivalent figures to include in the table.

Other Evidence on Energy Use by Different Tenures

Other research has shown significant variation in electricity consumption by home ownership type. Recent analysis of the UK's National Energy Efficiency Data-framework (NEED)[49] found that mean total electricity use in owner-occupied homes is almost 14% higher than in privately rented housing, which in turn is 8% higher than council housing/housing association buildings. Similarly, a study of 27 dwellings in Northern Ireland [50] found far higher electricity consumption in privately owned houses than rented ones, particularly during the evenings.

Although these studies consider total electricity use, rather than solely appliance use, this may help to explain the variation between HES electricity use and ECUK estimates. At the level of individual appliances, some research suggests variation in usage patterns with household type. For instance, the Energy Follow-up Study[51] found that mean TV use was 2.3 hours higher in local authority housing, and 1.8 hours per day higher registered social landlord housing, compared with owner-occupied homes.

Recommendations

■ Incomplete information about how the ECUK energy figures are calculated makes comparing against actual survey data difficult, particularly as the data presented is aggregated to an overall national stock level. Making the calculations transparent and presenting the tables with more disaggregation (e.g. split by tenure, household type, or size), would make the information more valuable and easier for researchers to evaluate.

■ Findings suggest that the ECUK energy use estimates for computing, cooking, lighting, and wet appliances are reasonable. However, the large discrepancy between cold appliance and consumer electronics use and measured households suggests that this calculation needs to be reviewed.

■ ECUK figures for appliance ownership are fairly close to the actual appliance ownership for the HES homes, apart from dishwashers and computer monitors. This suggests that further work may be needed to confirm that the ECUK ownership figures for dishwashers and monitors are reliable.

■ Around a fifth of computing energy use was found to be from items that are currently not explicitly included in the ECUK tables (e.g. hard drives and routers). This may suggest that some of the appliance types in ECUK should be updated/expanded to better reflect current household energy use.

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[49] Wyatt, P. (2013) A dwelling-level investigation into the physical and socio-economic drivers of domestic energy consumption in England. Energy Policy 60: 540-549.

[50] Yohanis, Yigzaw G, et al. (2008) Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. Energy and Buildings 30: 1053-1059.

[51] BRE (2013) Domestic appliances and cooking. (Energy Follow up Survey 2010/11.) London: DECC.

Homing in on secondary electric heating

The Departments wished to explore factors relating to use of secondary electric heating and how gas and electricity demand would change if gas room heaters were used instead.

In our analysis we define homes with secondary heating as homes with electric space heaters that were monitored and for which the main heating is not electric. There were 36 such households in the dataset. However, there were another 40 who claimed to have electric heaters. The reason these heaters were not monitored is not known. It could be because the households claimed to use them rarely.

An Energy Saving Trust survey of 60 properties in 2009[52] found that 25% (15/60) had electric heaters for secondary heating, one in a conservatory. This compares with 30% in the HES dataset (76/250), five of them in a conservatory.

Approach

This analysis was carried out in three parts.

Firstly we estimated the average annual electricity use for secondary heating and the peak electricity demand due to this heating. We used these results to determine potential savings if gas were used instead, and how much extra gas would be used.

Secondly, we developed a metric to rate each household as to how much secondary heating they used, and examined potential correlations with dwelling size, household occupancy and RdSAP rating.

Finally, we obtained a data set of annual gas meter readings for 224 of the households – the ones that were monitored for one month. For each of these we compared the actual gas use with that predicted by SAP/the Cambridge Housing Model (CHM), ignoring the secondary heating system, to see if households with secondary heating used less gas.

Annual and peak electricity use for secondary heating

Of the 26 households monitored for a year only five had secondary heating, and three of these used their heaters very little, a shown in the chart below. The total heating use is dominated by just two households, and even these two did not always use heating as you might expect from the external temperature.

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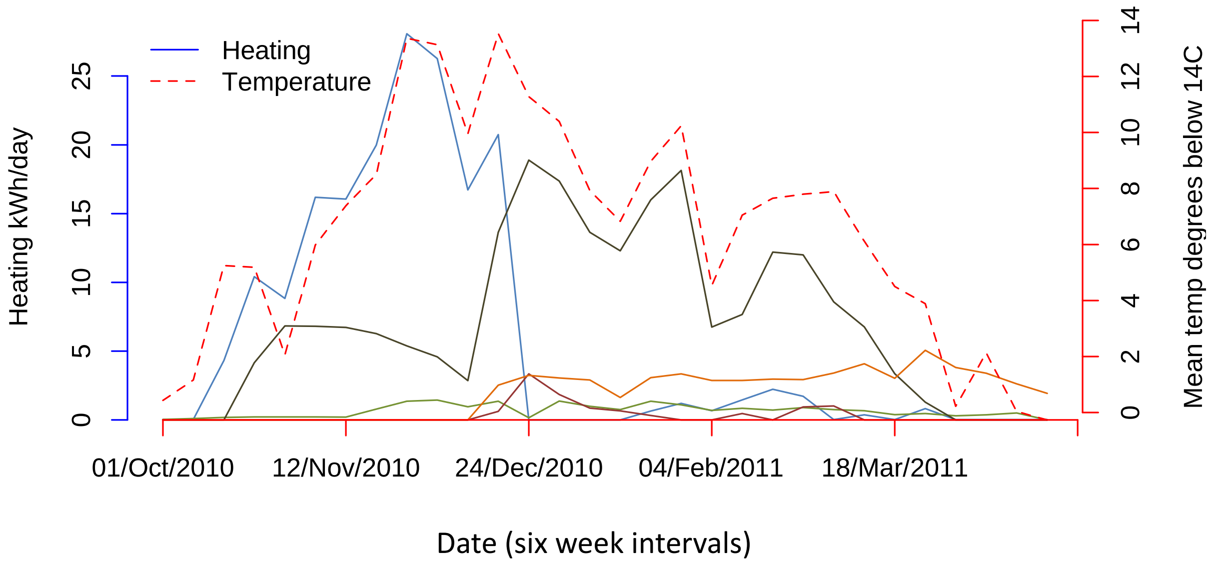
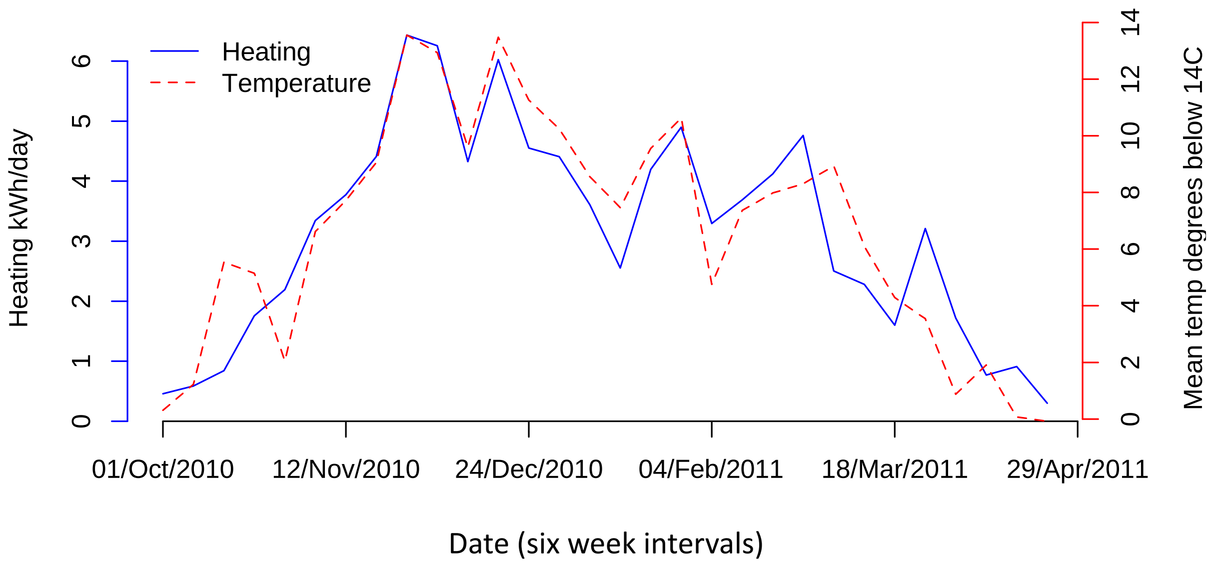
[52] Gastec (2009) Final Report: In-situ monitoring of efficiencies of condensing boilers and use of secondary heating online Available from http://www.energysavingtrust.org.uk/Publications2/Housing-professionals/Heating-systems/In-situ-monitoring-of-efficiencies-of-condensing-boilers-and-use-of-secondary-heating-trial-final-report, Accessed 18 Oct 2013.

Secondary heating and external temperature, by week for 5 households



Rather than using seasonal factors based on this tiny sample we determined the week by week average heating demand through the 2010/2011 heating season – based on all the households with secondary heating that were monitored at the time. The heating season we used was from the beginning of October to the end of April. The number of households monitored in each week varied between six and eleven, with an average close to eight. The mean heating use correlated fairly well with the external temperature (average recorded for the monitored households), see chart below.

Mean secondary heating and external temperature, by week from all households



We added up the average secondary heating demand for each week to get the average for the year. We also performed a similar calculation for the peak time heating 6-7pm and determined the load on the day for the highest use. For the annual total we determined 5% and 95% confidence intervals using a Monte Carlo technique: we calculated the annual total 10,000 times using random numbers generated using the mean and standard deviation from each week. The results are shown in the table below.

Electricity used	Annual total	Annual total 5% confidence intervals	Worst day 6-7pm
Average home with secondary heating	656 kWh	610 - 700 kWh	0.48 kW
Total for all 4.2 million in the UK*	2760 GWh	2560 – 2940 GWh	2.0 GW

* The UK totals were obtained by simple scaling for the number of homes with secondary heating. Since many households in the dataset had heaters that were not monitored, this could mean that heaters are often available but not used, in which case our estimates will be high.

The mean for supplementary heating is approximately 3.7% of the mean gas use for households with supplementary heating. Assuming 25% of the gas use is for water heating, the ratio for space heating only comes to 4.6%. This is a little higher than the 4.1% recorded in the Energy Saving Trust survey.[53] However, only one of the heaters in that survey was in a conservatory, compared to five in the HES.

Using a gas fire instead of electricity for secondary heating

Electric fires have many advantages. They can be installed anywhere there is an electricity socket, warm up very quickly, are often portable and are 100% efficient in the home. However, electricity is more expensive and has higher carbon emissions than gas. If gas central heating were used instead it would be difficult to heat only the area required, especially if heat is needed outside the normal heating program, as this may mean extending the heating hours for the central heating system and heating the whole dwelling.

A gas room heater can be used instead, but needs a mains gas supply or bottled gas. In our calculations we assume that the electric heater is replaced by a gas room heater with a balanced flue and give values for 75% and 90% heater efficiency.

Gas substitution	Annual total gas required kWh	Annual total 5% -95% confidence intervals
Average home with supplementary heating	730 - 870 kWh	680 - 940 kWh
Total for all 4.2 million in the UK	3060 - 3670 GWh	2850 – 3930 GWh

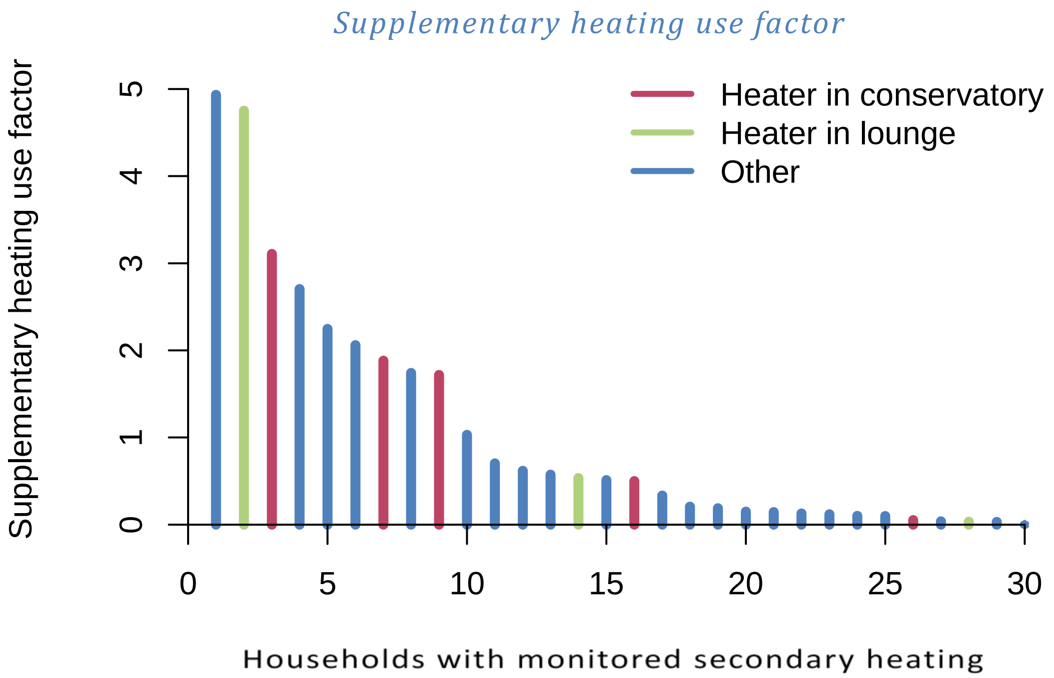
[53] Cited in: Royal Commission on Environmental Pollution (2011). Demographic Change and the Environment (Vol. 8001). London: The Stationery Office.

Factors linked to high use of secondary heating

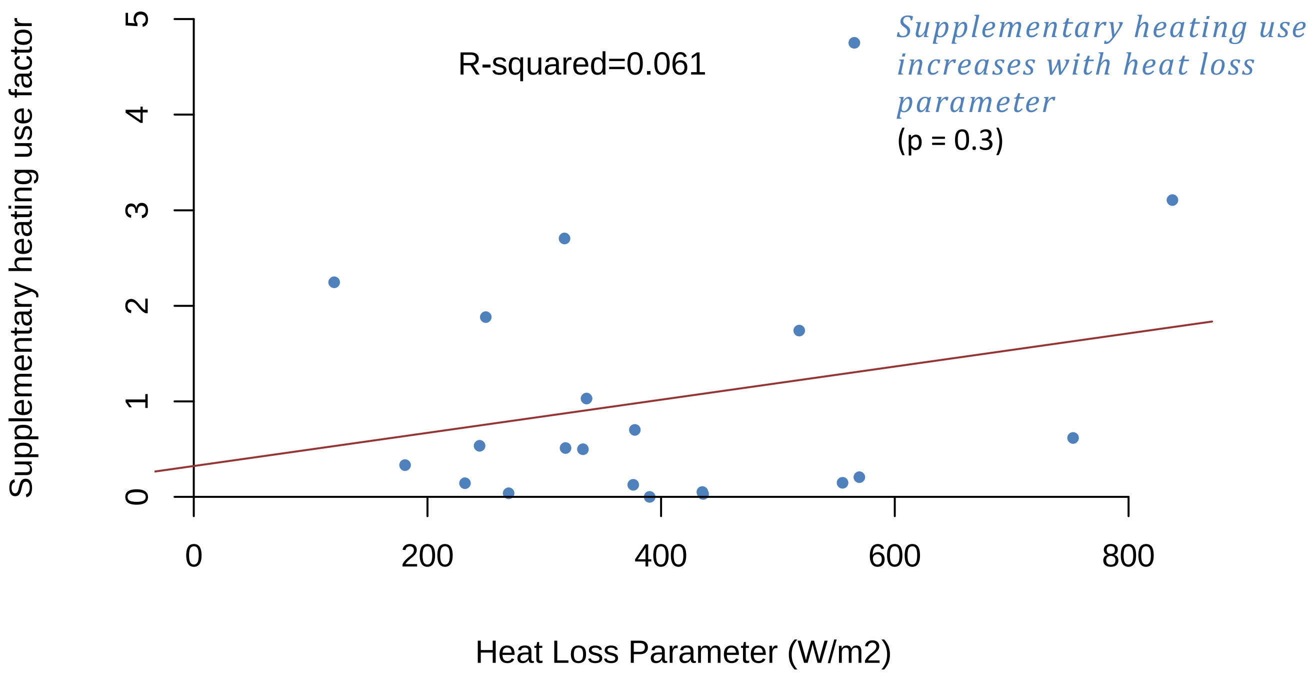
To compare households to according to how much energy their electric heaters used, we divided each household's mean secondary heating energy by the mean for all households over the same monitoring period. This gave a relative 'use factor' of one if the household is average, two if the household uses twice the average and so on. The range for all the households was 5 down to 0. For this analysis we used only the 30 households monitored during the heating season October through May.

In 21 of the 30 cases we know in which room(s) the heaters are located so we investigated if this was related to the amount of heating used. There were five heaters in conservatories and one in a garage, some in bedrooms, the lounge, and other places. (The RdSAP data suggests that 17 households had electric heating in the conservatory but only five such heaters were monitored, perhaps because the other households said they did not use those appliances. In fact, the whole dataset includes 129 heaters across 250 households, but 88 of these were not monitored.) The table below shows the mean use factor by room, where we have more than one instance. Heaters are apparently used most in the lounge and conservatory, but these differences are not statistically significant as there were too few examples.

Location	Number of dwellings with heaters	Secondary heating use factor
Lounge	3	1.8
Conservatory	5	1.5
Kitchen	2	0.3
Bedroom	5	0.2



We found no significant relationships between heating energy use and the size of the household, the size of the dwelling or the HLP (heat loss parameter, heat loss in W/m^2 for the dwelling. Of these factors the clearest trend was with the HLP, but even this was not very convincing. Only 21 data points were available, because we were not able to calculate the HLP for all homes.

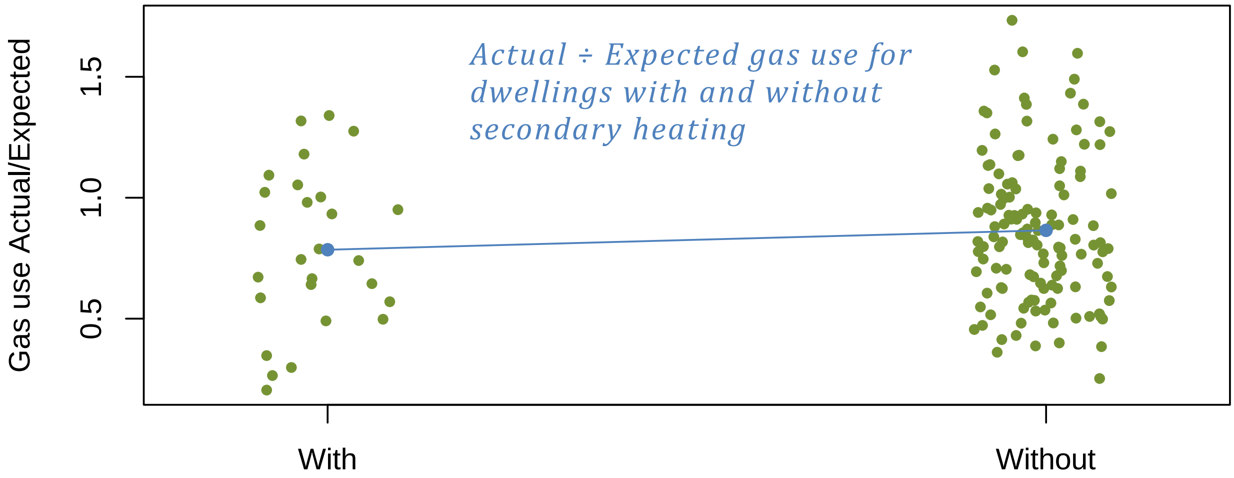


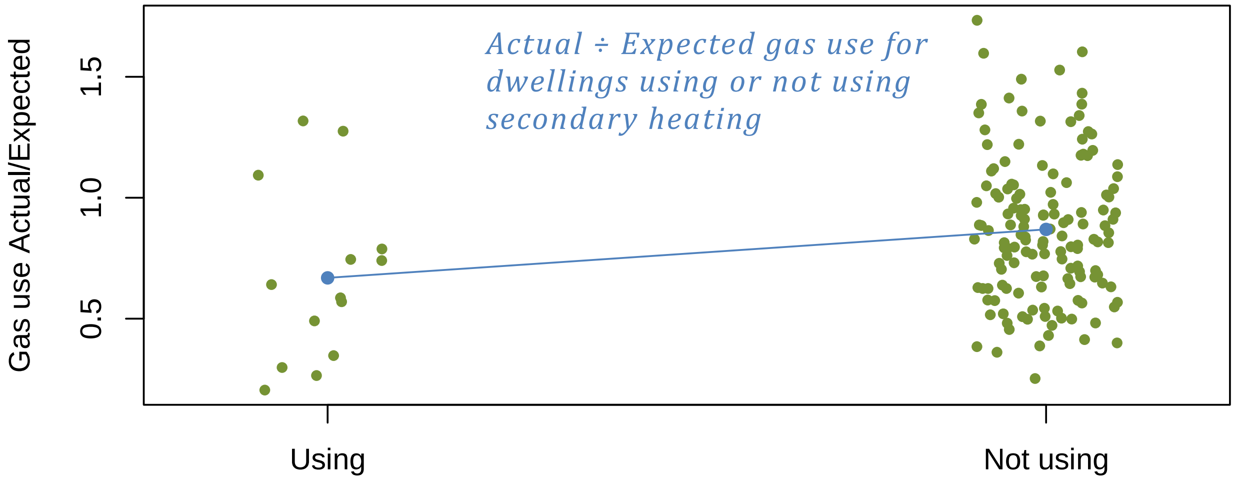
Comparing actual use between homes with and without secondary heating

The aim of this section was to determine if households using secondary heating also used less gas for central heating. We had a dataset for actual gas use (from MPAN meter readings) for some of the dwellings: most of those that were monitored for a month. As described in the modelling section from page 12 above, we used the Cambridge Housing Model to estimate gas use for each household, but this time we ignored secondary heating: we adjusted the input parameters to 'turn off' the secondary heating system.

There were 158 households for which we had gas use data and enough parameters to run the CHM. Of these, 27 had secondary heating, and 14 had a load factor of at least 20% - indicating they made some use of it. We calculated the ratio of actual/predicted gas use for all these dwellings and found some evidence, though not conclusive, that using secondary heating did reduce gas use. The results are shown in the table below and illustrated in the chart.

	Mean gas use actual/predicted	Number in sample	p-value for difference from the norm
Dwellings without secondary heating	0.86	131	-
Dwellings with secondary heating	0.78	27	0.29
Dwellings using secondary heating (use factor > 0.2)	0.67	14	0.08





Summary and recommendations

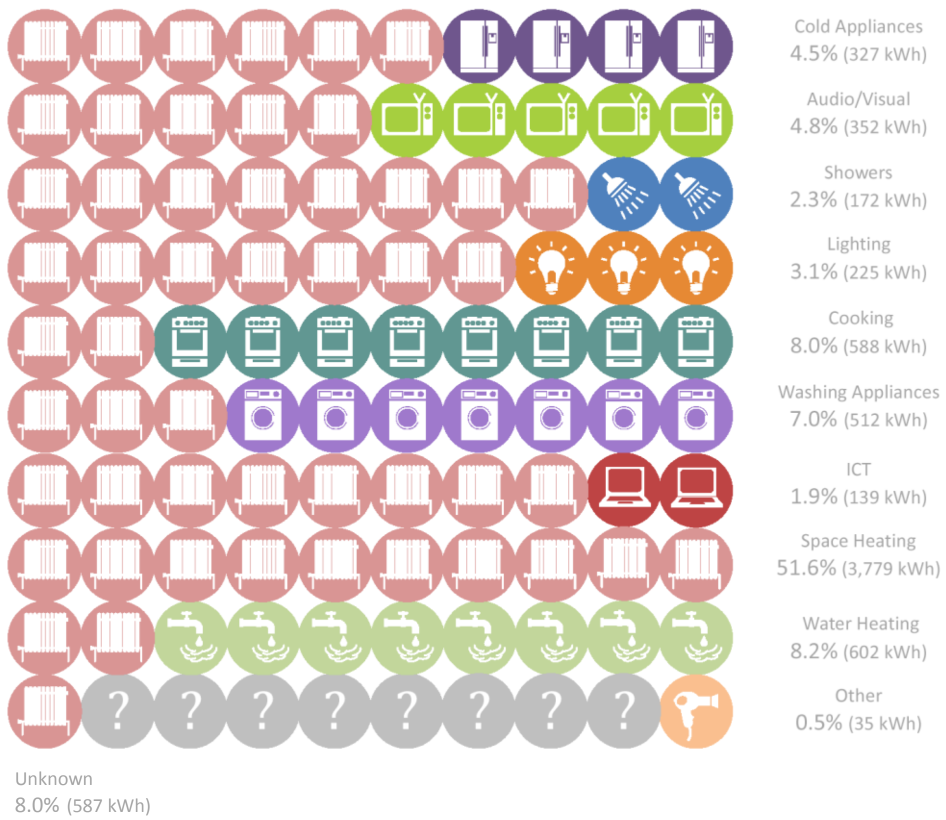
■ Based on the monitored heaters we found that homes with secondary electric heating use 610 to 700 kWh/year for this purpose, on average. However, many homes had heaters that were not monitored. If this is because they were never used, then our average figures may be too high.

■ The energy used for secondary heating is a very small fraction of all space heating energy – around 4.6%. However, it is a much larger fraction of the peak power demand between 6 and 7pm: just over half the average peak load of homes with secondary electric heating (although this is based on a very small sample of only five homes).

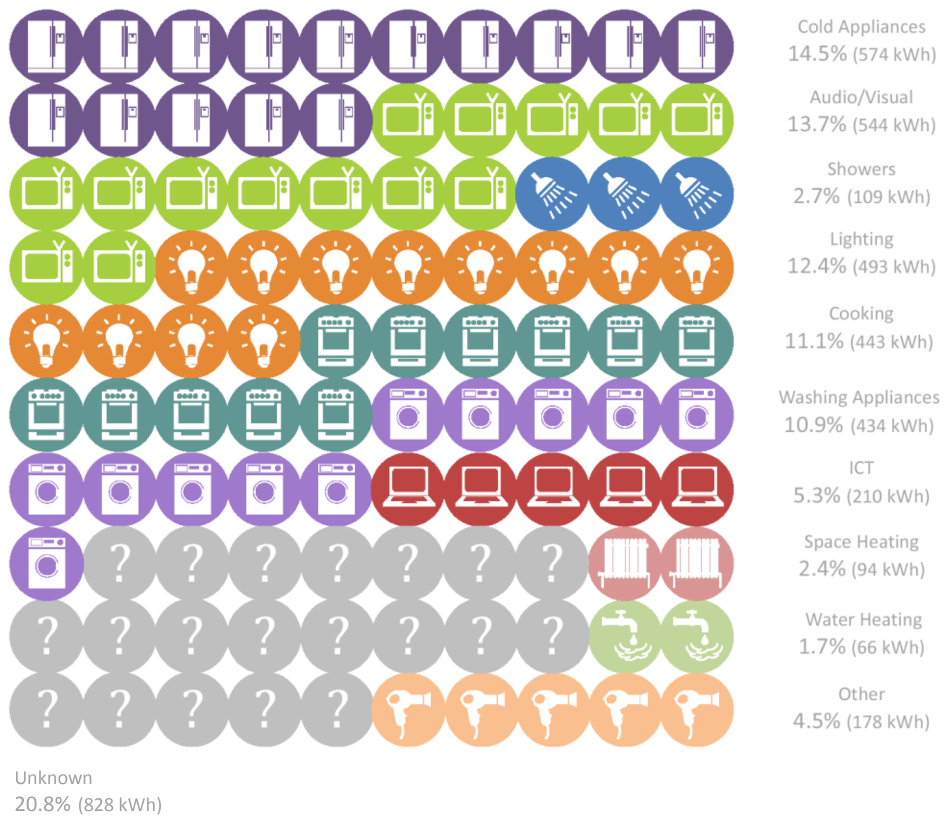
■ If all 4.2 million households in the UK with electric secondary heating could be persuaded to use a different form of heating instead, we could reduce the peak load by around 2 GW. However, this would increase gas (or other fuel) use by between 3,060 and 3,670 GWh a year.

■ There is limited evidence of how room heaters are used in different rooms, but there is some indication that heaters are used more when they are in the lounge or conservatory than when they are in the bedroom or kitchen.

Average electricity breakdown over year
9 homes with primary electric heating



Average electricity breakdown over year
241 homes without primary electric heating



Prepared by Cambridge Architectural Research, Loughborough University and Element Energy under contract to DECC and DEFRA. Views are the authors', not the Departments'. February 2014.