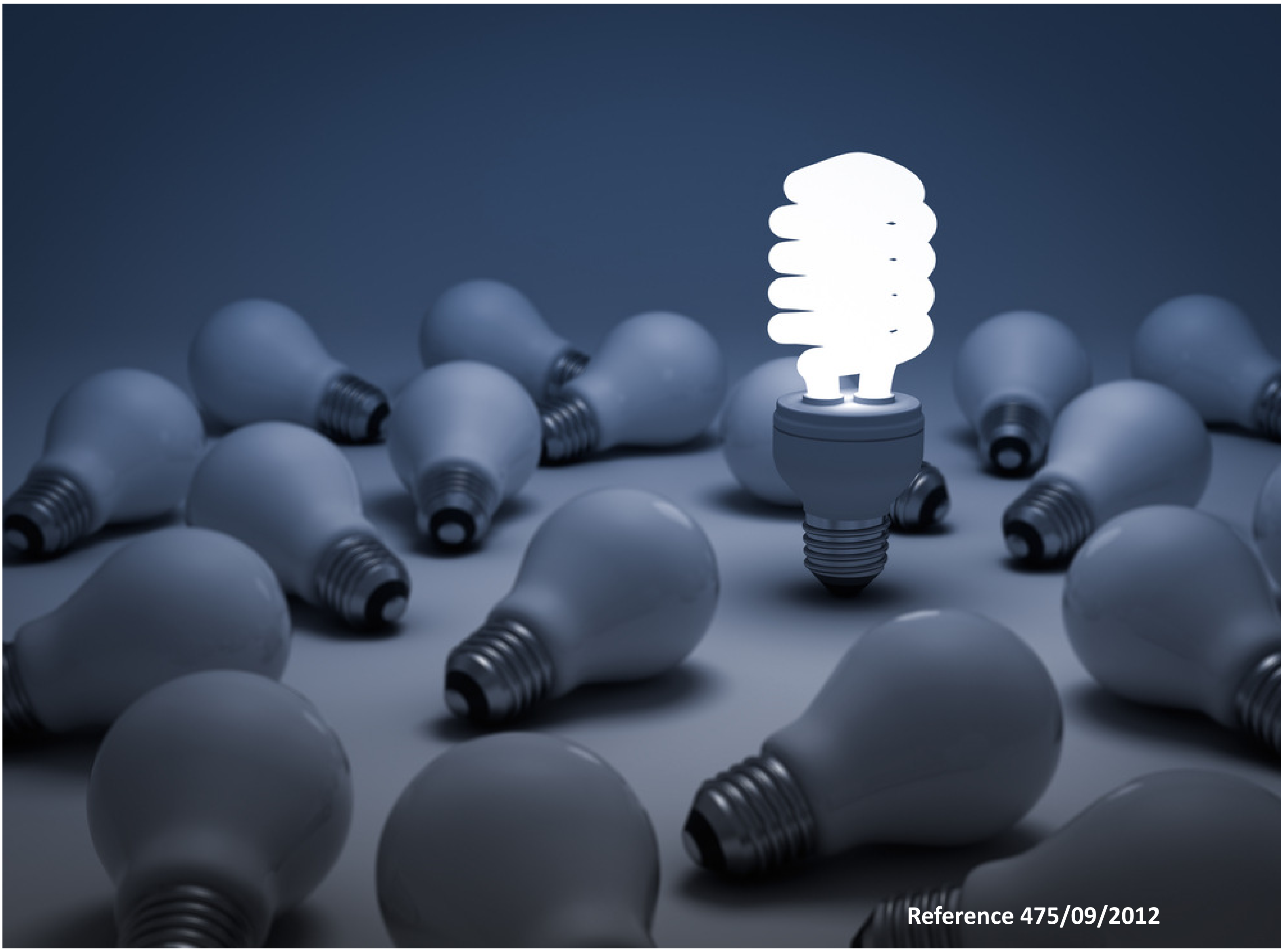
Further Analysis of the Household Electricity Survey: Lighting Study (Final Report)

21 May 2013



Reference 475/09/2012

Nicola Terry, Jason Palmer, Daniel Godoy, Steven Firth, Tom Kane, Amy Tillson

CAMBRIDGE ARCHITECTURAL RESEARCH LIMITED

Loughborough University

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Executive Summary

We have scrutinised electricity use for lighting in the Household Electricity Survey in considerable detail. We focused in particular on trying to see why some households have very high energy use for lighting, whereas others use very little energy for lights. We also looked at baseload lighting power (defined as the minimum electricity use through the day for lights by each household).

We looked in detail at daytime and night-time use of lights, the length of time households wait after sunrise before turning off lights, rebound effects, and associations between lights and other electrical appliance use.

We examined possible algorithms for estimating how much energy is used for lighting in homes, and developed an interactive 'Lighting Tool' for readers to compare modelled estimates of lighting energy against measured data for households in the Survey. We also looked at how geographical location affects lighting use, and whether there are links between longitude or latitude and lighting energy.

Finally, we looked into outdoor lighting and how household energy use for lighting could change over the next 10 years. What does the Survey tell us about the way households use outdoor lighting? Is there any evidence to say whether household use of electricity for lights will rise or fall in the next decade?

We found that the top 20% of households for lighting used more than 760 kWh/year, whereas the bottom 20% used less than 150 kWh/year. We also found some evidence people working part-time are more likely to be high users.

Older householders (65 and over) and single person households are most likely to be low users. The size of the dwelling is also significant (but only accounts for a small part of the variation between households). There is some correlation between high energy use for lighting and total electricity use, but some low lighting households that had very high electricity consumption overall.

Energy use for lighting does not appear to be linked to the proportion of low energy lights in these households. In fact, the total installed lighting wattage is much more significant in determining high energy use for lighting.

We found that households with fewer televisions and other appliances tend to use less energy for lighting.

Conversely, high lighting users often have high daytime lighting consumption. If the 37 using highest daytime lighting could make better use of daylight, they could save up to 65 W each during the day, or 105 kWh/year. High baseload lighting was also linked to high lighting use overall. 10% of these households had baseload lighting energy (minimum through the day/night) of 20W. These households were very likely to have high energy use for lighting overall.

We found no evidence of a rebound effect from comparing hours used against bulb power. Nor was there evidence of any rebound effect from low-energy bulbs: these householders use low energy bulbs in the same way as traditional bulbs and there were no lost savings.

We found that a household's location is not an important determinant of its energy use for lighting, and other factors are much more important – even after normalising for floor area and occupancy.

We compared households in the Electricity Survey against another recent survey, the Energy Follow-Up Survey of the English Housing Survey, and found similar lamp ownership and hours of lighting use between the two samples. Around half as much lighting was used in summer as in winter in both cases, with about 42 hours of lamp use per day on weekdays winter, on average.

Based on our analysis of data from the Household Electricity Survey, we developed a new algorithm for estimating lighting energy use, based on occupant activities, room use, sunshine, installed lamps, and 'unnecessary' use. This appears to be more reliable than existing approaches to estimating lighting use for samples of households, although it is rather complicated, and more empirical data is needed to improve the algorithm.

Regarding outdoor lights, we found that on average homes in the Survey had 168 Watts of installed outdoor lights, although some homes had much more than this (one had 1,500 Watts of halogen lights) and others recorded none at all.

Our projections of how electricity use for lights might change over the next 10 years combined data from the Survey with data from other sources about lighting efficiency, new house building, and take-up rates for low energy bulbs. We estimate that by 2024, if 80% of lights were converted to low energy bulbs, this would result in an average saving of around 230 kWh/year per home, or annual energy use for lighting of around 290 kWh.

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.

In each house individual appliances with plugs were monitored separately, and circuits in the consumer unit were also monitored. This included lighting circuits and lamps with plugs, as well as many other appliances. The monitoring provided energy use in 10-minute intervals for the households participating for a year, and 2 minute intervals for the other households.

As well as monitoring the lighting energy use, there was information collected on lamps installed in each room. Demographic data was also collected for each household.

In this report we investigate lighting use in detail, including:

- seasonal differences in use, based on day length (which affects uncertainty in the estimates of annual lighting consumption for households monitored for just one month)
- differences between high and low use households
- the timing of households' use of lights
- whether there is evidence of rebound effects as a result of improved energy-efficiency of lighting
- patterns linking lighting use with other appliances
- whether it is possible to model energy use for lighting more reliably than the existing Standard Assessment Procedure or BREDEM approach
- differences between energy used for lighting in households located in different parts of England
- what Wattage of outdoor lighting was installed in HES households, and
- how energy use for lighting could change over the next 10 years.

Households included

For this analysis we selected:

- Households monitored outside of the high summer period (30th May to 14th July) - because in summer so little lighting energy is needed the scaling up to annual consumption is uncertain (24 households excluded).
- Households where at least one lighting circuit was monitored. (13 households excluded, which sometimes had some lamps monitored, but this was likely to have missed most of the lighting energy use, which is almost always on a lighting circuit.)

This left 214 households.

Uncertainty in annual lighting estimates

Only 26 households in the survey were monitored for a whole year, and for the remainder we had to estimate annual lighting energy by scaling up from the monitored period. We used data from the 26 households to generate a lighting seasonality factors:

1. We calculated the electricity use on each day, 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.

2. 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.

This is described in more detail in the next section.

There are two sources of variation in this method:

1. Variation due to different households varying their use of lighting differently according to the season, and

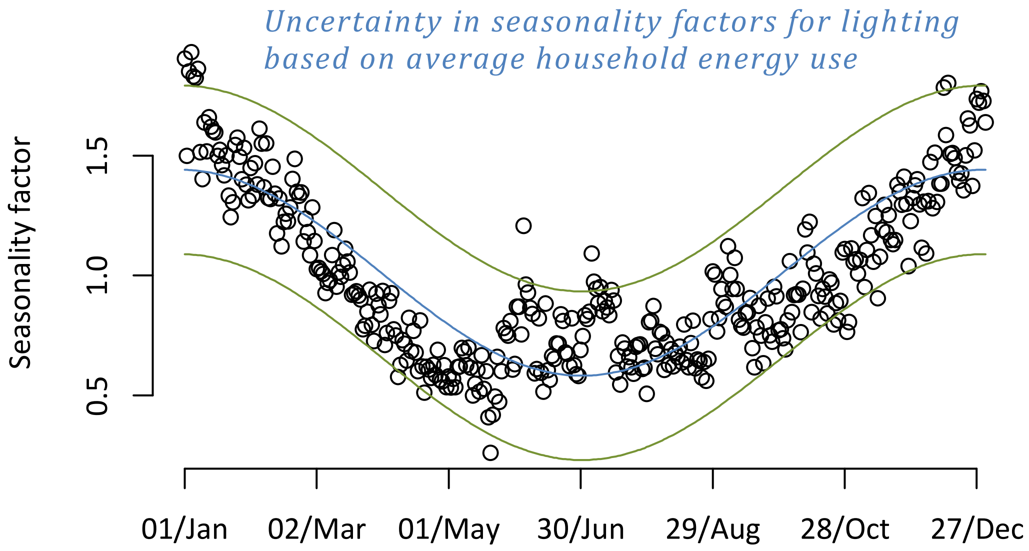
2. Variation due to day to day differences in behaviour.

In practice the seasonal variation is much greater than that due to day to day behaviour differences, as we explain below.

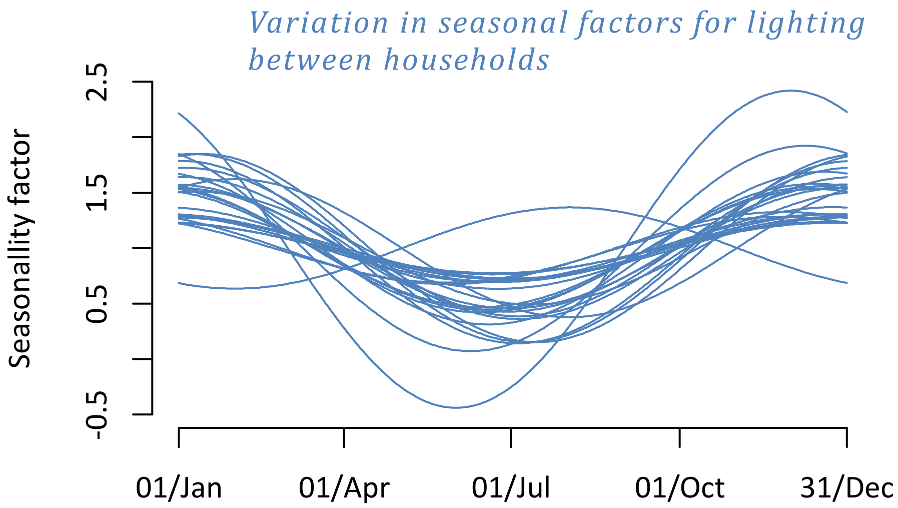
Seasonal adjustments

There were 26 households monitored for a year, but only 25 had monitoring of the lighting circuit. For the initial analysis we treated lighting the same as other appliance types[1]: we calculated the seasonal adjustment factors by fitting a sine/cosine curve to data points corresponding to the average daily consumption for all the monitored households. Using the daily average reduces the impact of anomalous households. The chart below shows 95% confidence intervals for the seasonal adjustment factor calculated in this way.

[1] See Palmer J et al (2013) Household Electricity Survey: Part 2 – Focus on appliances. London: DECC.

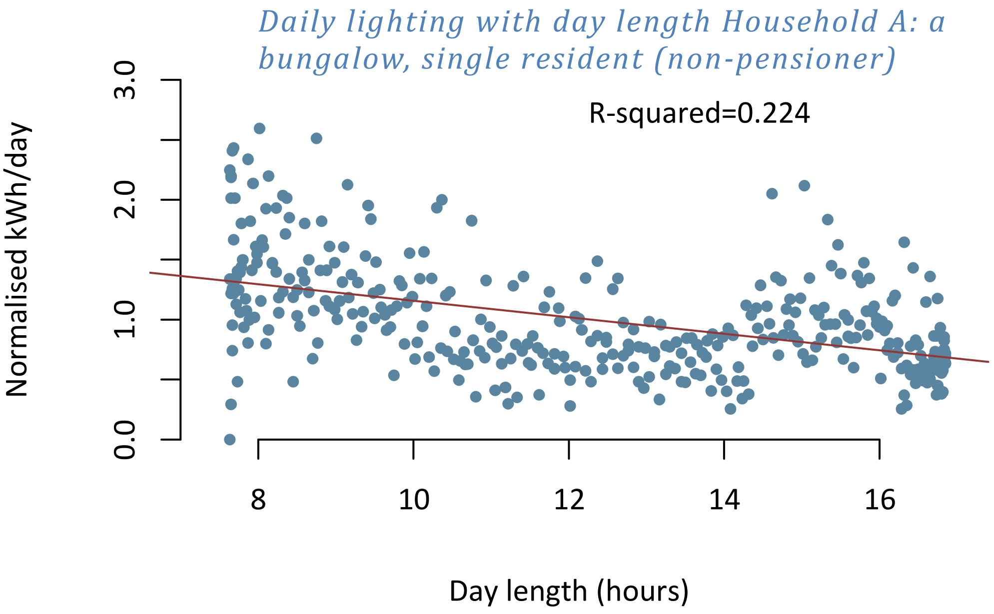


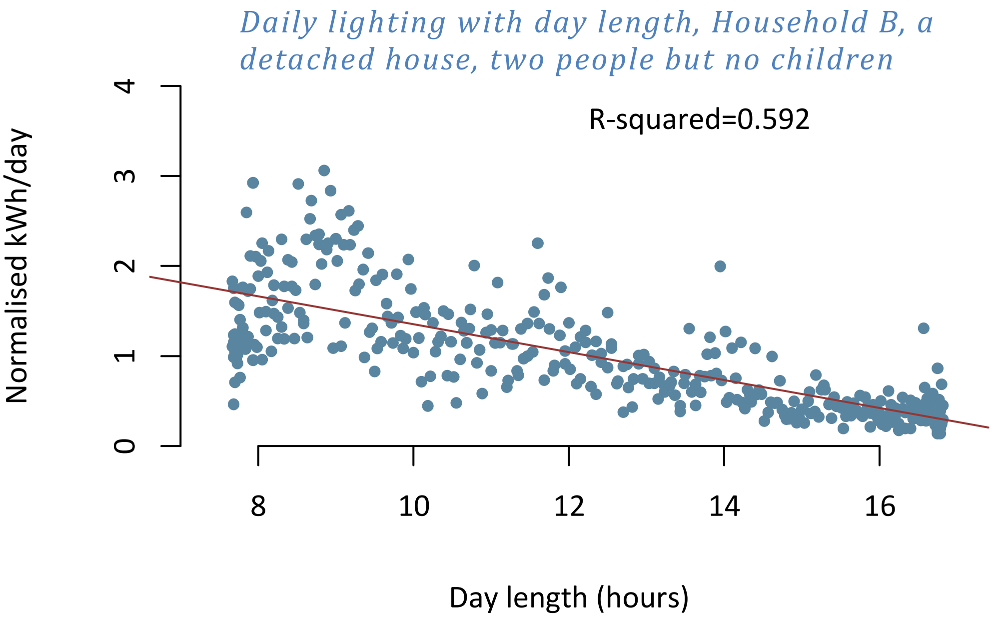
However, using the household average hides the variation between households. The chart below shows the seasonality curve calculated using the same method, on a more complex house-by-house basis.



Some households show much more seasonal variation than others, and the peaks and troughs also occur at different times. Inexplicably, one house even shows a maximum in the summer instead of the winter.

The sine/cosine method gives us two variables describing the adjustment curve: one determines when the peaks and troughs occur, and the other describes how high or low they are. To evaluate the uncertainty more simply we used a different model, based on a linear regression of lighting use against day length. This gives only one parameter for each household: the slope of the regression line. The charts below show two examples from the 25 households.





Among all 25, the slopes ranged between -32%/hour and +6%/hour with a median of 11.4%/hour – quite close to the mean 11.5%/hour. The standard deviation for the slope was 7.2%/hour.

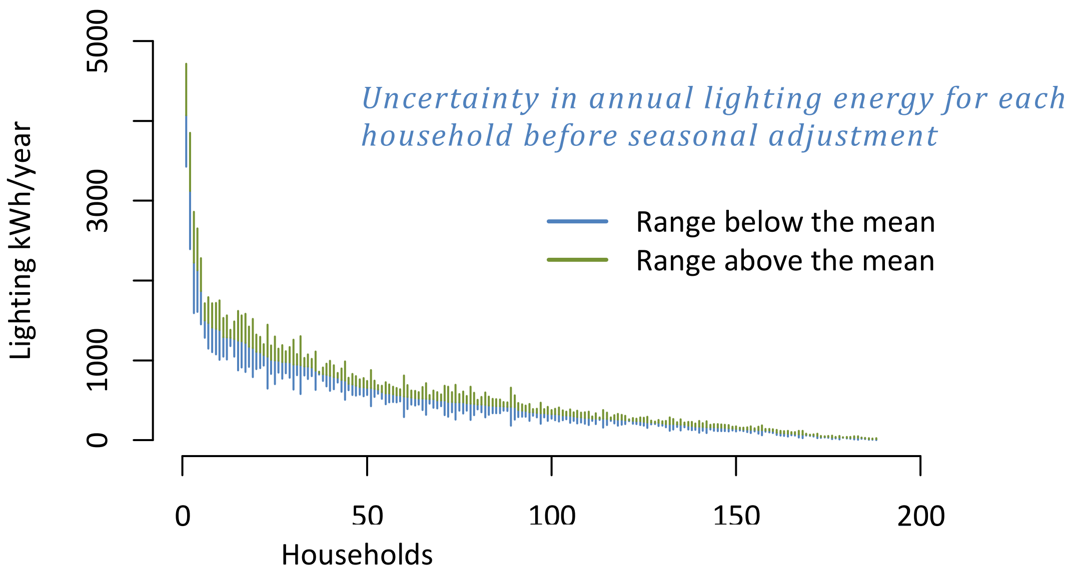
The R-squared parameter indicates how much of the variation in energy use is accounted for by day length. A value of one would mean all variation is accounted for, while zero would mean there was no relationship between energy use and day length. The R-squared parameters for the 25 households varied between 0.03 and 0.65, with a mean of 0.34, showing that day length was an important factor for most but there were other causes of variation too.

Day to day variation

The chart below shows the uncertainty in energy use for each of the month-monitored households, ignoring those excluded for other reasons. We calculated the 95% confidence intervals for the mean daily consumption using a weighted average of holidays and workdays. These values are not adjusted for seasonality and the chart shows only the small uncertainty in this part of the calculation.

Calculation details

For most households we had 25 to 30 sample days, which we divided into work days and holidays. We assumed a normal distribution for the daily consumption, and calculated the 95% confidence intervals for the sample mean. We then combined the holidays and workdays based on 254 workdays and 111 holidays in the year.

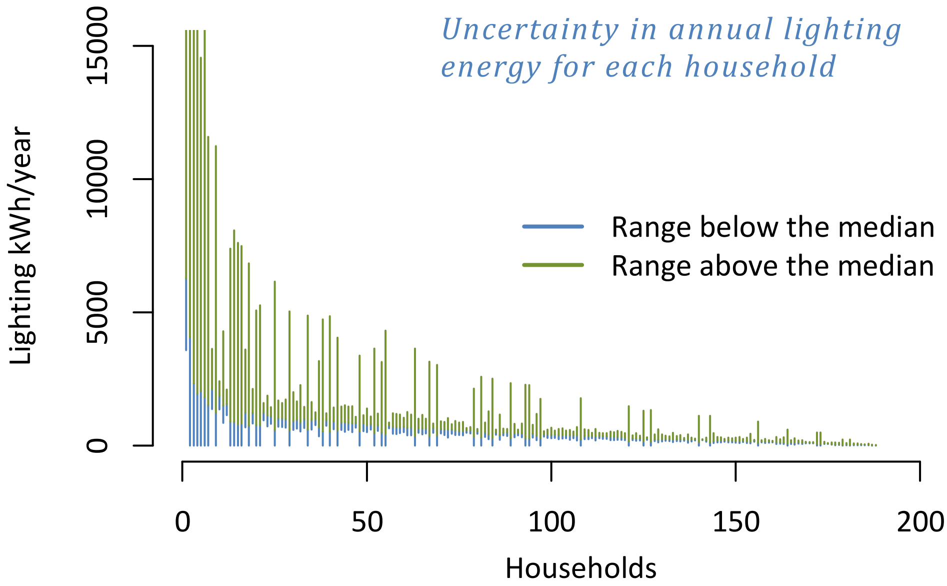


Overall uncertainty

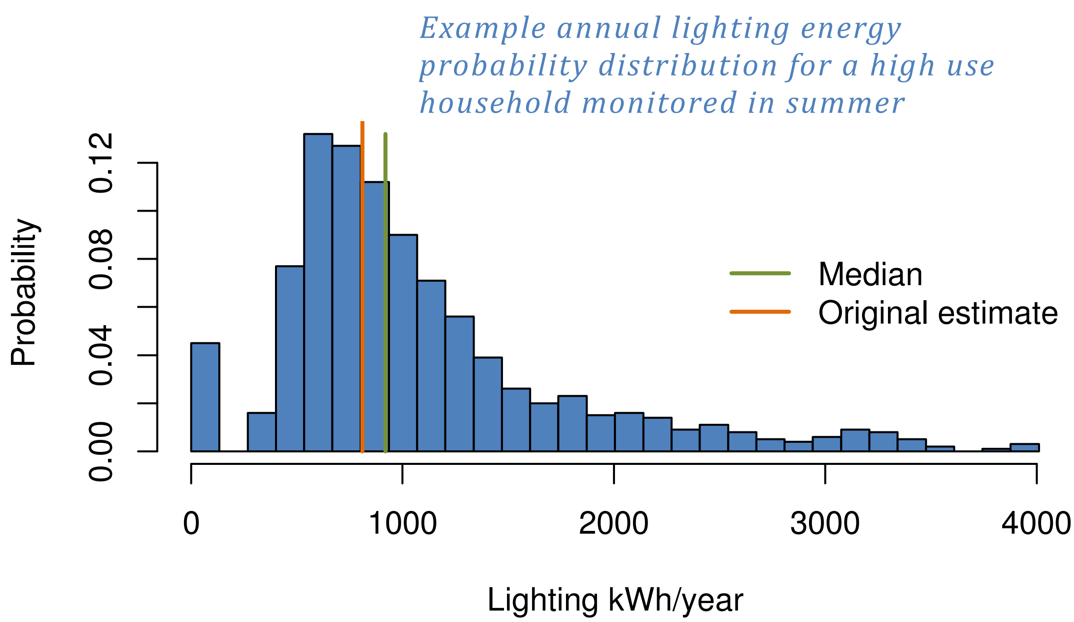
The total annual consumption is the mean (daily consumption/seasonal factor) x 365. Even assuming these parameters are normally distributed the result of division is not a normal distribution. Therefore we used a stochastic method (i.e. based on probabilities) to compute the overall confidence intervals for the annual lighting energy for each house. We generated 5000 randomly distributed sample values for each of the parameters and calculated the annual mean in each case. The chart below shows the 2.5%, 50% and 97.5% quantiles for the distribution obtained. (We show the median rather than the mean because this illustrates the skew in the distribution very well.)

Calculation details

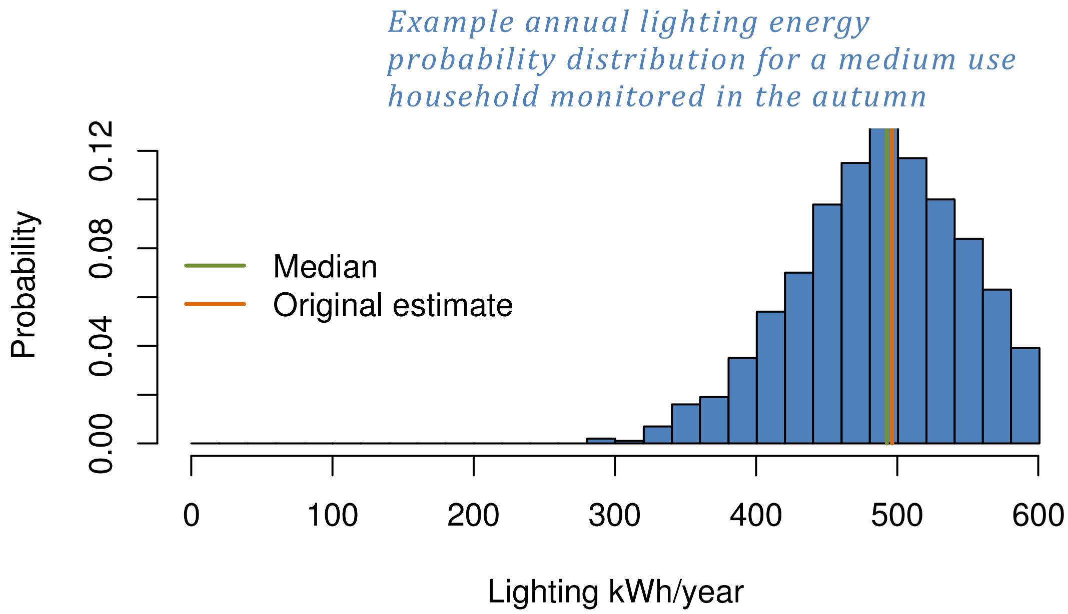
For each of the 5000 samples for each house we first generated a value for the daily use based on the mean and standard deviation for the sample mean for the daily sample points as described above, using a weighted average of holidays and workdays. We then generated a slope for the seasonality factor based on the mean and standard deviation from the 25 yearly households. We calculated the day length for the middle of the monitoring period and used this to determine the actual seasonality factor for the case.



For some households the uncertainty is large, especially above the median: these are the households monitored close to the summer period, when lights are needed and the seasonal adjustment means dividing by a small number (much less than 1). This magnifies the uncertainty in both the day to day variation and the seasonality factor. The charts below show some example cases.

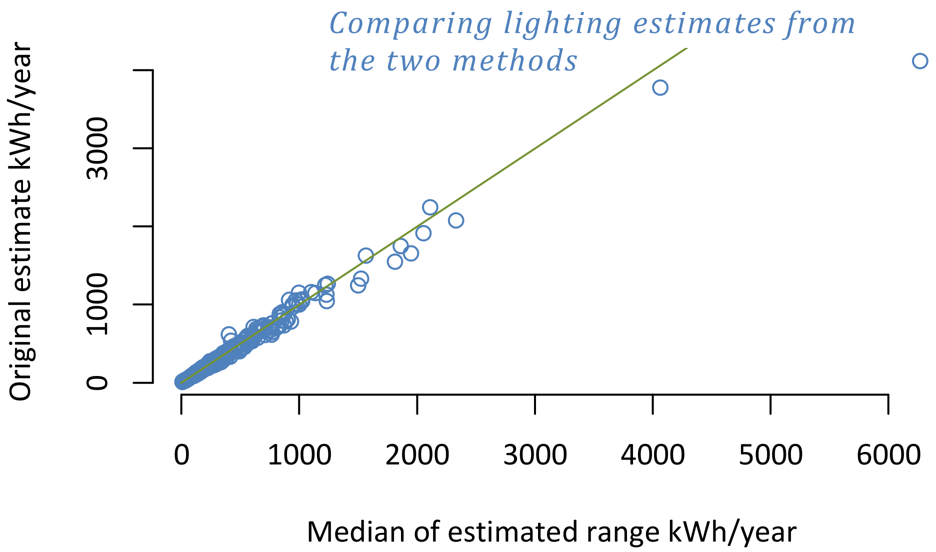


This house used an average 0.5 kWh/day in July/August. The difference between the two estimates is 12%.



This house used an average 0.48 kWh/day in September/October. The difference between the two estimates is 1%.

Although we used a completely different calculation method, the median annual lighting for most households was close to our original estimates, as shown in the chart below. In 60% of cases it was within 10%, and in all cases the original estimate was well within the 95% confidence range. The average of the original estimates for these houses was 518 kWh/year, and the average of the medians from the new method was a little higher: 550 kWh/year.



Other Research on Lighting Energy Use

DECC figures suggest the average annual energy consumption for lighting in a UK home is approximately 530 kWh, or about 3% of total household energy use (including heating and cooking)[2]. Annual energy use for lighting increased until 2004, when low energy lighting became more available. Since then it has decreased, but still accounts for a similar percentage of total household energy use. However, these figures are based on modelled data and are very few published studies of lighting use in UK homes.

In one study, Wall and Crosbie[3] collected illuminance data from 18 UK dwellings during the spring of 2007 . Householders were also interviewed about their use of lighting. Mean weekly electricity consumption for lighting was estimated to be 3.8 kWh. Annual figures were not estimated but with seasonal adjustment it is likely that this figure would be significantly lower than the annual energy use for lighting reported by DECC. The authors concluded that replacing incandescent light bulbs with compact fluorescent lamps (CFLs) would reduce average household electricity consumption by 50.9%. CFL lamps are more common now and even by the time of the HES report in 2010/2011 we would expect some of these savings to have already occurred.

There have been no previous studies which link lighting energy use with other appliance use. However, two studies[4,5] showed a clear correlation between average annual electricity consumption and floor area.

Investigate High/Low lighting users

We were interested to know as much as possible about high and low lighting users – why do some households use a lot of lighting and others only a little, and how can high users be targeted and encouraged to reduce their energy consumption?

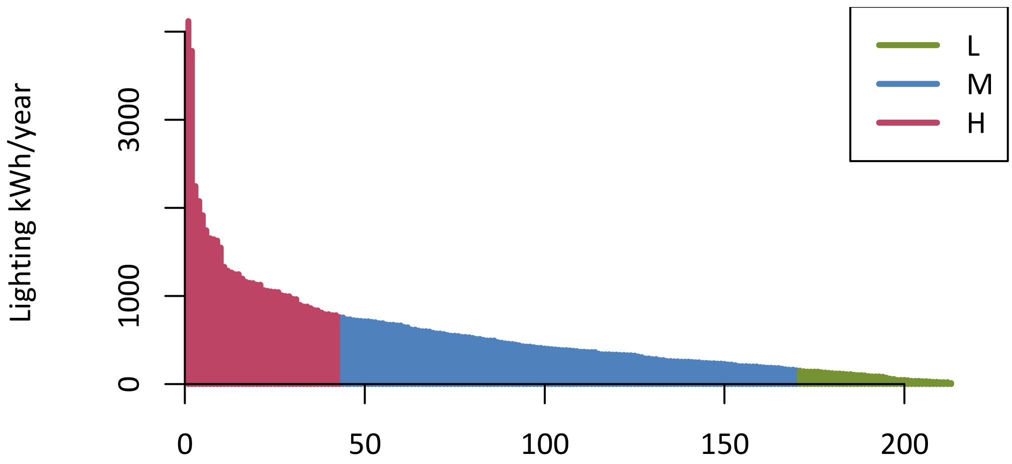
We classified the households as high/low users according to our estimate of their annual lighting energy use. We classified the top 20% (43) as high users, the bottom 20% as low users, and the middle 60% as medium. Their lighting use is as shown in the chart. The low users averaged 82 kWh/year and the high users averaged 1300 kWh/year (nearly 16 times as much).

[2] DECC (2012) The UK Housing Energy Fact File 2012, Department of Energy and Climate Change, London.

[3] Wall, R. & Crosbie, T. (2009) Potential for reducing electricity demand for lighting in households: An exploratory socio-technical study. Energy Policy 37, 1021–1031.

[4] Yohanis, Y. G., Mondol, J. D., Wright, A. & Norton, B. (2008) Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. Energy and Buildings 40, 1053–1059.

[5] Yao, R. & Steemers, K. (2005) A method of formulating energy load profile for domestic buildings in the UK. Energy and Buildings 37, 663–671.

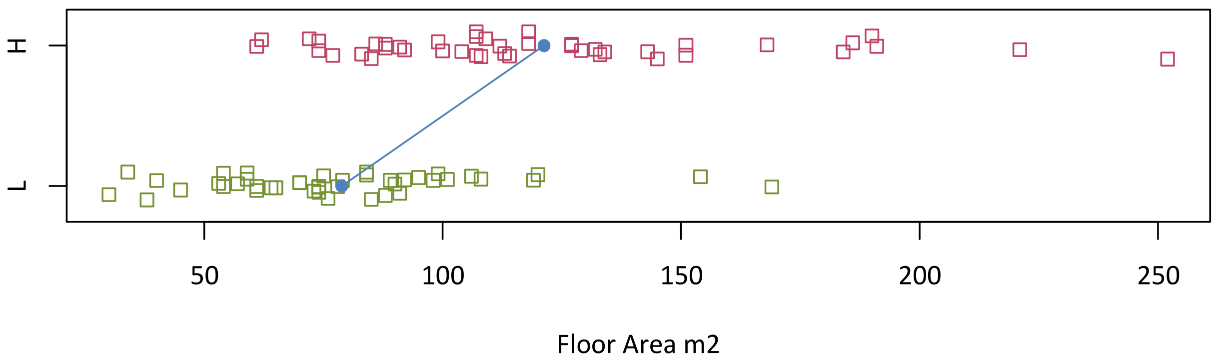


We compared low and high lighting users in various ways.

Demographics and housing characteristics

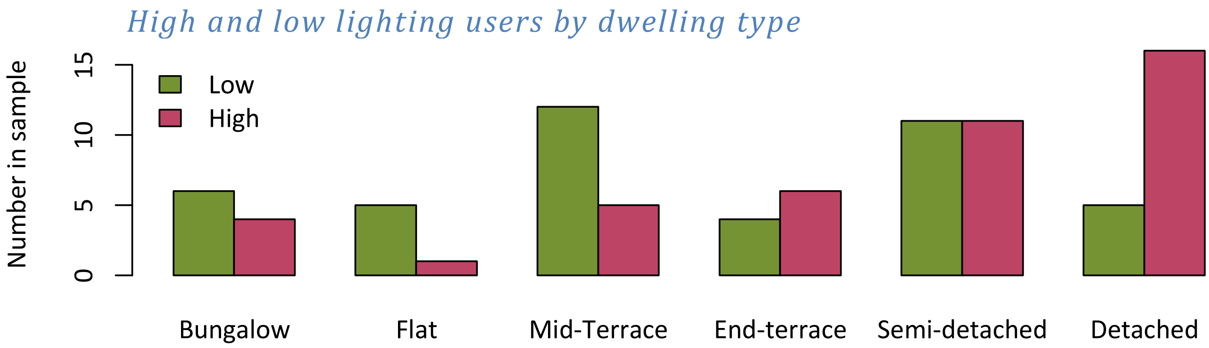
Living in a large dwelling is correlated with high lighting use, although there is a great deal of residual variation, see plot below. Both high and low lighting user groups were significantly different from the mean in dwelling size ($p < 0.01$).

Floor area of houses in low/high lighting groups

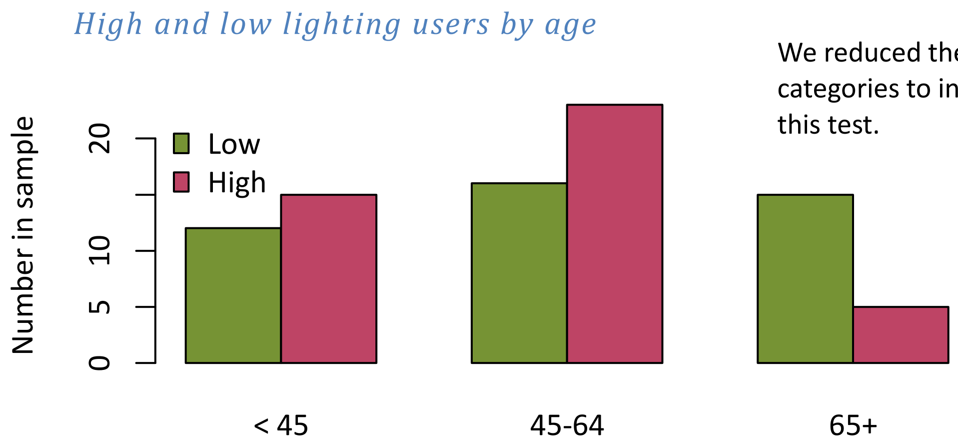


Each square corresponds to a household, and the blue line connects the medians of the two groups.

There was also a link with dwelling type: most households living in detached houses were high users, whereas those living in flats or mid-terraced houses were more likely to be low users. However this difference disappeared when dwelling size was taken into account by dividing lighting energy by floor area.



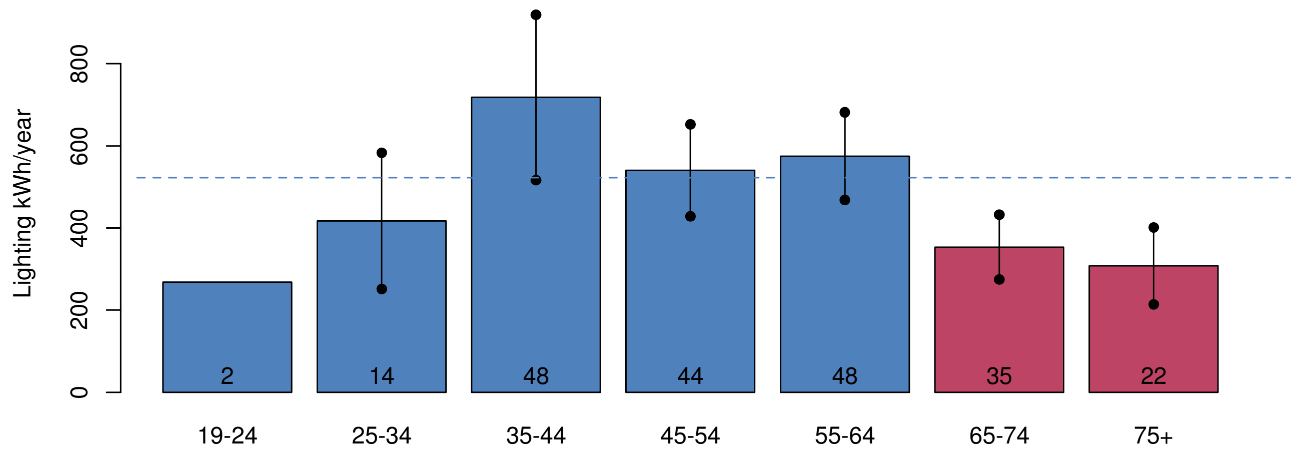
Householders over 65 were more likely to be low users ($p = 0.04$) and this was significant even after floor area had been taken into account (older households typically lived in smaller dwellings than 35 to 65 year olds). The low lighting use in the elderly could be an effect of age, in which case as the current population grows older they will also reduce their lighting consumption. However, it is more likely due to the social norms at the time when these people established their living habits. In the interviews, several elderly householders said they had always been careful with lights and other electricity use. This finding is consistent with a Swedish study from 2008[6].



We reduced the number of age categories to increase group sizes for this test.

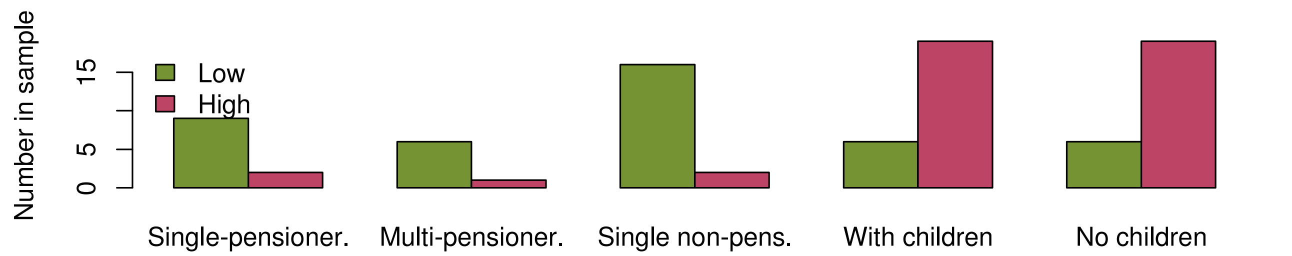
The highest using age group was 35-44, but the difference from the mean was not significant.

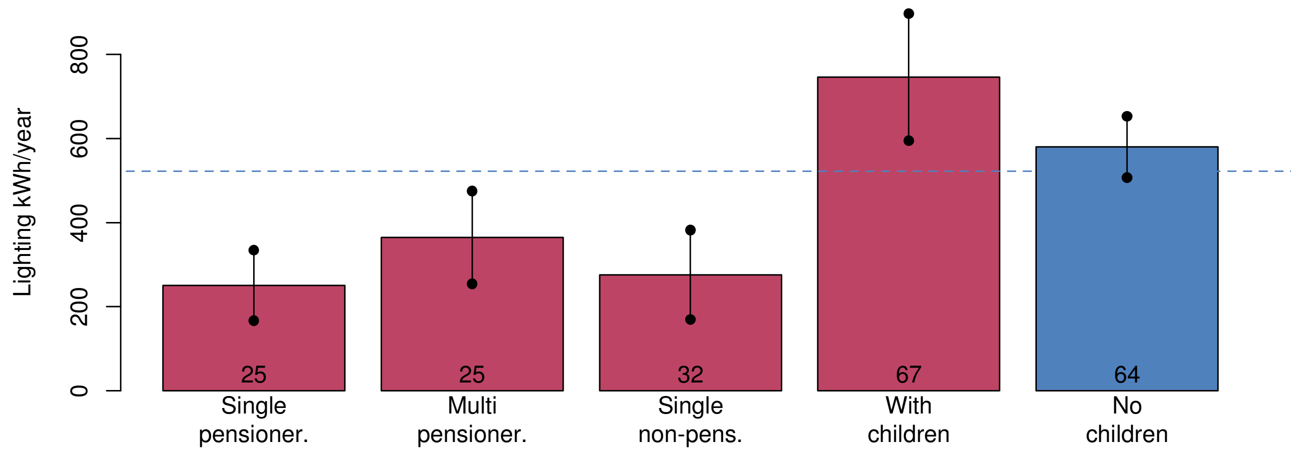
[6] Mats Bladh and Helena Krantz (2008) Towards a bright future? Household use of electric light: A microlevel study, Energy Policy 36(3521-3530)



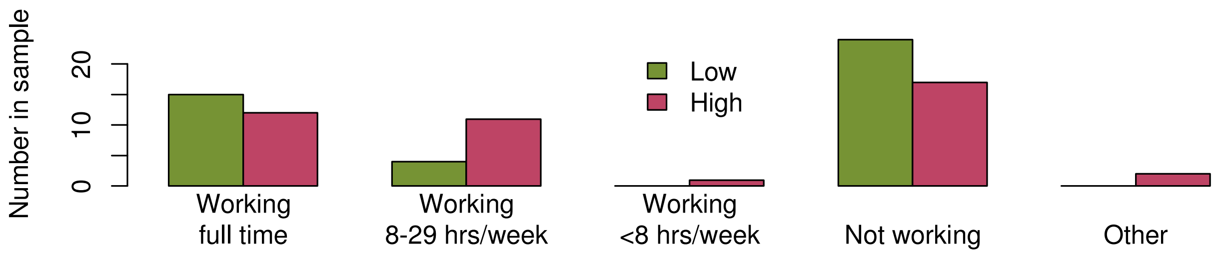
The figures at the base of each column show the number of households in the sample. The red bars show a statistically significant difference from the overall mean. The black lines are 95% confidence intervals for the mean.

Pensioners and single-person households were more likely to be low users, whereas other households with children were more likely to be high users.





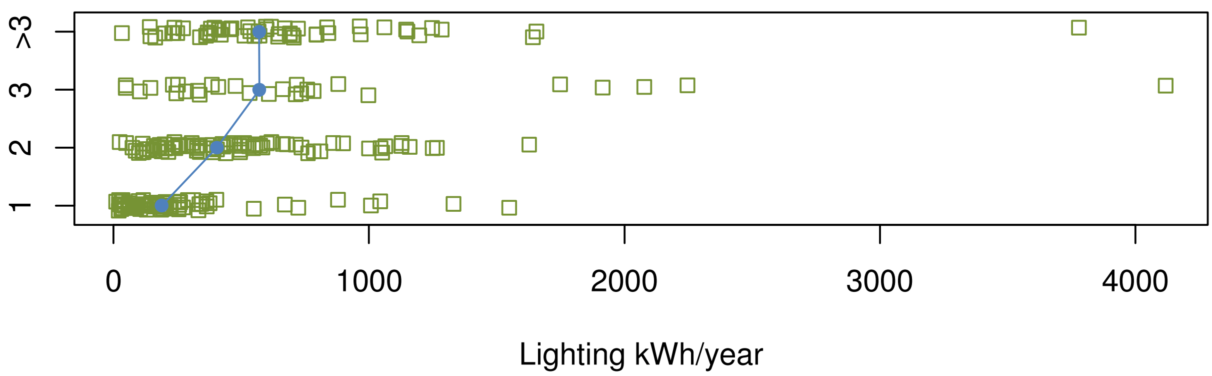
Working status yielded few statistically significant differences, except that retired households use rather less than average (131 kWh/year less), explained by the difference due to age. It appeared that people working part-time are more likely to be high users, whereas full-time or no employment made no difference. Perhaps this is because people working part-time are at home needing light for more of the time, and have sufficient income that they do not have to be so careful as people who are not working at all. Alternatively, it could be related to unsocial working hours for part-time workers, and hence lighting use in the late evening or early morning. This is shown in the chart below and the table that follows.



Status	Median lighting kWh/year	Mean lighting kWh/year	Number in sample	p-value
Full-time paid work (30+ hours/week)	386	463	68	0.18
Part time paid work (8-29 hours/week)	492	796	36	0.08
Part time paid work (< 8 hours/week)	532	697	4	(too few for t-test)
Retired	272	391	77	0.001
Not in paid employment (not seeking work)	420	492	14	0.78
Unemployed (seeking work)	445	742	10	0.34

Single person households used less lighting (245 kWh/year less than the average, $p < 0.0001$) and larger households with more than three people used more (156 kWh/year more than the average, $p = 0.05$).

Lighting energy use against household size



Each square corresponds to a household, and the blue line connects the medians of the two groups.

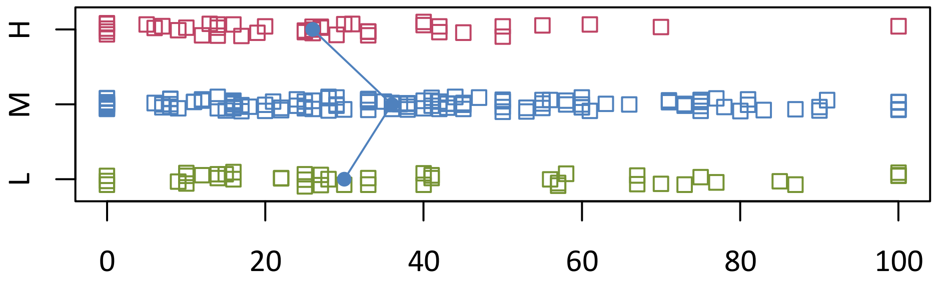
Finally we investigated socio-economic grade as a factor and found that A and B grades were more likely to be high users. However, this is largely explained by dwelling size, since these grades tend to have larger homes.

In summary, we found that working status is not significantly different between high and low groups but single person households and older householders (65 and over) are more likely to be low users. Also the size of the house is significant (though still only accounting for a small part of the variation between households). Other factors such as house type and socio-economic group are also significantly different in the two groups, though this can be explained by dwelling size.

Installed lighting

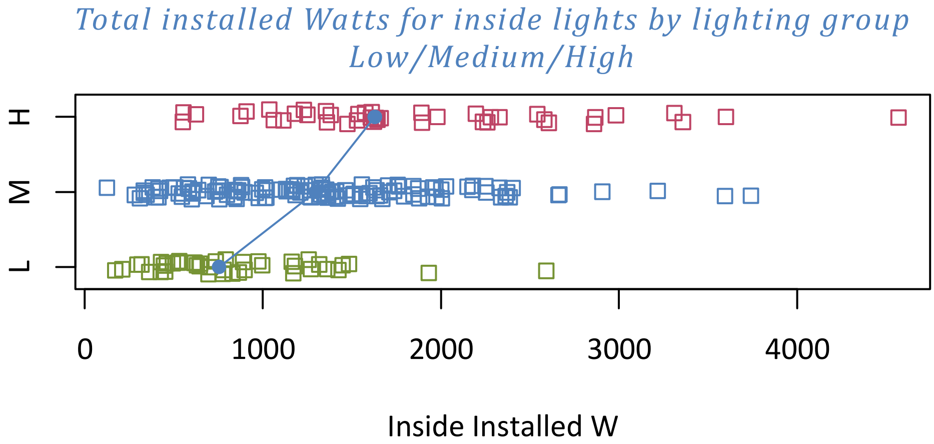
We confirmed the finding from earlier analysis that the low energy lighting fraction – the proportion of light sockets with low energy light bulbs installed – was little different between the high and low use groups.

Low energy lighting fraction by lighting group Low/Medium/High



However, we did find a difference between high and low use groups in terms of their total installed wattage. For all but four of the households the survey included data on the lamps installed in each room, even if they were on the lighting circuit. We added up the wattage of all the lamps in the house to obtain a total, and we also considered the total wattage of the lamps separately in the kitchen, the lounge (main lounge if there was more than one) and all the lamps inside the house (excluding patio, garage and other external lights). We found that the total of the inside lamps was the most strongly correlated with high lighting use and this was significant – even in a combined regression analysis taking into account floor area as well ($p = 0.003$). However, the R^2 (coefficient of determination) was still only 0.14, showing that these factors accounted for only a small part of the variation between households.

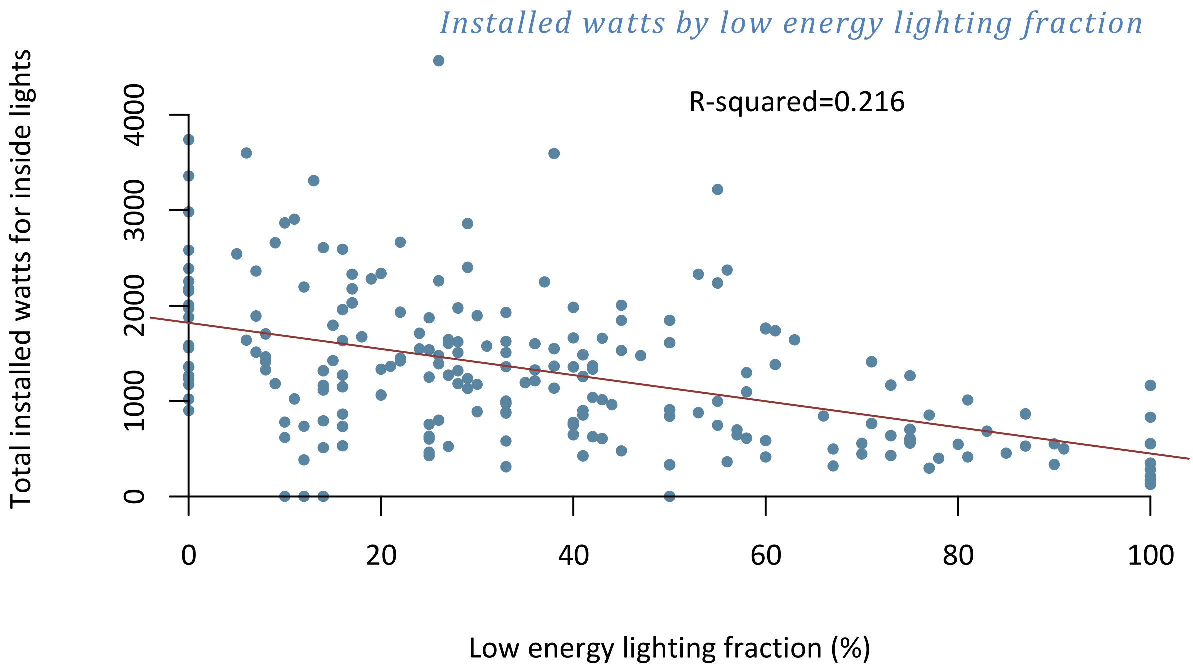
The chart below shows the wattage for each household. There were still households with low lighting use, even though they had a large amount of installed lighting capacity. They clearly were not using the lights they had available, at least not most of the time. However, on average the low lighting group had less than half the installed wattage of the high light group (850 W for low lighting users, 1330 W for medium, and 1870 W for high lighting users).



The blue line connects the medians of the three groups at 760, 1300 and 1600 W

There may be a case for policies aimed at curtailing the installed wattage of internal lighting. For new homes, this may be as straightforward as minor changes to the lighting requirements in Part L1A of the Building Regulations, and better enforcement of the existing lighting requirements. For existing homes, this is harder, but lighting requirements could be introduced into Part L1B (for existing homes that have substantial alterations).

One might expect that the installed wattage would be related to the low energy lighting fraction, and indeed it is, as shown by linear regression in the chart below, but there were many households with a high proportion of low energy lamps and still quite large installed Watts. Later in this report we discuss evidence for a rebound effect, whereby installing low energy lights might encourage householders to leave them on for longer.

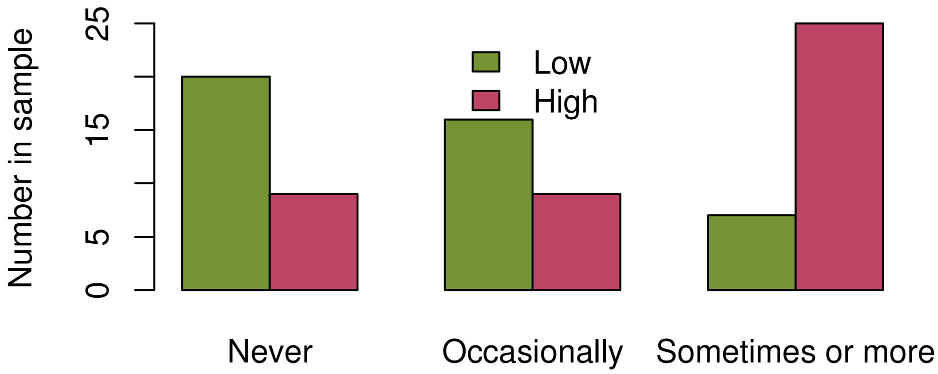


Earlier work on the same data[7] found that the room with the most installed lighting was the kitchen (mean 249 W) and then the lounge (225 W). The kitchen also had the highest proportion of halogen lighting and slightly less low energy lighting than other rooms (counting both CFL and fluorescent as low energy).

Behaviour statements

In an interview survey householders were asked how often they left lights on when they are not in the room. Their answers were slightly correlated with their lighting use ($p < 0.01$). However, one of the lowest lighting users said they always left lights on, and some of those who said they never did nonetheless had high use.

How often do you leave your lights on when you are not in the room?

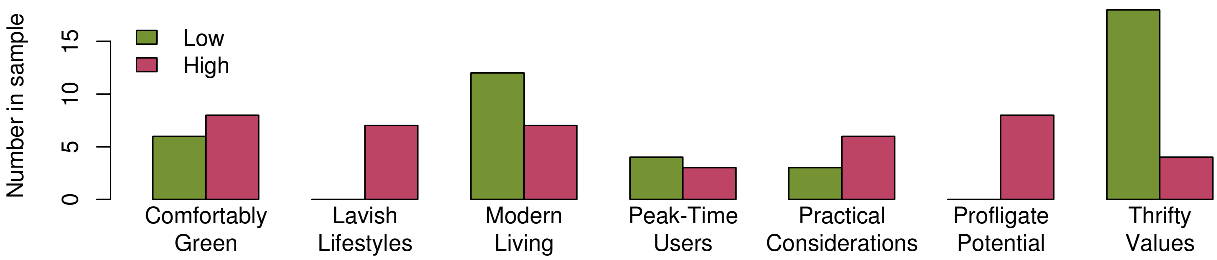


We compressed the answer categories from 6 to 3 in order to increase the number of samples in each group. The last category includes sometimes, quite often, often and always.

Low lighting use was also correlated with not overfilling kettles, and turning off mobile phone chargers, but households who claimed these behaviours were also likely to claim to turn lights off, so these behaviours are linked.

Another report on the same electricity data by Element Energy Ltd[8] explains how they combined data from the householders' stated beliefs, current actions and beliefs about the future with the socio-economic and other demographic data, overall electricity use and peak time use and conducted a cluster analysis. They classified the households into seven groups as shown in the chart below. There are no low users in the 'Lavish Lifestyles' or 'Profligate potential groups', whereas there are few high users and many low users in the 'Thrifty values' group, which seems consistent with Element's work.

High/Low lighting groups divided into consumer archetypes



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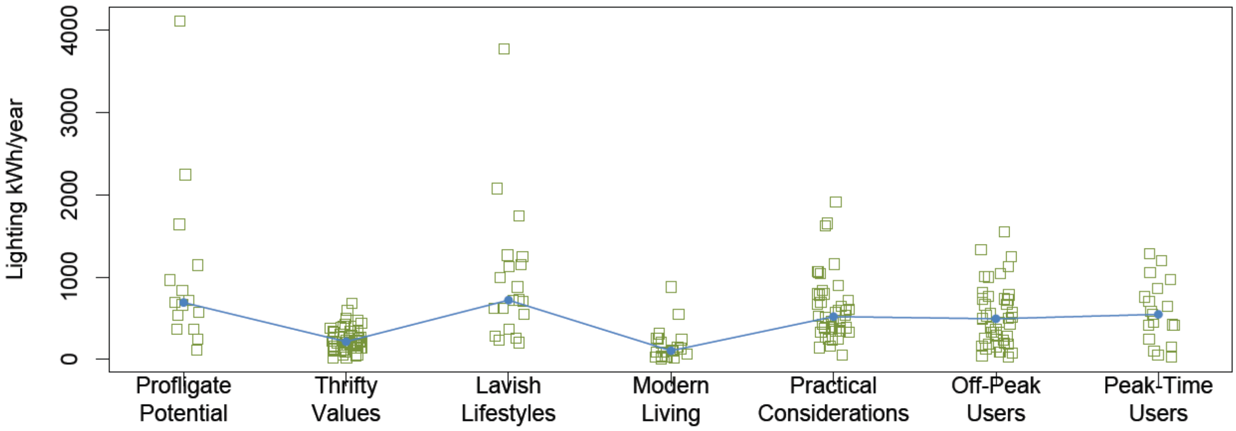
[7] Zimmerman et al (2012) Household Electricity Survey: A study of domestic electrical product usage. Milton Keynes: Intertek/EST/DECC/DEFRA.

[8] Element Energy Ltd (unpublished?) Further Analysis of Data from the Household Electricity Usage Study: Consumer Archetypes. London: DECC and DEFRA.

We also examined how energy use for lighting varied between the seven clusters Element had defined, and we found significant differences between the energy used by different clusters, see chart and table below. The 'profligate potential' cluster used most energy, on average, for lighting, while 'thrifty values' and 'modern living' clusters used significantly less than all other clusters. (Significance test at the 5% confidence interval.)

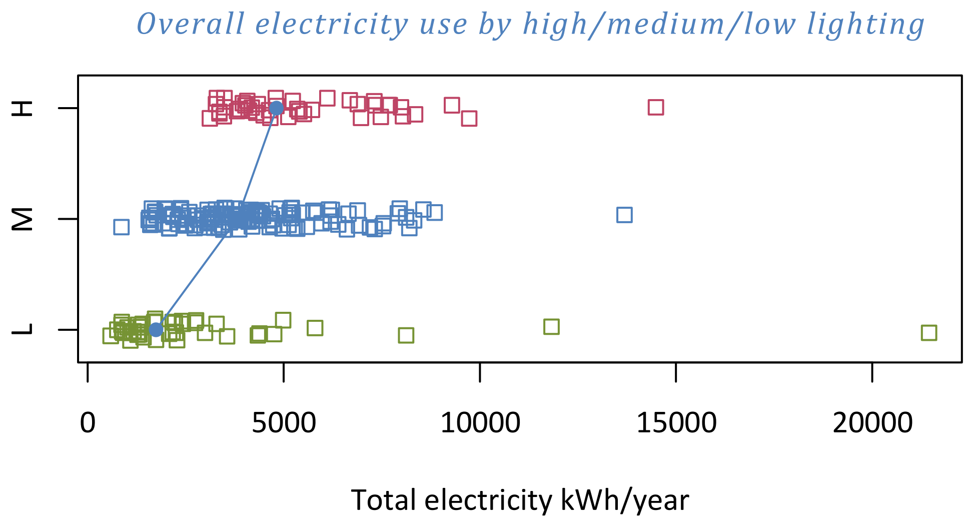


Readers should also note that the 'thrifty values' cluster was quite large – the largest of all clusters, with 51 cases across the HES sample. It is a relatively common profile, with remarkably consistent energy use for lighting, and because lighting energy use is already low in this group the opportunities for achieving savings are likely to be limited. It is almost certainly better to focus efforts on energy saving from lighting elsewhere.

Cluster	Mean lighting kWh/year	Number in sample	p-value
Profligate Potential	1015	15	0.08
Thrifty Values	243	51	< 0.0001
Lavish Lifestyles	977	20	0.02
Modern Living	172	21	< 0.0001
Practical Considerations	616	44	0.13
Off-Peak Users	525	43	0.97
Peak-Time Users	572	19	0.58

Other energy use

High lighting users tended to use more electricity overall, though there were some low lighting households that had very high electricity consumption overall (probably because they use electric space heating).



Each square corresponds to a household, and the blue line connects the medians of the two groups.

Low lighting users had fewer TVs than other households. They also had fewer computers and other appliances in general (see table below).

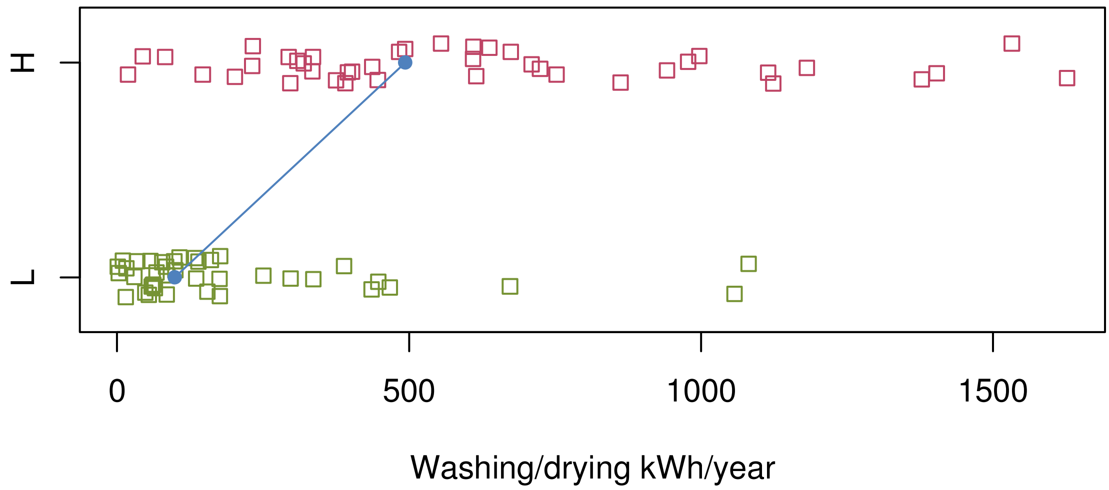
Appliance	Mean for low lighting group (p-value)	Mean for high lighting group (p-value)
Televisions	1.7 (0.0002)	2.7 (0.03)
Computers	1.2 (< 0.0001)	2.1 (0.05)
All electrical items	34 (< 0.0001)	47 (0.01)

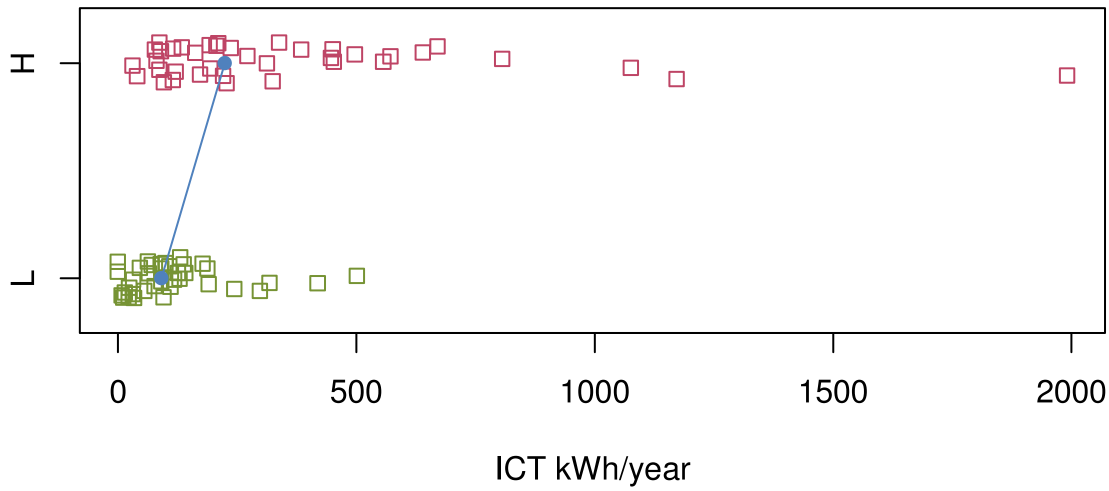
We determined the rank of each household for each category of appliance, and used linear regression to determine if high use of energy for lighting was also correlated with high use for the other categories. We also calculated the Pearson correlation for the ranks: this varies between zero (meaning no correlation) and one (meaning identity).

The table below shows the top six results. In all cases the correlation was positive, i.e. high use of the appliance was correlated with high use of lighting. The strongest correlation (lowest p-value) was with use of washing/drying appliances, then cooking and then with cold appliances. TVs were also correlated with lighting, but less strongly. There is a correlation between some of these parameters and demographics parameters including household type, the size of the dwelling and social grade. For example, washing and AV use are both greater in households with children. After adding these parameters into the regression we found the ranking for cold appliances, washing and AV were no longer significant. However cooking remained significant and ICT also became significant.

Appliance category	Pearson correlation with ranks for appliances and lighting energy	P-value for regression with ranks for appliances and lighting energy without floor area or social grade	P-value with household type, floor area and social grade
Washing (washing machines, dryers and dish washers)	0.40	0.000009	0.055
Cooking	0.34	0.0018	0.033
Fridges and freezers	0.30	0.017	0.0966
AV (TVs, video etc).	0.27	0.023	0.133
ICT (computers etc.)	0.17	0.056	0.043
Showers	0.02	0.27	0.834

The strip charts below for washing and ICT appliances illustrate these relationships.





As before, each square corresponds to a household, and the blue line connects the medians of the two groups.

Characteristics of the lighting profiles

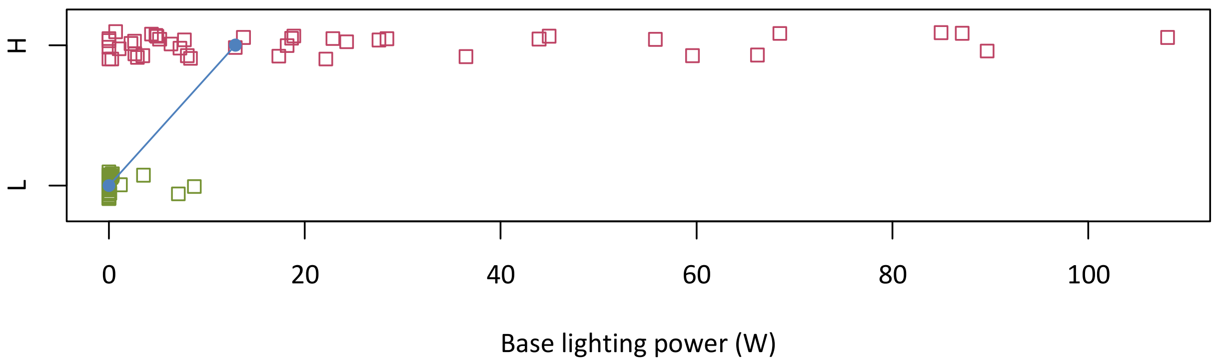
We analysed the lighting profiles of each household in three ways:

- Base load – the minimum for an average day.
- Daytime – the average load during the daytime in spring and summer.
- Morning switch off – the average time the household left lights on in the morning after sunrise (winter time only).

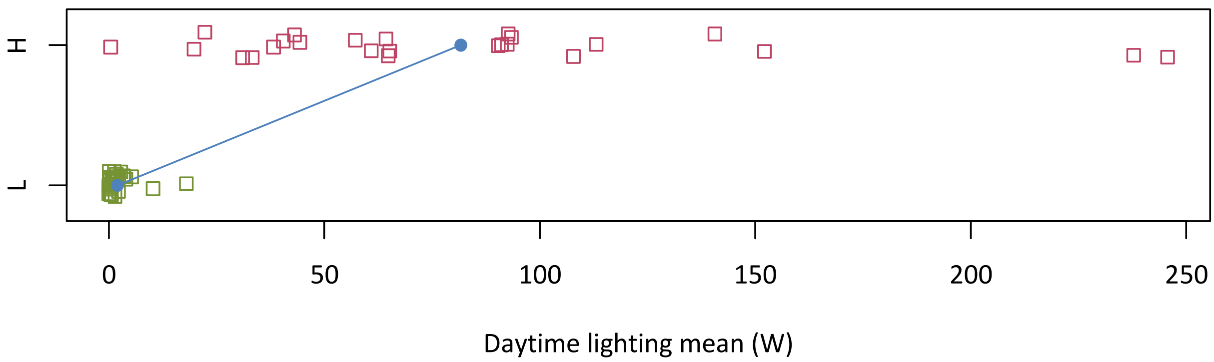
We describe our methods in detail later in this report. This section draws out summary findings comparing the high and low use households.

The high use households had an average of 24 W for base load, compared to 0.5 W for the low users. Added up over the year, 24 W running continuously is 210 kWh, which is well above the limit for the low lighting group (154 kWh/year). This means that an average base load alone would take a household out of the low user group.

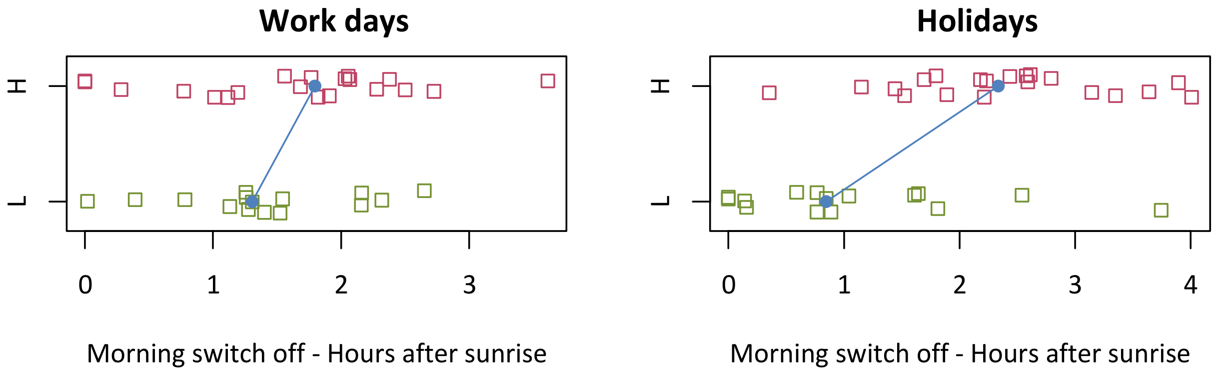
There was no significant correlation between base load and low energy lighting fraction.



For high users the average daytime lighting was 78 W, while for low users it was just 2 W. We defined daytime lighting as between 9am and 6pm (BST), April to September. This therefore accounts for about 1620 hours in the year and 78 W for this time comes to 126 kWh/year.



There was little difference in switch off time (delay between sunrise and switching off lights) on workdays, but on holidays the high users were much more likely to delay turning off lights in the morning.



These findings are summarised in the table below, which shows characteristics where the high and low use households differ significantly.

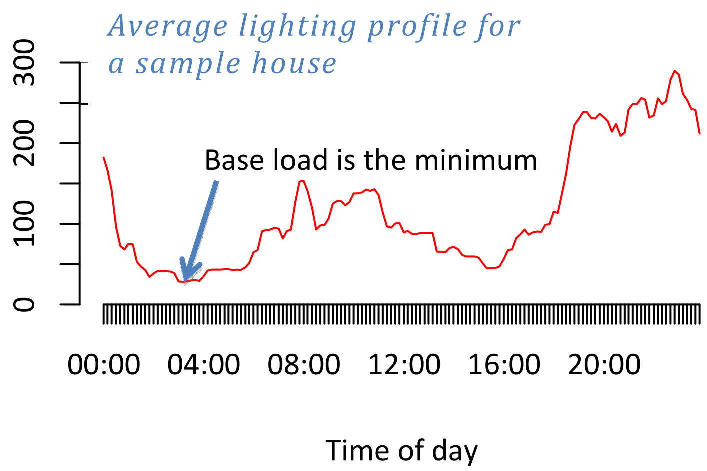
High use households	Low use households
Large dwelling (mean 121 m^2)	Small dwelling (mean 79 m^2)
More detached houses (34%)	Fewer detached houses (11%)
Fewer flats, bungalows and mid-terrace houses (13%)	More flats, bungalows and mid-terrace houses (29%)
More of socio-economic group A/B (53%)	Less of socio-economic group A/B (23%)
Few single person households (9%)	More single person households (25%)
Few householders aged 65+ (9%)	More householders aged 65+ (26%)
High installed watts (mean 1830 W)	Low installed watts (mean 830 W)
Few of those who claim never to leave lights on (13%)	More of those claiming never to leave lights on (28%)
Average 2.7 TVs per house, 2.1 computers	Average 1.7 TVs per house, 1.2 computers
Are ranked high for energy use for washing/drying, cooking and AV	Are ranked lower for energy use for washing/drying, cooking and AV
High base load (mean 24 W)	Low base load (mean 0.5 W)
High daytime lighting (mean 78W)	Low daytime lighting (mean 2W)
Slow to turn lights off in the morning (mean 2.4 hours after sunrise on holidays)	Quick to turn lights off in the morning (mean 1.1 hours after sunrise on holidays)

Base load lighting

Some households have lights on all the time and this can quickly add up over the year – just 10 W comes to 88 kWh/year. It is hard to understand why it should be necessary to leave any lights on all the time, however (though many householders have some lighting for security or safety in the night-time). Therefore we looked to see how householders vary in this respect.

Approach

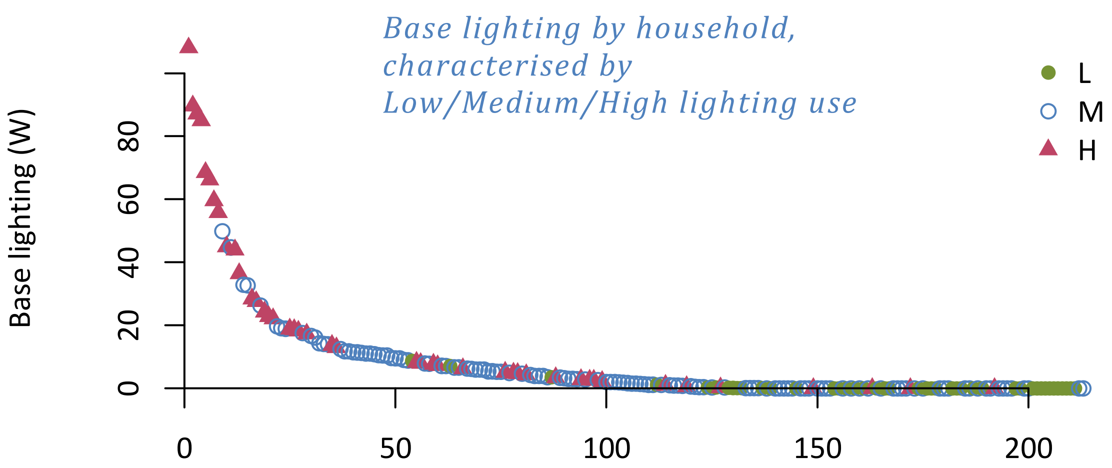
We calculated the base load for each house by taking the average lighting profile through the day (all lights added together) and finding the minimum Watts. This could be during the day or night – in the example profile below it is during the night.



Analysis

The average base load for all the houses was 8.2 W (95% confidence range is to 5.9 to 10.5 W) adding up to 72 kWh/year. However, 21 households (10%) had a base load above 20 W. The following chart shows the variation between households. High base load households were very likely to be high lighting users overall.

NB The cut-off at 760 W for high users represents a continuous 87 W base load, so three of these households would qualify as high users on base load alone.



It is possible that base load lighting could be reduced, either by replacing lights in constant use with more efficient bulbs such as LEDs, or by turning lights off when not needed. The next section considers how much could be saved during the day.

Daytime Lighting

During the daytime there should be little need for lighting in most places in the dwelling: when electric lighting is used it could be because there is activity in an area with inadequate lighting (some households have very poor natural lighting), or it could be due to carelessly leaving lights on. In either case this could contribute to high lighting consumption that could be reduced.

Approach

We determined the mean lighting power for each household on each day during the daytime in spring and summer.

- From April to September (135 households)
- Between 9am and 6pm (8am to 5pm GMT)

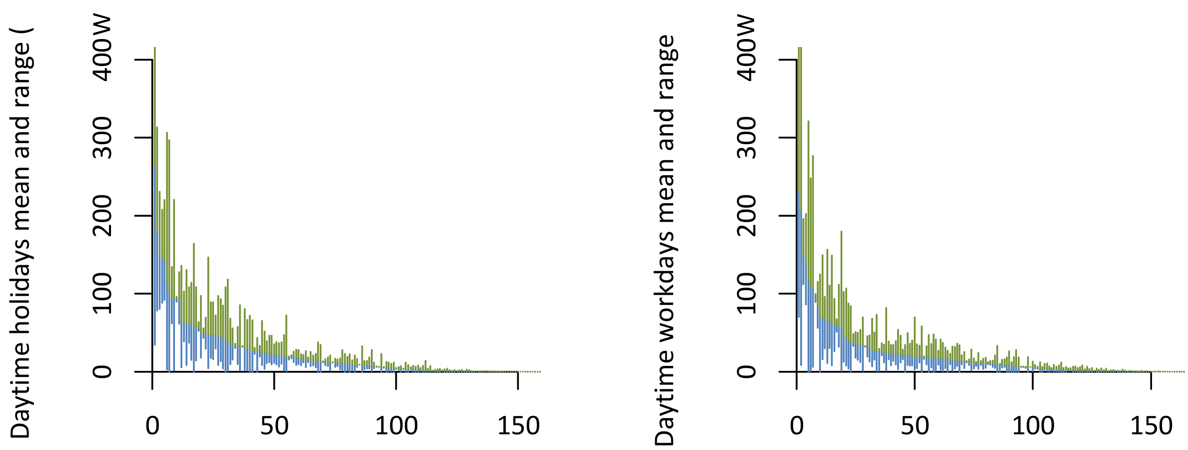
We looked at both the mean and day-to-day variation for each dwelling. We looked at holidays and workdays separately because some households are out during work days. We compared daytime use with night-time use (between 2am and 4 am) and looked for correlations with the overall lighting use, demographic and attitude data.

Analysis

The mean daytime lighting power consumption across all the households was 24 W. However, the top 37 households (27%) were responsible for three quarters of the energy use. They averaged 67 W, and between them they were responsible for 2.5 KW of lighting during the day. The chart below shows the mean and the variation between days (using 10% and 90% deciles) for each house.

There was little difference overall between workdays and holidays: the mean for workdays was 23.6 W, and for holidays 25.6 W. However, there was more variation during holidays. The chart below shows the mean and the variation between days (using 10% and 90% deciles) for each house.

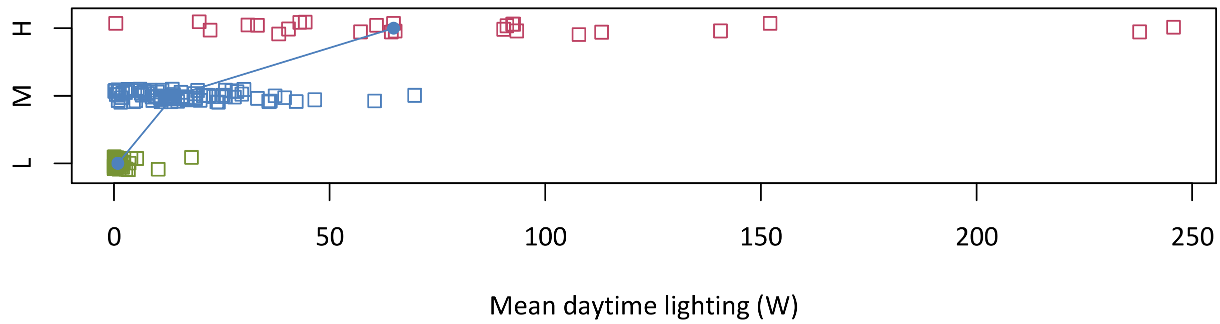
Daytime lighting mean power with 10% to 90% range for each household

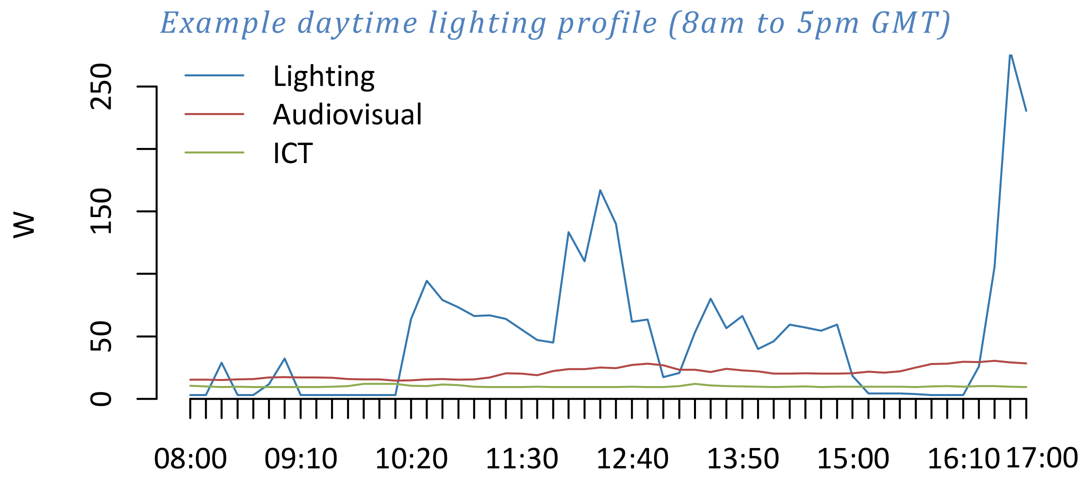


The daytime users were rarely consistent from day to day, which implies that they did not simply leave lights on all the time.

If the top 37 daytime lighting users could make better use of daylight they could save up to 65 W each during the day, or 105 kWh/year (based on 9 hours, 180 days in the year). (Mean electricity use for lighting by these 37 high daytime lighting users was 65 W.)

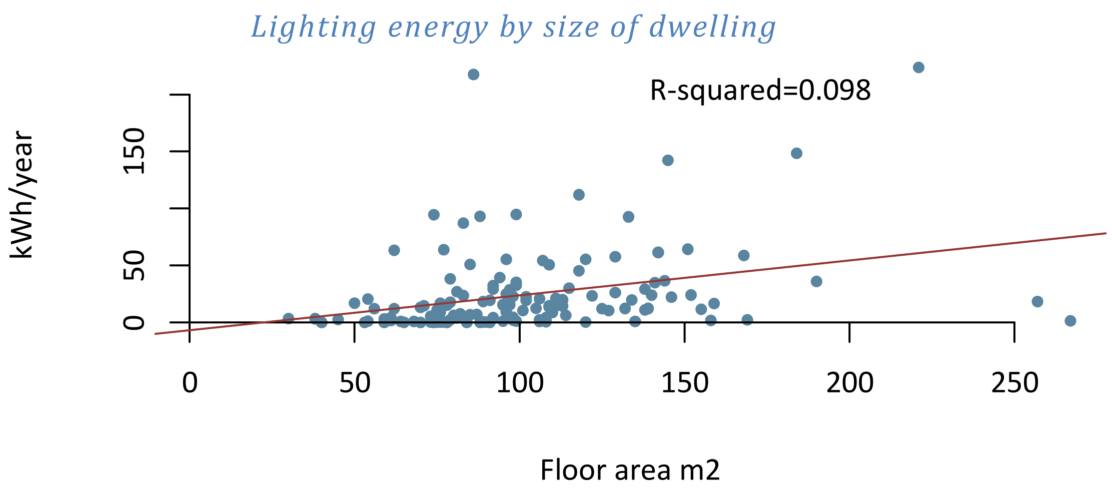
High lighting users often have high daytime lighting consumption:



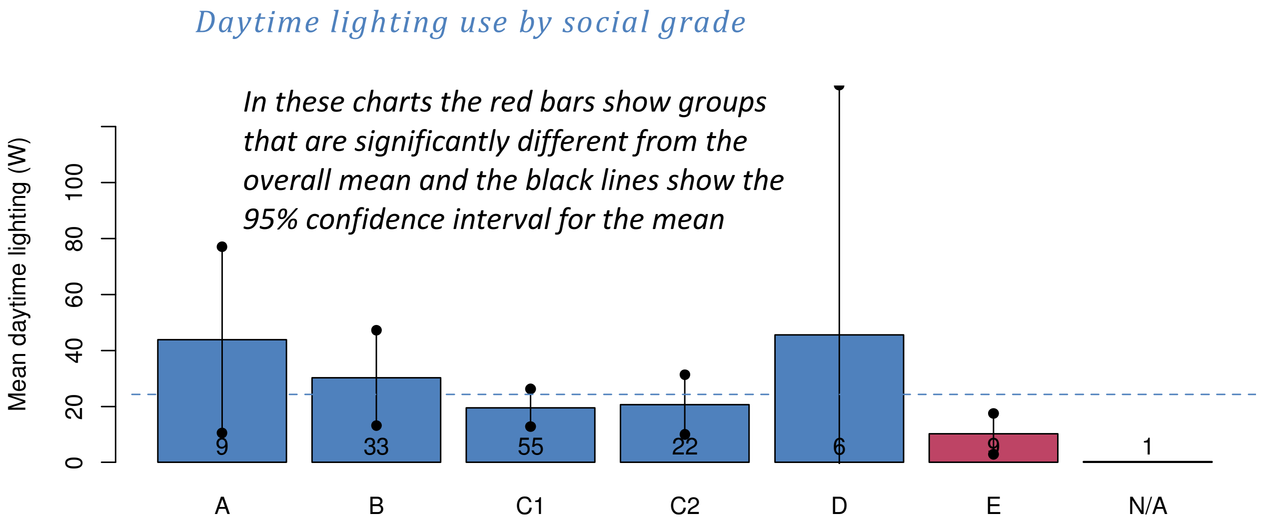


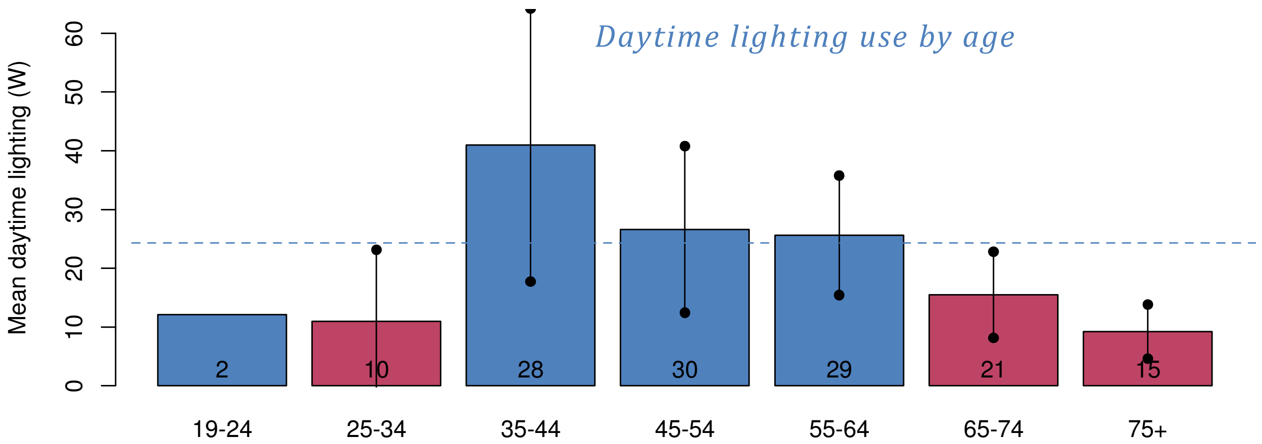
This chart shows the average daily profile for one house. Lights are switched on and off during the day. Note that daytime lighting is not related to ICT or TV use.

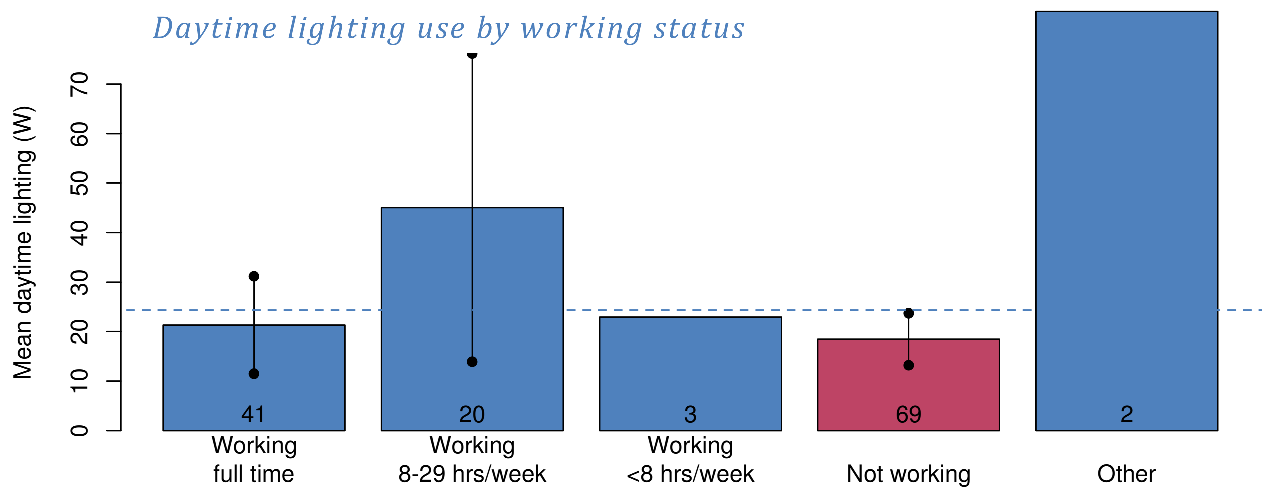
The size of the dwelling was a significant factor for daytime lighting (p=0.003), but three large dwellings used less than 5kWh/year for daytime lights, as shown in the chart below.

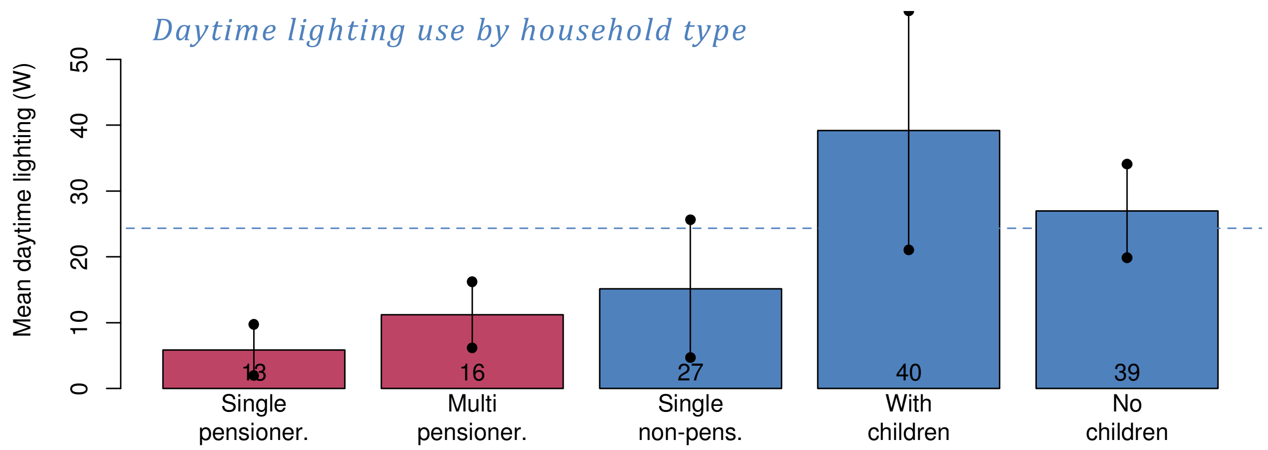


As with overall lighting, we found social class, age and pensioner status were significant factors for daytime lighting. House type and house age were not. For working status, the 'not working' group used significantly less than the mean, while part time workers were not significantly different. Perhaps this is because householders who are at home during the day are more careful with their energy use, especially as they are likely to have lower income.









Many of the high daytime users (> 36 W) claimed not to leave lights on when they were not in the room: 18 out of 36 said they did this only occasionally or never.

Night time lighting

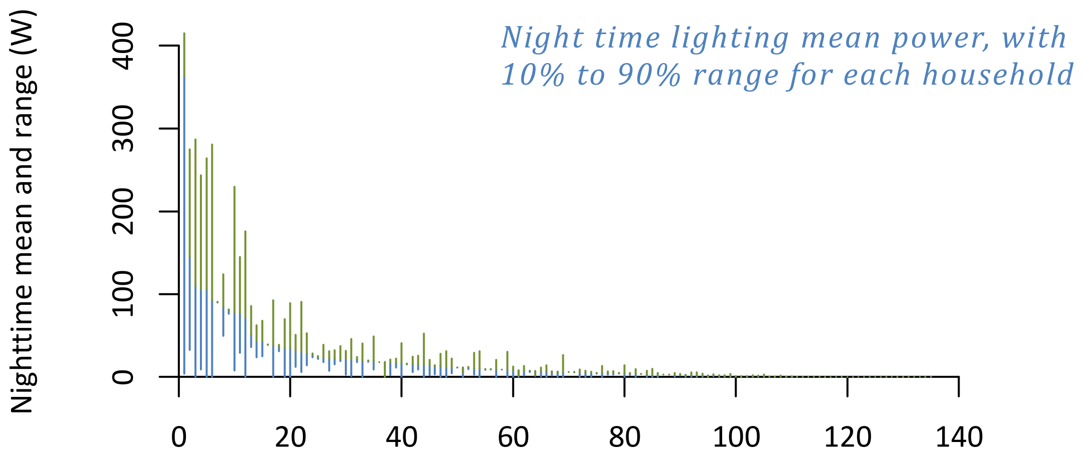
From the interviews we knew that some households leave lights on for personal safety or security, and our earlier analysis[9] shows that approximately one third of households left some lights on consistently overnight for at least five hours. The average across all houses of this consistent use was 12 W. In this analysis we looked at the inconsistent use as well, which might be due to varying need (such as shift work, insomnia or parties) or simply forgetting to turn lights off at night.

Approach

In this analysis we established the mean and variation in each household for all lighting between 2 and 4 am.

Analysis

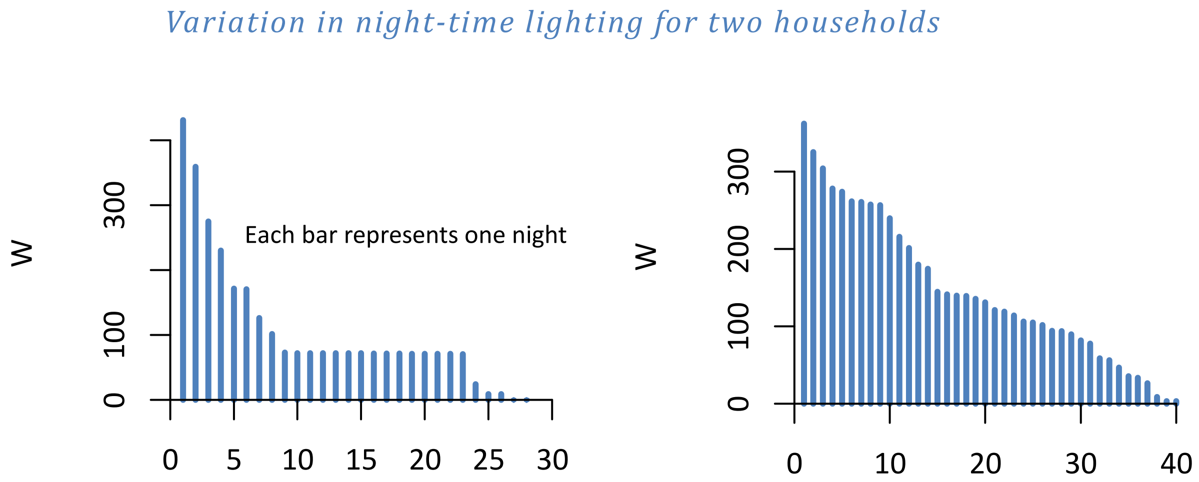
The average night-time lighting was on average a little less than the daytime use (19 W from 2am to 4 am, compared to 25 W from 9am to 6pm). There was more consistency in night-time use too: 25% of the households using more than 15W on average varied by less than 10 W. However, there was still considerable variation, especially among the high users, which may suggest these lights are not just for security.



High night-time use is slightly more common on Saturday and Sunday mornings (25 out of 67 cases where night time use > 300W), which suggests that there may be weekend parties. However, there are also a number of households with consistently high mean lighting at night.

[9] See Palmer et al (2013) Household Electricity Survey: Part 2 – Focus on appliances. London: DECC/DEFRA.

These charts show the variation in night time lighting for some of the high-use households.



Households with high lighting use at night were often also high daytime users: 15 households were in the top 30 for both.

Night time energy use can be related to shift working, but we had no information about this in the HES dataset. There was no significant relationship between night time energy use and working status.

Morning switch off

We analysed the use of lighting for each day and each house to determine the time in the morning when lights were turned off after the morning peak. We found this varied a great deal from house to house. We compared these switching times to sunset and sunrise times for each day, and looked at the length of time after sunrise before lights were switched off.

Approach

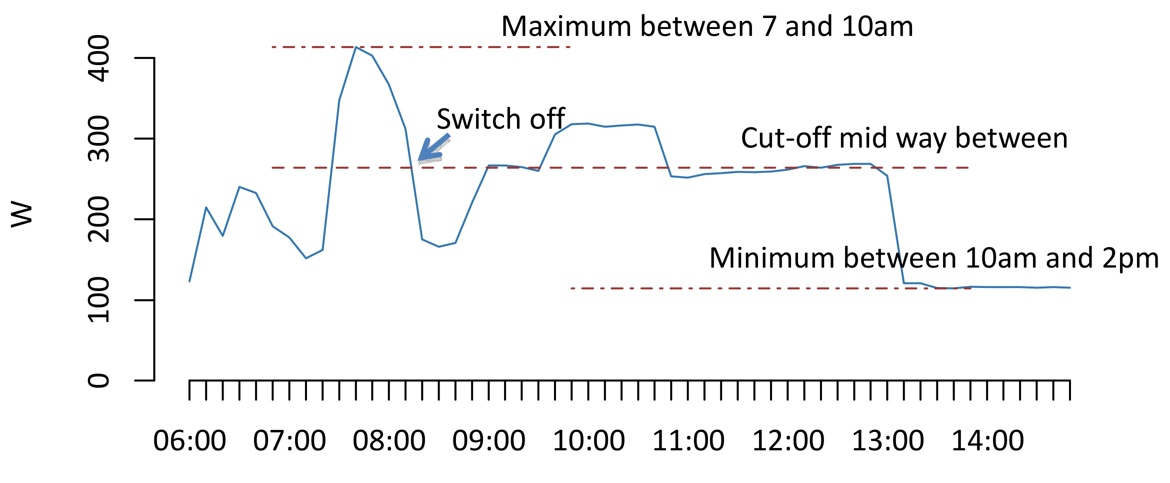
For morning switch-off we considered only homes monitored during the winter, so that lights would be necessary in the morning for getting up. There were 109 homes monitored in this period. We investigated working days separately from holidays.

For each household we averaged the lighting use over a period of two weeks and identified the switch-off time as follows:

1. We found the maximum level of light used between 7 and 10 am (morning peak)
2. We found the minimum level of light used over midday between 10 and 2 (base)
3. We rejected cases where the morning peak was less than the midday minimum, and chose a cut-off level half-way between the morning peak and the base
4. We selected the time when lighting consumption fell to the cut-off level.

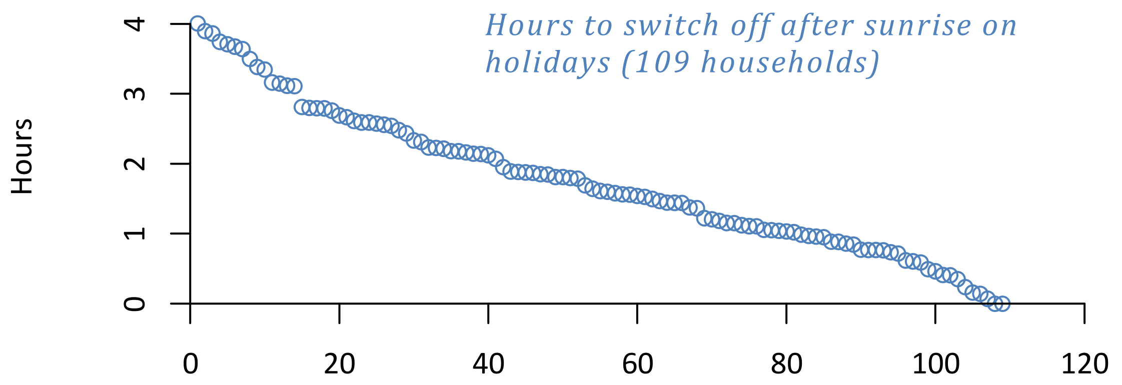
Then we found the time between sunrise (for the central day of the period) and switch off time.

Sample lighting profile showing algorithm to determine the morning switch-off time

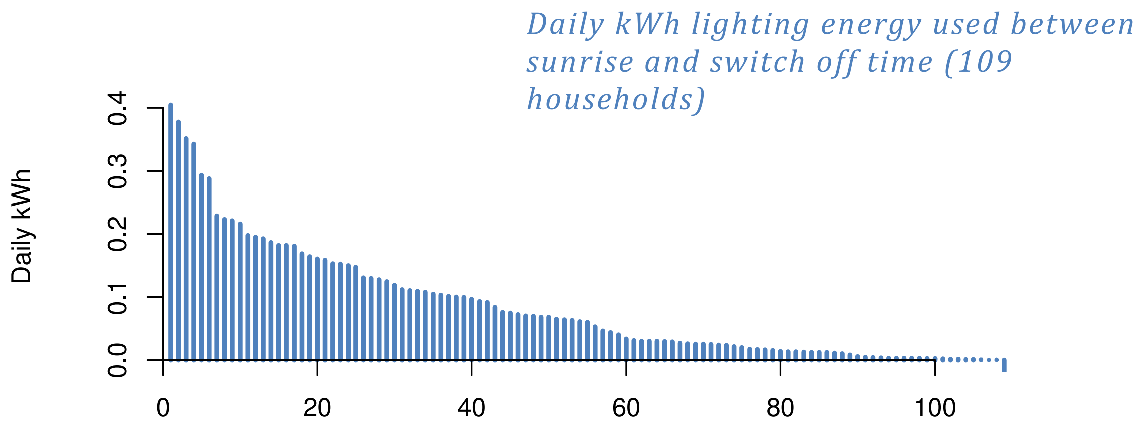


Analysis

There was considerable variation in how long households left lights on after sunrise. The difference between working days and holidays was not significant (1.75 hours on holidays compared to 1.58 hours on work days).



We also calculated the lighting energy consumed between sunrise and the switch off time, over and above the daytime base load. The average extra energy use was very similar on workdays and holidays: 0.10 kWh/day on workdays, and 0.08 kWh on holidays. However, four households used more than 0.3 kWh/day extra between sunrise and switch-off.



If the extra lights left on after sunrise are not needed, the potential savings from turning them off would be significant and high-use households could be deemed particularly wasteful in this respect. The table below shows the energy used, and hence the savings which could be made, by lighting group.

Lighting group	Number in sample	Median daily kWh, sunrise to switch off	Mean daily kWh, sunrise to switch off	P-value	Potential savings kWh/year (assume 180 days)
Low	15	0.003	0.009	0.000	1.6
Medium	74	0.063	0.078	0.060	14
High	20	0.157	0.155	0.018	28

('Low' and 'High' are significant relationships at the 5% level.)

Rebound effects when a low energy light bulb is replaced

Some householders may be tempted to be less careful about turning lights off when they are not needed if they have installed low energy light bulbs. If this happened then these households would lose some of the savings which would be expected from using low energy bulbs. We looked for evidence of this from the households in the survey, in order to estimate how much savings were being lost.

Approach

We used evidence from the data on lamps that are plugged into sockets for this task – unfortunately we cannot distinguish individual bulbs on the lighting circuits. For the lamps we looked for a correlation between light bulb power and hours of use. If there were a rebound effect then you would expect low-power bulbs to be used for longer.

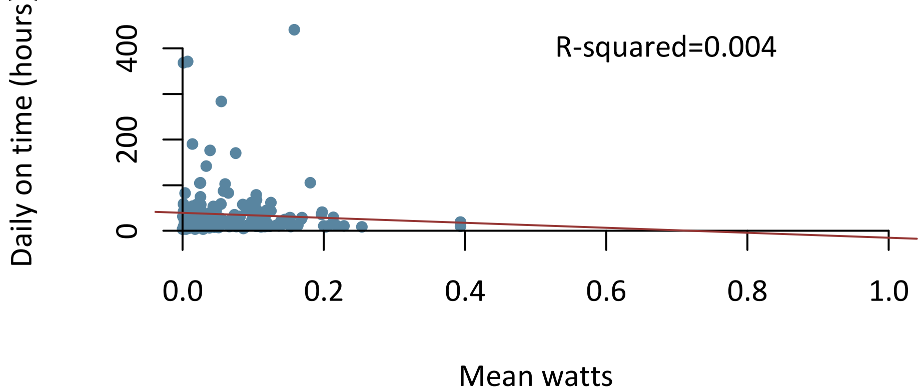
This would not, however, be enough to prove that householders were being less careful with low-energy bulbs, as it might simply be that lights used a lot would blow more often and be replaced with low-energy bulbs in the normal course of events, or possibly the householder might intentionally replace heavily used bulbs in order to reduce their energy bills. Therefore we also looked for more specific evidence from the households that were monitored for a year, during which time some of the bulbs were replaced. Finally, we investigated cases where there was a drop in bulb wattage from the first half of the monitoring period to the second half.

Analysis

Lamp use is heavily influenced by day length, so to minimise this confusing effect we initially looked at lamps monitored during December and January – when days are consistently short. There were 196 lamps monitored during that time, in 65 houses.

We judged that lamps were on when drawing more than 3 W, and we determined both the average daily on time and the average Watts when they were on.

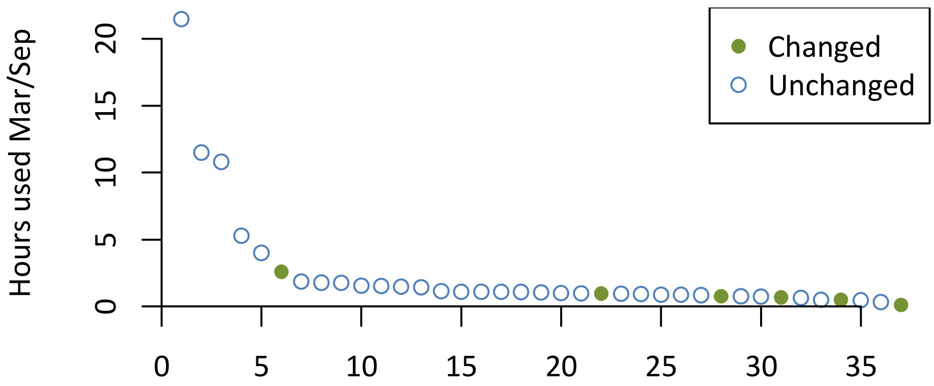
We found no significant indication of a rebound effect by comparing hours used with bulb power, as shown in the chart. However, there was a great deal of variation, so we continued the analysis to look for specific cases where a bulb was changed.



We looked at lamp data for the 26 annual households, comparing bulb wattage in September 2010 with bulb wattage in March 2011 (for 14 days either side of the equinox so the day length was comparable in both cases). Out of 37 lamps monitored, we found six cases where there was a change in wattage between September and March – more than 20%. For each of these we compared the hours of use in March with those the previous September, as shown in the table below. We found only one case where the lamp was used more in March than before, and a great deal of variation.

Case	Lamp Watts September 2010	Lamp Watts March 2011	Hours used March/September
Household 1	70	48	0.1
Household 2	37	19	2.6
Household 3	98	43	0.7
Household 4	16	5	0.5
Household 5	52	10	0.7
Household 6	39	11	1.0

We then compared the March/September use ratio for these lamps with the other lamps, as shown in the chart below. The ratios we saw in the changed bulbs were in the normal range, so there was no evidence of rebound effect in this small sample either.



Our sample is small but it suggests that householders use low energy bulbs in the same way as traditional bulbs and there are no lost savings due to the rebound effect.

Activities where lights are used

The HES dataset allows us to identify activities such as cooking, watching TV, etc. that are associated with using lights, by determining which appliances are switched on together with lights, or are already being used when lights are switched on.

For this analysis we looked only at appliances which are associated with activities that may need light: TVs, laptops, desktop PCs or monitors, games consoles, cookers, showers, vacuum cleaners, hair dryers and so on.

For each household we analysed the profiles in time slots of 10 minutes to determine which of these appliances were on (or switched on) in each period and if lights were switched on during that period. We then used cluster analysis to determine which appliances were associated with lights being switched on.

We found that there were a number of activities associated with using lighting – in this section we say that activities are associated with lighting if they occur simultaneously at least 10% more often than would be expected by chance alone. (This is explained further in the notes about cluster analysis below.) We found that these associations were weaker in summer, but not very different in the summer from during the rest of the year.

Appliance	Households where appliance use was associated with lights	
	Summer (90 houses)	Rest of the year (207 houses)
TV	16%	21%
DVD	10%	7%
Shower	11%	16%
Hair dryer	6%	4%
Microwave	9%	16%
Kettle	2%	11%
Cooker	3%	15%
Dishwasher	7%	9%
Tumble dryer	4%	7%
Vacuum cleaner	1%	6%
Laptop	9%	8%
Computer monitor	3%	9%
Desktop computer	2%	9%

The activities include leisure (TV and DVD), personal care (shower and hair dryer), cooking (microwave, cooker and kettle), housework, and ICT use. The strongest association was with watching TV (16% of households even in summer). This is a little surprising since TV screens are bright and there should not need to be additional lighting needed beyond what is needed for the time of day.

It is a little strange that householders are more likely to turn the lights on to use the dishwasher or tumble dryer than the washing machine.

There was also a strong association with showering, which may reflect the fact that some shower rooms have no windows, or small windows and so little or no natural light. However, this activity does not take long so the lighting use associated with it is small.

There are also associations with using kettles, cookers and microwaves which relate to activities (making tea and cooking) which often do need good light levels. Vacuum cleaning is another similar case, though only 6% of households used extra lights for this activity, even outside the summer period.

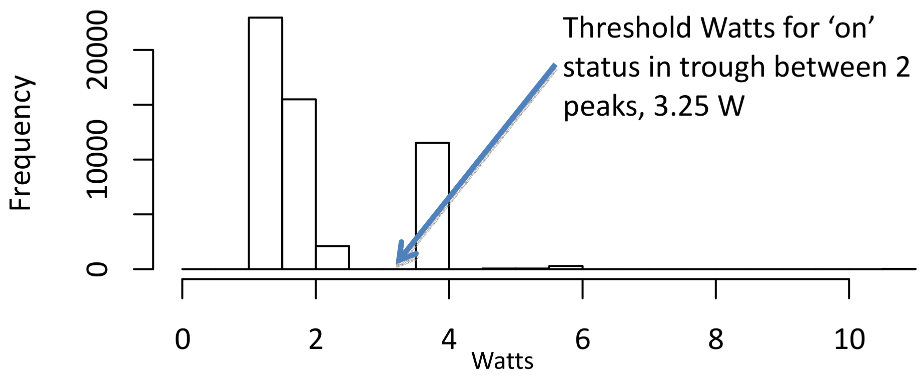
Using computer equipment was also associated with lighting in 8-9% of households outside the summer. Strangely, using laptops was much less seasonal.

How we calculated this

When is an appliance on?
Some appliances draw power even when they are not on, because they have a standby or energy saving mode. For most appliances we computed a threshold Watts value for each appliance by

analysing its profile. We generated a histogram for the power use and identified the bottom of the trough between the first and second peaks in power use, since the first peak is usually standby (or 0 W). Sometimes there are higher peaks corresponding to different working loads. We also ignored any initial peak if it accounted for less than 10% of the time. The chart below shows an example histogram for a laptop. There are peaks at about 1-1.5 W, and just under 4W. The threshold chosen was 3.25 W.

Histogram of power use for a laptop



We set a minimum threshold for the 'on' power of 3 W, since readings lower than that were sometimes erratic and unlikely to be relevant. Also, if there was only one peak then we discarded that appliance because it either was not used or the standby state could not be distinguished. We also ignored any appliance that seemed to be on for more than 70% of the time.

Lamps normally take no power when they are off, and we used a threshold of 5 W for lamps in general. For the lighting circuits we deemed that an increment of 5 W or more indicated a 'switch on event'.

How did we do the cluster analysis?

For each household we calculated the set of appliances (other than lamps) which were on in each time interval of 10 minutes. We did not distinguish between appliances of the same kind – so in homes where there was more than one TV we coded all TVs simply as 'TV'. Then we added 'light' to the sets where a light was switched on during that time interval.

We ran these appliance sets through a cluster analysis to determine frequent item sets (using the apriori algorithm[10]) and selected rules for which items were likely to be in a set which also contained 'light', indicating that a light had been switched on. We selected only rules for which the calculated 'lift' was at least 1.1 (this means that the item occurred with the light at least 10% more often than would be expected by chance alone).

[10] **Apriori** is a classic algorithm for frequent item set mining and association rule learning over transactions. It proceeds by identifying the frequent individual items and extending them to larger and larger item sets as long as those item sets appear sufficiently often in the data. The frequent item sets determined by Apriori can be used to determine association rules which highlight general trends: this has applications in domains such as shopping behaviour, analysing the contents of supermarket customers' shopping baskets.

Observations and recommendations

The top 20% of households for lighting used more than 760 kWh/year whereas the bottom 20% used less than 150 kWh/year.

Households with high lighting use (in the top 20%) were more likely to be A or B social grade, and to live in a large home. They were likely to be larger households (3 or more people) and to have many appliances. They were also likely to rank high on use of washing appliances and cooking. They were less likely to be pensioners. It is not clear if households that are younger now will moderate their lighting use as they become pensioners – unless this is forced by a change in circumstances.

Lighting consumption was not significantly related to the proportion of low energy lights in the household, but high-use households were also usually high on total installed Watts (inside the house). There was a huge range in installed Watts even between dwellings with at least 80% low energy lights (from 125 W to 1200 W). This suggests that even when traditional bulbs have been phased out there will still be large differences in lighting use between households.

There is no evidence of rebound effects from householders using their lights more when they have installed low energy bulbs.

Households with high lighting use tend to:

- Have lights on all the time, day and night (mean base load 24 W compared to 0.5 W for low users).
- Use lights during the daytime (mean 78 W compared to 2 W for low users)
- Are slow to turn lights off in the morning after sunrise.

All of these behaviours are potential targets for savings but the largest savings to be made are probably from daytime lighting (9 – 6pm, April to September). The average for all households in the daytime is 25 W for lighting, but the bottom 10% use less than 0.5 W while the top 10% use more than 63 W. Over a year this amounts to 102 kWh each for the top 10%. Some of this lighting may be necessary due to poor daylighting in the home: only 5% of households were consistent in using lighting during the daytime, which suggests that lights are being switched on for a reason. Light levels can be improved by suitable décor, as well as by adding windows.

Recommendations

■ Consider targeted campaigns focused on reducing energy use for lighting, aimed at households with high baseload lighting energy, and/or known to use lights during the day, and/or continuously, day and night. These are likely to be the households offering most potential for savings from lighting.

■ Explore whether households with part-time work (found to have high energy use for lighting, on average) can reduce their use of electric lighting, or improve the efficiency of light fittings.

■ Continue efforts to install low-energy bulbs and light fittings – there is no evidence in the HES suggesting rebound effects undermine savings.

Lighting energy and geography, and comparisons with the Energy Follow Up Survey

The Departments were interested to find out the extent to which lighting energy use is determined by geographic region. There is a hypothesis in the field of household energy that energy use for lighting through the year is unaffected by location: that households located in the North do not use more or less energy for lighting, on average, than households in the South. Nor is there deemed to be any difference between yearly energy use for lighting between households in the east or west of the country. This hypothesis is reflected in the lighting algorithms in SAP[11].

However, the difference in latitude between Southampton and Newcastle leads to a difference in day length on the shortest day of 45 minutes. Readers might expect this to lead to a difference in lighting energy use. There could also be a difference due to longitude because households further west experience sunset later than those in the East – the difference between London and Bristol is about 10 minutes.

We set out to quantify the extent of the variation in lighting energy due to latitude (north-south) and longitude (east-west) location. We also wanted to explore the link between lighting energy and regional cloud cover, and to compare lighting energy use in the HES households with lighting energy in the Energy Follow-Up Survey (EFUS) of the English Housing Survey, carried out in 2010-11.

Approach

In order to examine the relationship between household lighting use and location, the first step was to estimate the location of each home.

Longitudes and Latitudes

The HES data includes the postcode district (the first part of the postcode e.g. CB2) for each household. As more detailed information on the precise location was not available, we used the longitude and latitude of the centre of the postcode district to represent the location of each household. Readers should note that the areas covered by postcode districts can be very large (around 3000 cover the UK) and consequently, the locations used for each house are only approximate.

Further, only 84 distinct postcode districts cover the entire HES sample. This means that multiple dwellings have been selected from some postcode districts. In these instances, without any further way of determining location, we assumed that the households have identical longitude/latitude.

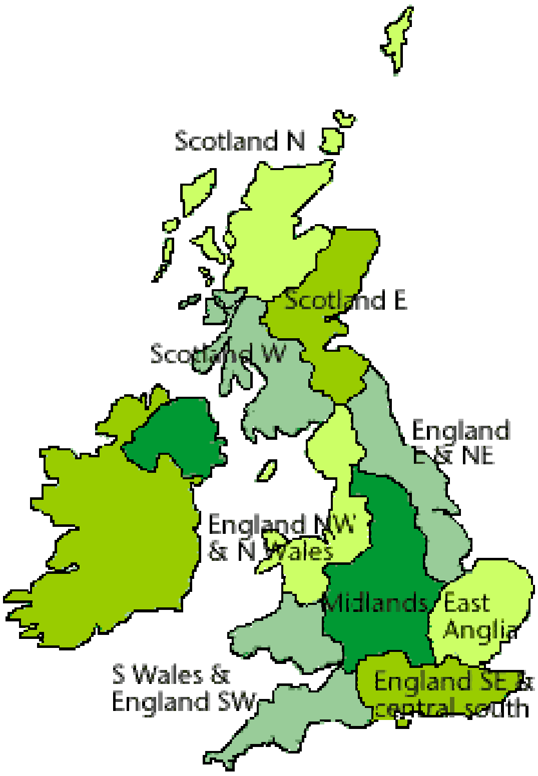
Regions

We used the postcode districts to determine the region that each household is located in. As the work in this section is based around environmental data, the regions used here refer to the UK

[11] BRE (2012) Draft SAP 2012: The government's Standard Assessment Procedure for energy rating of dwellings. Watford: BRE. Appendix L1, p78.

‘climate districts’ used by the Met Office rather than the government regions. These are the regions defined by the Met Office, and used to generate climate types and present historical data at a regional scale.

The map below, taken from the Met Office website, shows these regions.



Depending on the needs of each individual task (primarily based on the available weather data), some work in this section uses annual lighting energy use, while other work uses average daily energy use.

Where annual energy data is presented, we included both the HES monitored data for households that were monitored for an entire year, and annualised data for those where monitoring occurred for less than a year. The annualising process (where less than 12 months’ data was adjusted for seasonality to estimate energy use over a full year) was explained on page 4 of this report. Households with annualised data are identified on graphs where appropriate.

Where we used average daily energy, this refers to solely the HES monitored data. For example, where monitoring only took place in January, then we only present this data.

In keeping with past analysis on the HES data, a number of households have been excluded from the analysis:

- Annualised data excludes any households where monitoring only occurred during the summer. This is due to the difficulty in accurately scaling up from the low lighting-use summer to estimate yearly energy use.

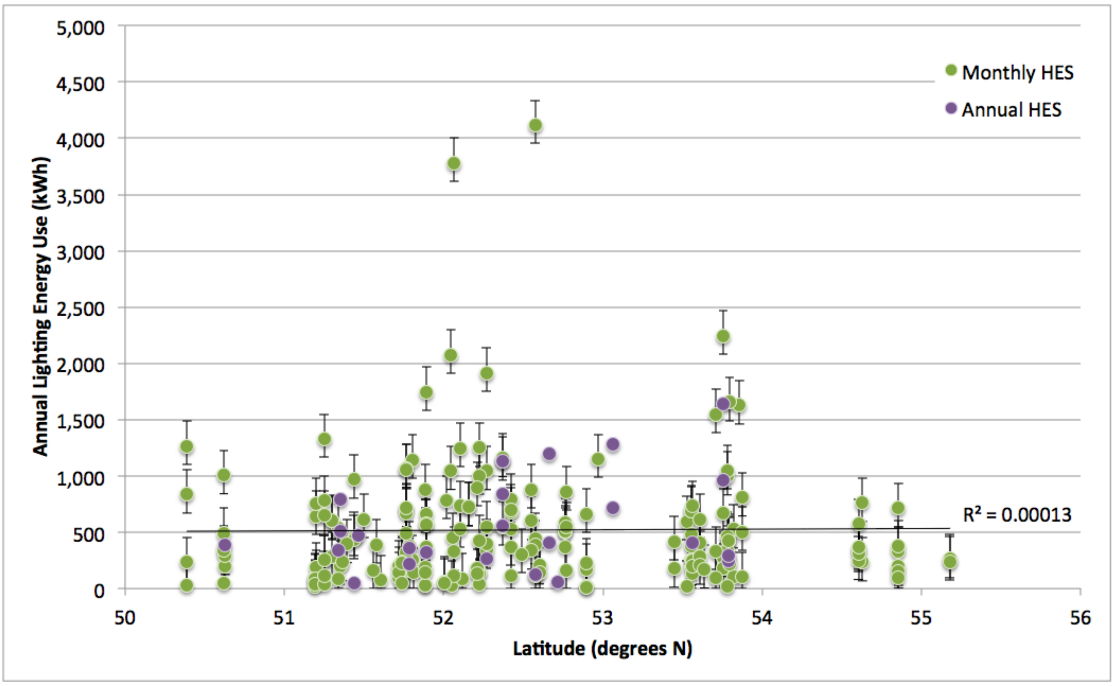
- Both annual and daily energy figures exclude any households where monitoring did not cover at least one lighting distribution board.

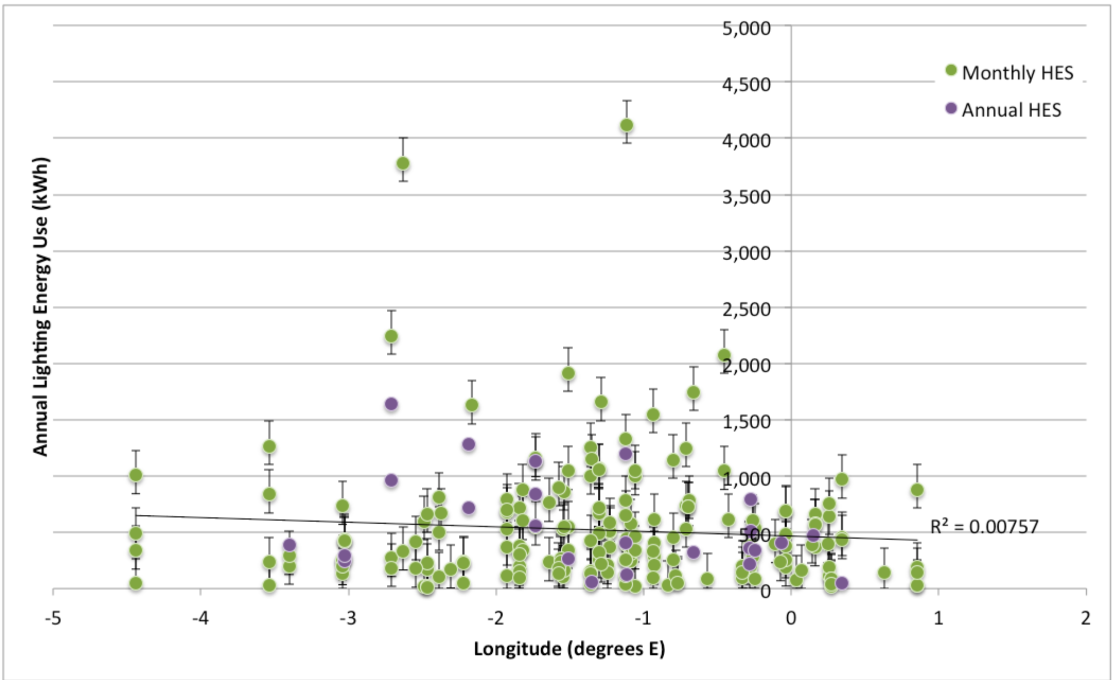
Findings

Building Location

The graphs below present the annual lighting consumption against the longitude and latitude for each house in the HES sample.

The green points represent households where the seasonal adjustment has been carried out (where data from part of the year has been factored up to a whole year, which introduces uncertainty, shown in the uncertainty bars, see pages 5-10 above). The purple points represent those in which monitoring took place for an entire year, and are more reliable.





The relatively flat best-fit lines and low R^2 values suggest that, at the stock level, household location is not a key driver for lighting energy consumption. (R^2 is the *coefficient of determination*, measured from 0 to 1, and it shows how closely two variables are related, with higher values showing closer correlation.)

We have noted before that both floor area and building occupancy are key drivers for lighting energy consumption. Depending on the distribution of the HES sample buildings, this could potentially affect the trends in the graphs above. For instance, if households in the sample tend to be larger in the South, then this would counter any benefits from greater hours of daylight. To account for this, we repeated the analysis, normalising energy consumption for floor area and occupancy. Again, there was no clear trend with respect to latitude or longitude, and for conciseness we have not included these graphs.

Regional Daylight

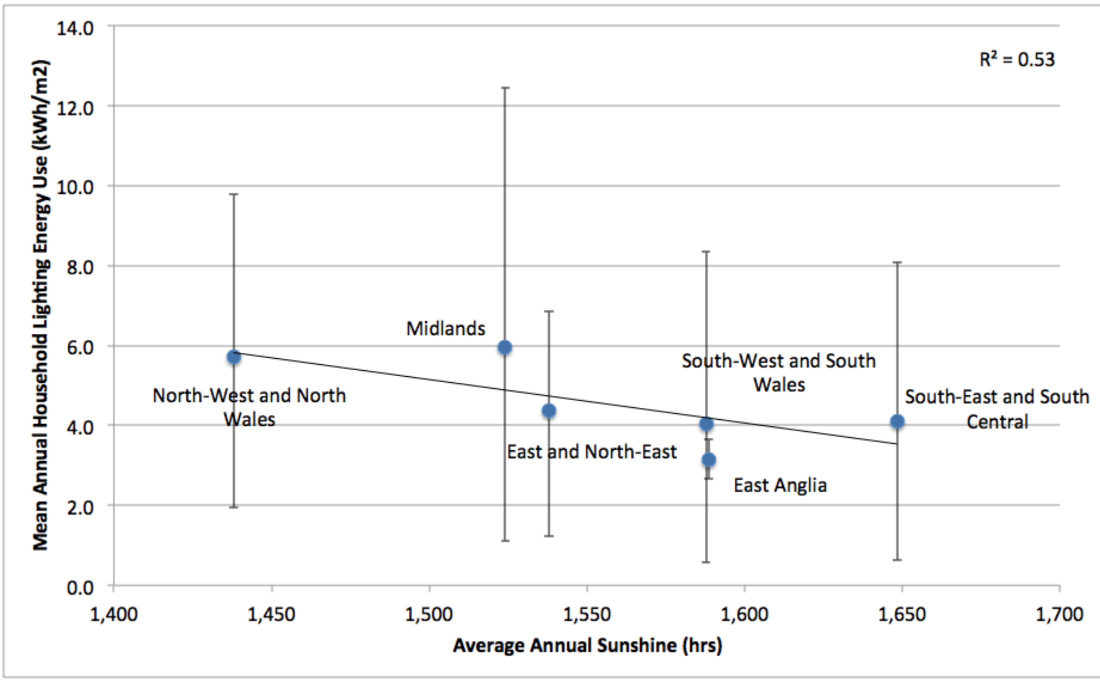
The graph below presents the lighting energy use results at a regional scale using the Met Office climate districts (as shown on the map above).

Mean annual lighting energy use for households is presented for each of the districts, and plotted against the average total hours of sunshine for 2010-2011. The weather data was taken from the Met Office website[12]. In order to normalise within each region for floor area, the energy use is presented as kWh/m^2.

Due to the relatively small number of households in the HES sample that were monitored for the entire year, the regional average data does include energy data obtained through annualising.

The mean consumption figures suggest a weak link between lighting energy and latitude, with the more southerly regions using less energy for lighting than the north, despite some anomalies, such as the average consumption in the Midlands being the highest. (Notice that the R^2 is much higher than earlier graphs, which underlines there being a link between *mean* energy use and latitude, but the R^2 for all data points would be much lower.) However, taking the 10- and 90- percentile figures (shown by the error bars on the graph) into consideration reveals a huge range within each region. This implies that the impact of building location is in fact not key to defining a household's lighting electricity use, even after controlling for floor area, and may help to explain the lack of any clear trend in the previous household-scale graphs.

[12] http://www.metoffice.gov.uk/climate/uk/datasets/



[n=250 households]

Local Daylight

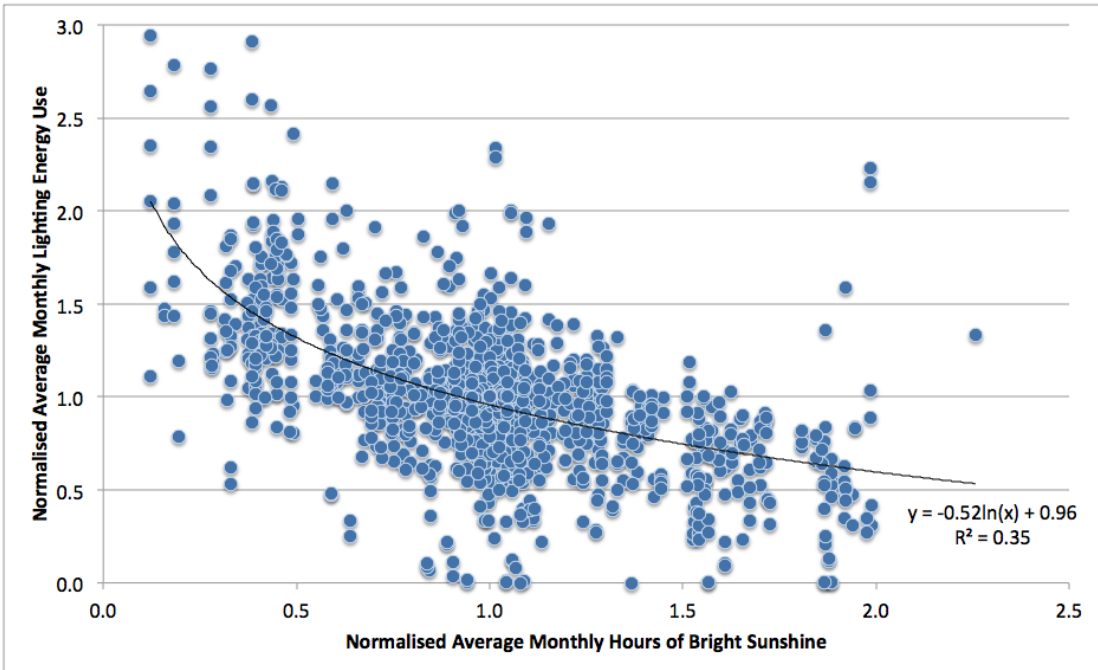
We examined location above to see whether lighting energy use relates to the available daylight, which varies across the UK. However, available daylight also varies with cloud cover, which can differ considerably *within* a single region. So we carried out further analysis, examining the local weather for each building during the period of monitoring.

We collected the local weather data from the Met Office website[13] for the longitude and latitude of each building (based on the postcode district, as discussed previously). This consisted of the monthly average hours of 'bright sunshine', which takes account of cloud cover. For each dwelling we determined the overall average sunshine and daily lighting use, then used this to normalise the data for each month of monitoring. For example, for a dwelling monitored in April and May we determined the average for April and May separately, normalised these figures and plotted two corresponding points on the graph below. This shows how much more lighting is used when there is less sunshine in individual dwellings, and allows us to put to one side concerns about different monitoring periods, household sizes, occupancy etc. It also avoids the uncertainty introduced by making a seasonal adjustment.

The graph below shows the impact of local bright sunshine on household lighting energy use across the HES sample. It suggests that there is a fairly strong correlation between household lighting energy use and local bright sunshine. The logarithmic line-of-best-fit may reflect the fact that a minimum level of artificial lighting is required, to cover night-time occupancy, or internal rooms with little or no access to daylight.

[13] See http://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/index.html

The graph also reveals a small number of households that buck the trend. The points in the top-right represent months of higher household lighting use despite greater availability of sunshine. It is possible these points reflect broader occupancy factors (e.g. school holidays during summer may mean more daytime use of the home, and/or greater use of outdoor lighting on summer evenings, and corresponding higher use of lighting) or even design issues (e.g. if large areas of glazing result in overheating, then blinds may be drawn, requiring artificial lighting). More detailed data-collection for individual cases would be required to determine this.



[n=238 (all homes with lighting distribution boards monitored and two or more months of data)]

Energy Follow-Up Survey (EFUS)

It was not possible to compare HES lighting electricity use with equivalent results from the 2011 Energy Follow-Up Survey (EFUS, see box below)[14], as only total household electricity use was available. However, a comparison of a few key EFUS results with the equivalent data from the HES is presented below.

> *Energy Follow-Up Survey*
> The EFUS was based on interviews and monitoring of 2,616 households taken from the stratified sample that makes up the English Housing Survey. (Stratified based on tenure.) Householders were self-selecting, in that they were asked if they would be prepared to participate first[15]. Energy monitoring was much less detailed than the HES, with only a very limited breakdown of electricity use by final uses.

[14] BRE (2013) Energy Follow-up Survey 2011. Watford/London: BRE/DECC.
[15] BRE (2013) EFUS Methodology Report. Watford/London: BRE/DECC.

A key difference between the samples of households for HES and EFUS is that the former only included owner-occupied residences, while the latter included rented accommodation and social housing. Comparing the two is important as it could indicate whether or not the findings of the HES lighting work would be applicable to the overall UK housing stock.

The table below presents the average number of lamps in the living room, bedroom and kitchens of the HES houses with the EFUS equivalents. The distribution of different lamp types is also shown for these three rooms. Around twice the number of lamps is present in kitchens and living rooms compared to the number of lamps in bedrooms, with slightly more lamps recorded in EFUS households, on average.

	HES			EFUS		
	Kitchen	Living Rm	Bedroom	Kitchen	Living Rm	Bedroom
Mean Lamps per Room	4.7	4.5	1.9	5.3	5.9	2.9

The differences in the number of lamps per room reported are difficult to account for without further information. For instance, it may be linked to larger average room sizes in the EFUS study. The next table shows the breakdown of lamps into different types of lighting: traditional tungsten bulbs versus newer compact fluorescents (CFLs), light-emitting diodes (LEDs), halogens and others.

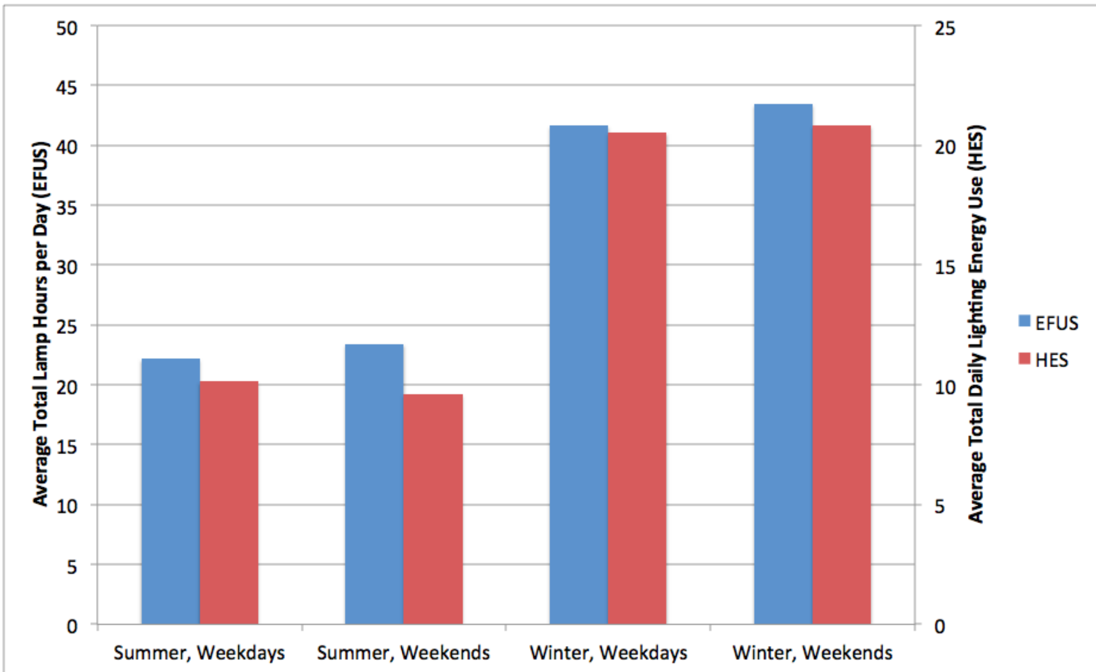
Percentage of Lamps	HES	EFUS
Lamp Type		
Tungsten	40	32
CFL	24	21
LED	1	5
Halogen	30	29
Fluorescent	5	6
Unknown/Mixed	-	7

The table suggests similar lamp ownership between the HES and EFUS samples, although it is interesting to note that the households in the EFUS sample appear to have a higher proportion of installed LED lamps, on average, whereas HES households typically have more tungsten bulbs and CFLs.

Comparing hours of lighting use

Although EFUS did not monitor lighting electricity consumption specifically, occupants were asked about the hours that each set of lights in the house were typically in use during winter and summer, on weekends and weekdays.

In the HES, lighting energy use has generally been monitored at the distribution board, so results at the scale of 'sets of lights' cannot be obtained. However, the daily lighting energy consumption is partly a function of the hours of use of lighting, so the graph below compares these two figures.



Although the two sets of data presented are different (notably because the HES is metered energy use whereas EFUS is self-reported hours of use data from survey participants), and thus not directly compatible, they do suggest similar trends across seasons between EFUS and HES. Around half as much lighting is used in summer as in winter in both cases. The only slight difference is that the HES result reveals a drop in lighting use in summer between weekdays and weekends, while the EFUS survey suggests a slight increase. The reason for this is not clear, but could reflect differences in the occupants' behaviour, or simply the fact that the EFUS results are based on questionnaires rather than monitoring of actual use.

The similarities between the two datasets indicate that the lighting use trends found in the HES may be applicable to a wider portion of the residential stock than simply owner-occupied homes.

Recommendations

■ The analysis suggests that, although there is some correlation between location and annual lighting energy use, the wide scatter indicates that other factors (such as occupant behaviour or building design) are more important in determining household energy use.

■ However, for individual buildings, the analysis reveals a strong relationship between monthly lighting consumption and

Other Research on LEDs

A lighting study by the Energy Saving Trust measured the performance and energy-saving potential of over 4,250 LED light fittings across 35 different sites[14]. In-situ energy performance lighting was monitored before and after the upgrade to LED light fittings. Figures were not reported for individual residences, but significant energy savings were observed and the trial suggested that the payback period for the investment in LED light fittings was around two years.

[16] Energy Saving Trust (2011) Lit up : an LED lighting field trial, The Energy Saving Trust, London.

local weather. This suggests that location is less important in shaping *annual* energy use for lighting, but more important in determining the *monthly* profile of lighting energy through the year. For models aimed at robust estimates of energy use month-by-month (say, for examining the peak load through the year), it may be worth including location and local sunshine information. However, for models aimed mainly at annual energy use (like SAP or BREDEM), other factors are more important.

■ The fact that a number of households presented unusual lighting profiles (increasing use of lights with increasing daylight) may warrant further research. It is possible that this simply reflects logical factors outside of the data collected for the HES (e.g. families going on holiday at certain times). However, it may also be due to household behaviour or building design (e.g. blinds down in the summer), which may provide an opportunity for energy saving.

Modelling lighting use

It is often useful for policy decisions and planning energy generation and supply to know what proportion of electricity is used for different purposes. Currently, DECC uses the procedure in SAP 2009 to estimate the energy used for lighting in the UK housing stock. (The SAP algorithms are embedded in the Cambridge Housing Model and the forthcoming National Household Model. The Cambridge Housing Model is used to estimate the proportion of household electricity used for heating, lighting and appliances in *Energy Consumption in the UK*[17] and the *Housing Energy Fact File*[18].) The key part of this procedure is an equation that defines the relationship between lighting and two building variables: the number of occupants and the floor area of each dwelling.

This section explores the possibility of using the HES data to generate an alternative, bottom-up approach to estimating household lighting electricity use.

Approach

The current SAP algorithm is outlined below. Full details are available in SAP 2009[19] (and the algorithm is identical in the Draft SAP 2012[20]).

The existing SAP algorithm uses a statistical relationship to estimate annual lighting energy consumption for a household (kWh/yr), based on floor area (m^2) and household occupancy:

$$\text{Lighting Use} = 59.73 \times (\text{Floor Area} \times \text{Occupants})^{0.4714}$$

Two adjustment factors are then used to account for the presence of low-energy lamps installed in the household, and the availability of daylight from the building design:

$$\text{Low-Energy Lamps} = 1 - 0.5 \times \%\ \text{Low-Energy Light}$$

$$\text{Daylight} = \frac{\Sigma(0.9 \times \text{Window Area} \times \text{Light Transmittance} \times \text{Frame Factor} \times \text{Light Access})}{\text{Floor Area}}$$

The following equation is used to estimate the monthly energy use:

$$\text{Proportion} = 1 + 0.5 \times \cos[2\pi\ (\text{MonthNo} - 0.2) / 12)] \times \text{Days} / 365$$

While the origin of this procedure is not detailed in SAP, the first equation in particular appears to be a statistical relationship, presumably taken from an historical survey. (We think this is probably

[17] https://www.gov.uk/government/collections/energy-consumption-in-the-uk
[18] Palmer, J. Cooper I. 2014. The UK Housing Energy Fact File. London: DECC. https://www.gov.uk/government/publications/housing-energy-fact-file-2012-energy-use-in-homes
[19] BRE (2011) SAP 2012: The government's Standard Assessment Procedure for energy rating of dwellings. Watford: BRE.
[20] BRE (2012) Draft SAP 2012: The government's Standard Assessment Procedure for energy rating of dwellings. Watford: BRE. Appendix L1, p78.

unpublished monitoring work of around 30 households in Gloucestershire, undertaken in the 1990s.)

The accuracy of this approach has been explored in a previous report[21]. That report shows that across the HES sample, the SAP algorithm gives a reasonable match with monitored energy data. However, it cannot account for the wide variation in energy use and, importantly, SAP overestimates aggregate lighting energy consumption for the HES households by around 20%.

Palmer et al (2013) also proposed a possible updated algorithm for lighting. This uses the same structure as the existing SAP equation, but represents the best fit for the HES sample.

Readers should note that SAP is not intended to accurately represent reality, nor indeed for modelling the whole housing stock, but instead to provide a means for checking building design against Building Regulations. It remains the most widely-used and best-tested set of algorithms for modelling energy use in homes, but there are weaknesses of statistical/ best-fit approaches to calculations aside from accuracy:

- Accounting for variations from typical building design or occupancy behaviour is difficult. e.g. 'How would a household with night-shift work differ from one with day-shift work?'
- Considering the impact of changes can also be complex. e.g 'What is the impact of changes to British Summer Time/Greenwich Mean Time?', or 'Which rooms are most appropriate for use with low-energy lighting?'
- Over time, the statistical relationship needs to be re-calculated to account for changes in typical behaviour.

To address some of these issues, we explored the possibility of using the HES data to generate a simple but more transparent and bottom-up based approach to estimating household lighting electricity use.

Broadly, the approach taken in estimating the lighting electricity consumption for each household was:

1. Use the occupants' details to estimate their typical behaviour throughout each day (e.g. are they employed, and so at work during weekdays?)
2. Attribute occupants' activities to rooms, and
3. Relate room use to lighting demand via the installed lamp power, along with factors to account for daylight and behaviour.

Readers should note that although the model procedure is in place, due to limitations in data availability, some of the input data used are based on our best assumptions rather than existing research or data. Further, in some aspects (where UK data was absent) we have used behaviour data from abroad, which is likely to be different from England. These issues mean that the results presented should be treated with caution. However, as more empirical data becomes available, the results can be refined and improved.

The flow chart below gives a simplified overview of the calculation procedure we undertook for each household, and this is followed by a more detailed step-by-step description.

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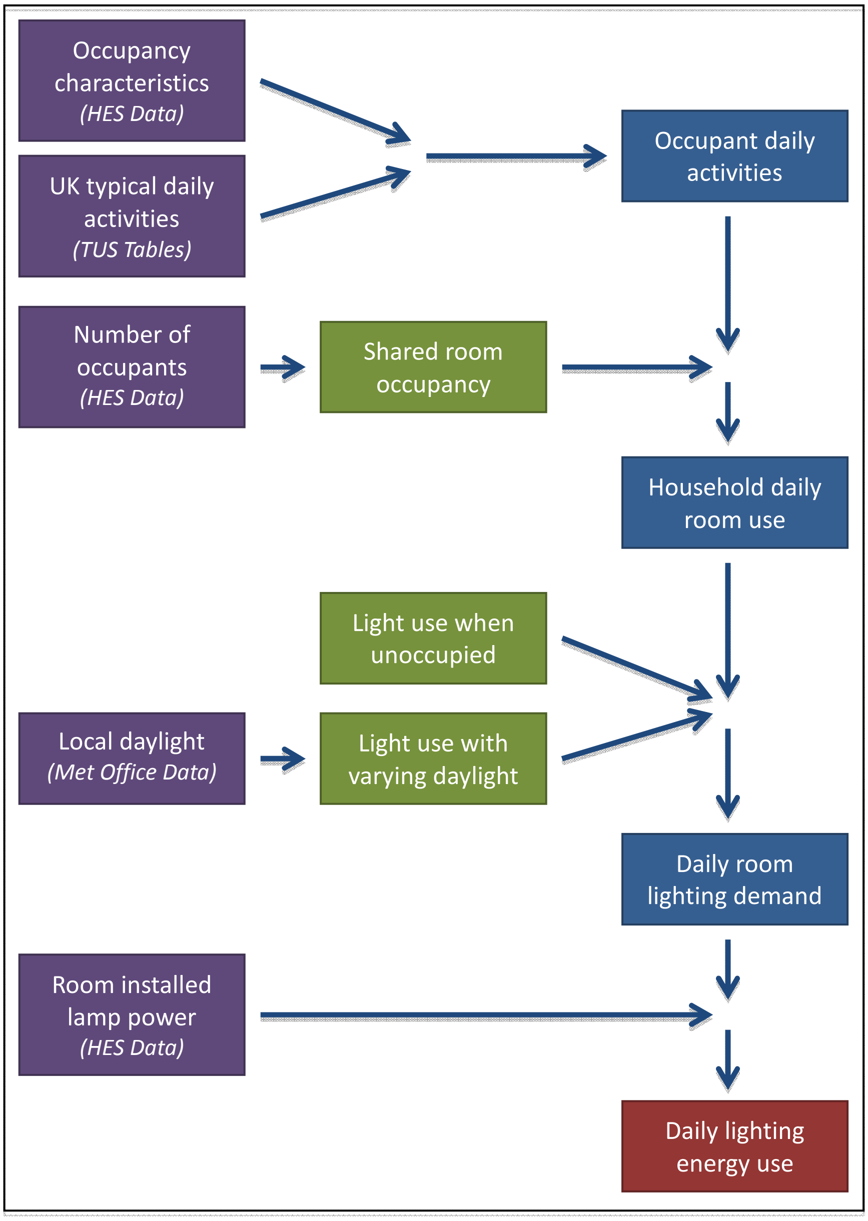
[21] Palmer, J. et al (2013) Energy use at home: models, labels and unusual appliances. London: DECC.



The various pieces of data used are summarised in the table below.

Data	Source	Notes
Dwelling		
Total floor area	HES house data	
Room breakdown	HES lamp data	This provides a breakdown of the installed lamp power per room of the house. This was compared with the 'number of rooms' from the HES SAP data, to identify incomplete lamp/room data
Location	HES house data	Post code data was used
Daylight correction factor	SAP calculation	Calculated from HES house
Lighting		
Installed lamp power per room	HES lamps data	See 'room breakdown' note above
Occupants		
No. occupants	HES occupancy data	

Presence of children	HES occupancy data	For households with >3 occupants and children, the number of dependent children was assumed to be <2
Employment status	HES occupancy data	
Social grade	HES occupancy data	
Weather		
Avg monthly sunshine	Met Office	
Avg monthly bright sunshine	Met Office	
Behaviour		
Typical daily activities	Time Use Survey	Best estimates were used to allocate these behaviour profiles to different rooms
Lights left on in empty rooms	Lutron Survey	The only available data was from a small American survey, so this can only be considered indicative

1 Data Gathering

We gathered information about the house from the HES database and historic weather data from the Met Office. The data gathered for each house is summarised here:

1a Dwelling and occupant data

The dwelling information gathered included the floor area and installed lamp power for each room. The occupants' information included the number of occupants, their social grade, and the employment status of the principal occupant.

1b Gather weather data

The average daily hours of sunshine (sunrise to sunset) and average daily hours of bright sunshine (when there is no cloud cover) were collected for each month from the Met Office online historic data. We used postcodes to estimate the house location. For each month, days were split into three periods: darkness (i.e. sunset to sunrise), bright sunshine, and dull sunshine (the average hours of sunshine minus the average hours of bright sunshine).

2 Daily room use

We estimated the number of hours that each room was occupied for. Unfortunately, we could not find a source of data for the time that people spend in different rooms and this information could not be extracted directly from the HES data. Instead, we estimated this using the next four steps.

2a Occupant daily activities

We estimated the proportion of time that each occupant spends each day doing different activities using their characteristics (e.g. their working status), and the National Statistics 2005 Time Use Survey[22] tables. The TUS used diary-based surveys of UK households to estimate the proportion of the day that the population typically spends doing different activities. The impact of factors such as working status is considered in the study, along with the variation between weekdays and weekends. Readers should note that any changes in typical household behaviour in the intervening years between the data collection for the TUS and the HES affect the analysis presented here. We had to make some simplifications in order to make the HES and TUS compatible. For instance, we

[22] National Statistics (2016) Time Use Survey 2005. London: National Statistics.

assumed behaviour on 'holidays' (used in the HES analysis, and defined in a previous report[23]) to be analogous to behaviour on 'weekends', and social grades to relate to the work types used in the TUS data. These assumptions will, naturally, affect the accuracy of this work, although the HES 'holiday' refers to national bank holidays and weekends, rather than explicitly occupier's time off from work or school. Overall, this gives the parameterised function:

$$T_{OA\ o,a,d} = \Pi_f\ (T_{OAF\ o,a,d,f})$$

where

T_{OA} = occupant time spent per activity (% time per day)
T_{OAF} = occupant time adjustment per activity for different social factors
o = occupant number
a = activity (sleep/ rest/ eating & drinking/ sports/ etc.)
d = day type (workday/ holiday)
f = social factors (social grade/ employment/ etc.)

2b Occupant time at home

The TUS also presents the proportion of time for each activity that is typically spent at home (e.g. on average, 89% of the time in 'paid work' is spent outside the home, whereas 97% of time spent sleeping is at home). We used this data to convert the estimates of occupancy behaviour (defined in step 2a), into estimates of the amount of time that each occupant spends in the dwelling daily. Each activity was allocated to different rooms in the dwelling using our best estimates. Where the household did not have a specific room type, we adjusted the room allocations accordingly (e.g. if a house did not have a 'study', then we assumed work at home took place in the living room). This gives the forumula:

$$T_{OHA\ o,a,d} = T_{OA\ o,a,d} \times T_{H\ a,d}$$

where

T_{OHA} = occupant time spent at home per activity (% time per day)
T_{H} = occupant time spent at home per activity (% of time)

2c Multi-occupant room use

In order to account for the fact that multiple occupants may choose to use a single room simultaneously, we implemented an 'effective room occupancy' approach. This is the same as that used in Loughborough University's lighting model, CREST[24]. We extended the approach so that room use follows pattern of lighting energy and occupancy. For instance, if two-person homes use 150% of the lighting use of equivalent one-person houses, then we assumed that, on average, adding a second occupant results in a 50% increase in room use compared with a single-occupant home. In this way, we applied correction factors to the room use of successive occupants in

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[23] Palmer, J. et al (2013) Further Analysis of the Household Electricity Survey: Early findings. London: DECC.
[24] Richardson I. et al (2009) Domestic lighting: A high-resolution energy demand model. Energy and Buildings, 41 (7), pp. 781-789. https://dspace.lboro.ac.uk/dspace-jspui/handle/2134/4759

households with more than one occupant. For activities likely to be undertaken individually (e.g. washing and using the bathroom) the *effective room occupancy* correction was not used.

The equation used to determine the effective occupancy for each additional occupant, taken from the HES data, is:

$E_{FF\,o} = (0.2545 \times o) + 0.6629 - E_{FF\,o-1}$

where

E_{FF} = effective occupancy (%)

2d Times of use

There are exceptions, but electric lighting is usually needed when rooms are in use and daylight is insufficient to light rooms. Bearing this in mind, we divided room hours of use into the three periods defined in Step 1b (dark/bright sunshine/dull sunshine). Although the raw TUS data includes information on when the different activities typically take place, this data was not available in tabular form. Therefore, we allocated the activities using the following simple assumptions:

1. Sleep is assumed to occur when it is dark. In instances when the hours of darkness are shorter than the average time asleep then the remainder of the sleep is assumed to occur during daylight hours
2. Conversely, being away from home for paid work is assumed to occur during daylight hours
3. Households with multiple occupants with different sleeping or working hours were assumed to overlap
4. All other activities (spent at home or away) were allocated proportionally across the remaining time, when the house was assumed to be occupied by people that are awake.

This gives:

$T_{R\,r,t,d,m} = \Sigma_a \left(R_{A\,r} \times \Sigma_o \left(T_{OHA\,o,a,d} \times E_{FF\,o}\right)\right) \times \left(T_{A\,d,t,m} \div \Sigma_d T_{A\,d,t,m}\right)$

where

T_R = total time each room is occupied (% time per day)
T_A = total time awake at home (% of time)
R_A = room use per activity (% of time)
r = room type (kitchen/ bedroom/ lounge/ etc.)
t = time of day (dark/ dull sunshine/ bright sunshine)

3 Estimate the lighting consumption per room

Having estimated the hours of use of each room estimated (Step 2), and the installed lamp powers for each room (Step 1a), we could calculate the total lighting consumption. However, we could not simply assume that lights are switched on when a room is occupied. If there is sufficient daylight in a room then electric lighting may not be required, or lights may be left on (accidentally or otherwise) when a room is no longer occupied, or lights may be intentionally left off due to the activities (e.g. lights off to watch tv) or task lighting may be used instead of ceiling lights. This meant we had to apply two further corrections: a daylight correction and a waste correction.

3a Daylight correction

We used correction factors to account for the fact that – depending on the available daylight – lights are not required throughout the occupied period for each room. As detailed information about the window sizes and arrangements for the HES sample households was not available, we made simple assumptions to estimate how often lights would be switched on when a given room was occupied during hours of darkness, dull sunshine, and bright sunshine. These were adjusted to account for the SAP daylight correction where possible, but were assumed to be constant for all rooms. In reality, the impact of daylight also varies from room to room. For instance, internal spaces may have a greater requirement for artificial lighting than perimeter spaces, or certain rooms may typically have smaller windows than others for factors such as privacy.

3b Unnecessary use correction

We also included correction factors to account for the fact that lights may be left on when rooms are unoccupied. Unfortunately, we could not find clear data showing the amount of time that lights are left on for unoccupied residential buildings. Instead we used the results of a recent survey[25] by a lighting manufacturer (Lutron) to approximate this issue. The survey questioned American households on the likelihood that different rooms are left on unnecessarily and, for the purposes of this study, we assumed this to be a proxy for the unnecessary use correction factor for each room. (Lighting habits are almost certainly different in the US from those in the UK, but we could not find equivalent research in the UK. This is one area where we anticipate that future empirical research in this country could help to refine the approach adopted here.)

3c Lighting energy use

Finally, we calculated the average daily energy use for lighting across the households by adding together the expected hours of room use, making the daylighting and wastage adjustments, and multiplying by the installed lamp power of each room. Overall, this gives the equation:

$$Q_{R\,r,d,m} = \Sigma_t \; (T_{R\,r,t,d,m} \times U_{D\,r,t} \times U_{W\,r} \times I_{R\,r} \times 24)$$

where

Q_R = lighting energy use per room (kWh/day)
U_D = daylighting energy use (%)
U_W = unnecessary energy use (%)
I_R = average installed lamp power per room type (kW)

and

$$Q_T = \Sigma_m \; \Sigma_d \; \Sigma_r \; (Q_{R\,r,d,m} \times D_{d,m})$$

where

Q_T = household annual lighting energy use (kWh)
D = days per month

[25] See http://www.lutron.com/en-US/general/Pages/Promos/WhoLeftTheLightsOnInfographic.aspx

Results

The approach described above was carried out for the HES sample households to compare with the monitored energy use, and also compared against equivalent results from the existing SAP method.

To reiterate, limitations in the data available meant that we had to make assumptions based on the authors' expert judgement, rather than published empirical research. Consequently, the results should be treated with caution. It is likely that with better data, the model may provide a better fit.

A number of checks were carried out prior to running the calculations, resulting in several households being excluded from the analysis that follows. The reasons are outlined below:

1. Households where lamp information appeared incomplete were excluded, e.g. if the database suggested that a house had no lighting in bedrooms or bathrooms.
2. Households where no lighting distribution boards were monitored were also excluded.
3. Households where there was insufficient information to run a SAP calculation (detailed in the previous HES report) were also excluded.

We carried out the analysis solely for months when monitoring took place, in order to ignore any assumptions that were included in the seasonal adjustment (described on pages 5-10). Consequently, we only evaluated annual results where monitoring covered an entire year. For the remaining households, the analysis only considers one or two months.

The tables and graphs below present the aggregated results for the HES sample buildings. The first set includes only those households where monitoring was carried out for the entire year (i.e. 'total lighting electricity consumption' is *annual* use). The second set includes all the HES households (i.e. 'total lighting electricity consumption' is *monthly* use for those months where monitoring took place).

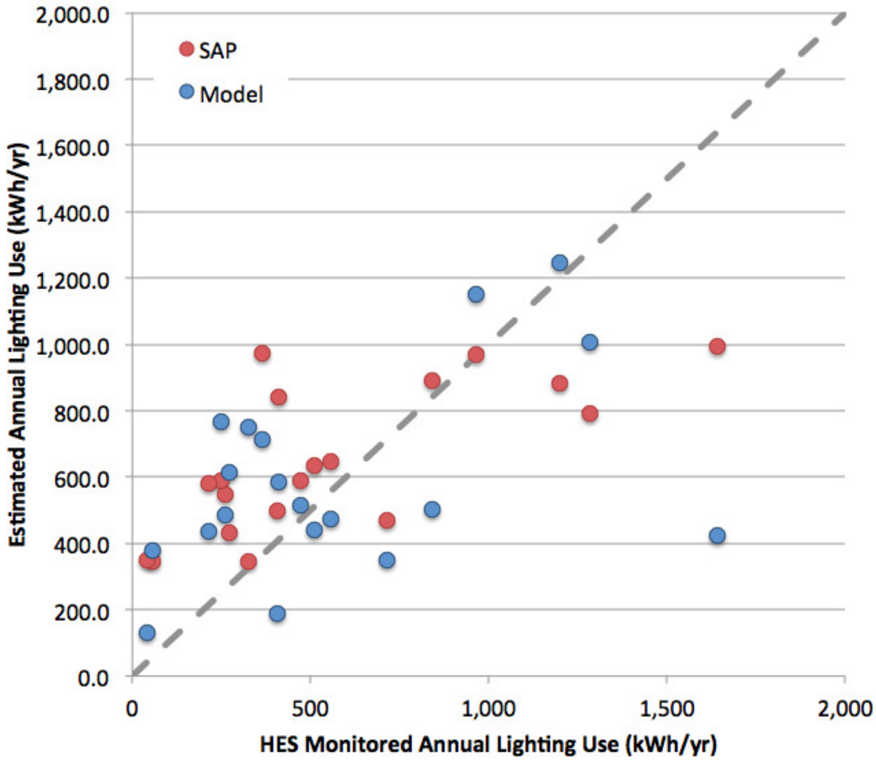
The error for SAP and the model was calculated for each house as (Estimate Energy - Actual Energy) / Actual Energy x 100, and the overall results are presented below, comparing the errors using the SAP and modelled estimates. Therefore, an error of 24% in the SAP calculation for a household means that the SAP estimate is 24% higher than the actual monitored lighting energy use. Note that, using this calculation, the minimum possible value is -100 (i.e. estimate is 100% lower than actual, meaning that estimated energy = 0 kWh/m^2), whereas there is no maximum (e.g. in houses where actual lighting energy use is far lower than expected).

The results for the 19 households monitored for a year, and with adequate input data, suggest that the new model is somewhat more accurate than SAP, on average across the HES homes, see table below.

	HES Data	SAP Estimate	Model Estimate
No. of Households	19	19	19
Household Annual Lighting Electricity Use (kWh/yr)			
Mean	568	651	587

Median	410	588	504
Error in Household Calculation (%)			
Mean	-	102	70
Median	-	24	19

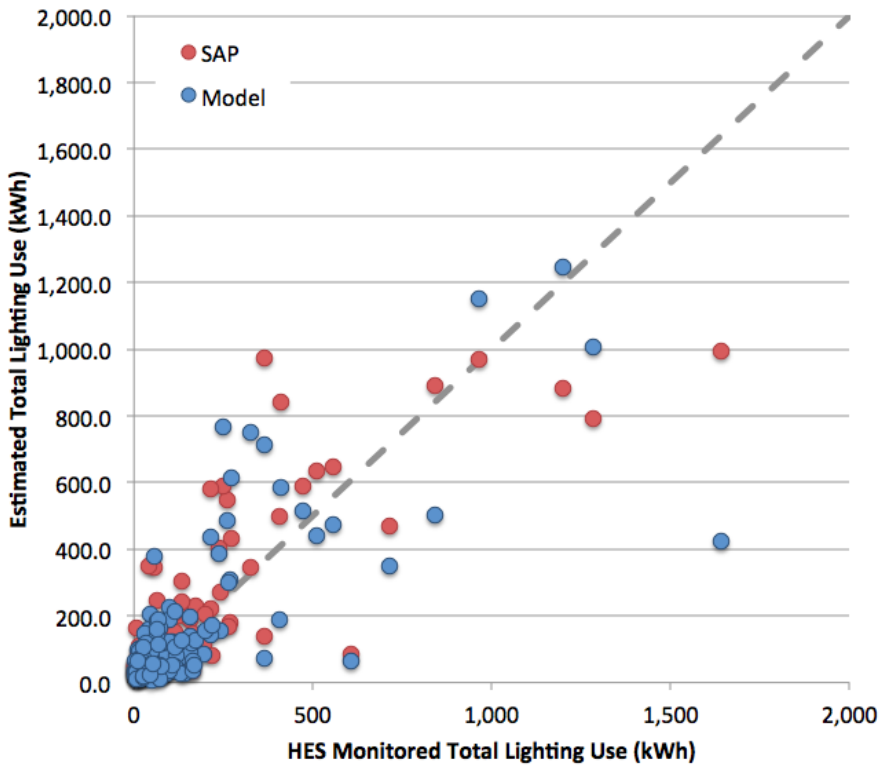
Plotting the new estimates ('Model', shown blue in the graph below) against measured energy use in these 19 homes gives a very different pattern of estimates from SAP estimates (shown red below). The graph shows the parity line (where the estimate exactly matches the measurement) as a grey dotted line. If the estimates were perfect, all of the points would fall on this line. The graph shows that although the mean and median estimates are better than SAP overall, the new estimate is not always better, and in some cases is much worse than the SAP estimate of lighting energy. For instance, the blue point in the bottom-right, which represents a large dwelling, where annual lighting electricity use is massively underestimated using both approaches (a factor of 4 in the model, and a factor of 1.6 with SAP). Such underestimates are almost certainly a result of quirks in lighting energy use for individual households that would be virtually impossible to capture in this kind of model.



Again, the results for all 165 households with sufficient input data suggest that overall the new method of estimating energy use results in closer estimates than SAP, see table below.

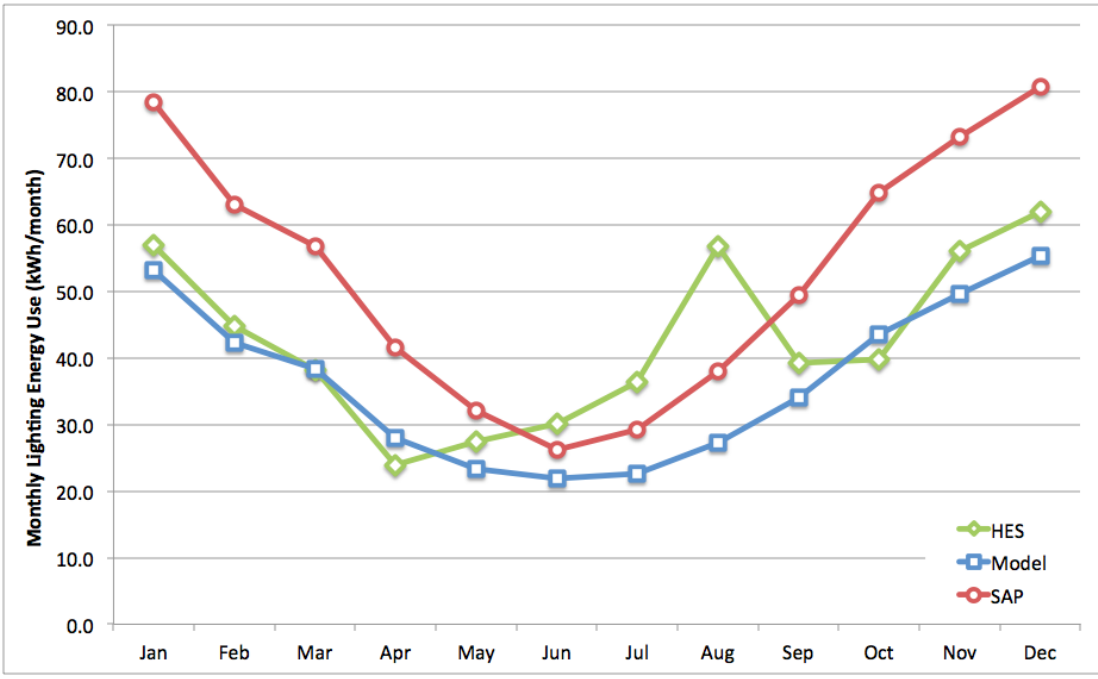
	HES Data	SAP Estimate	Model Estimate
No. of Households	165	165	165
Household Total Lighting Electricity Use (kWh)			
Mean	130	159	137
Median	57	82	69
Error in Household Calculation (%)			
Mean	-	161	117
Median	-	60	27

Similarly, the graph plotting all 165 households shows that although the new method is closer to measured energy use than SAP for lighting overall, it is not necessarily better for individual dwellings. The blue outlier from the plot of 19 households above (bottom-right) still remains.

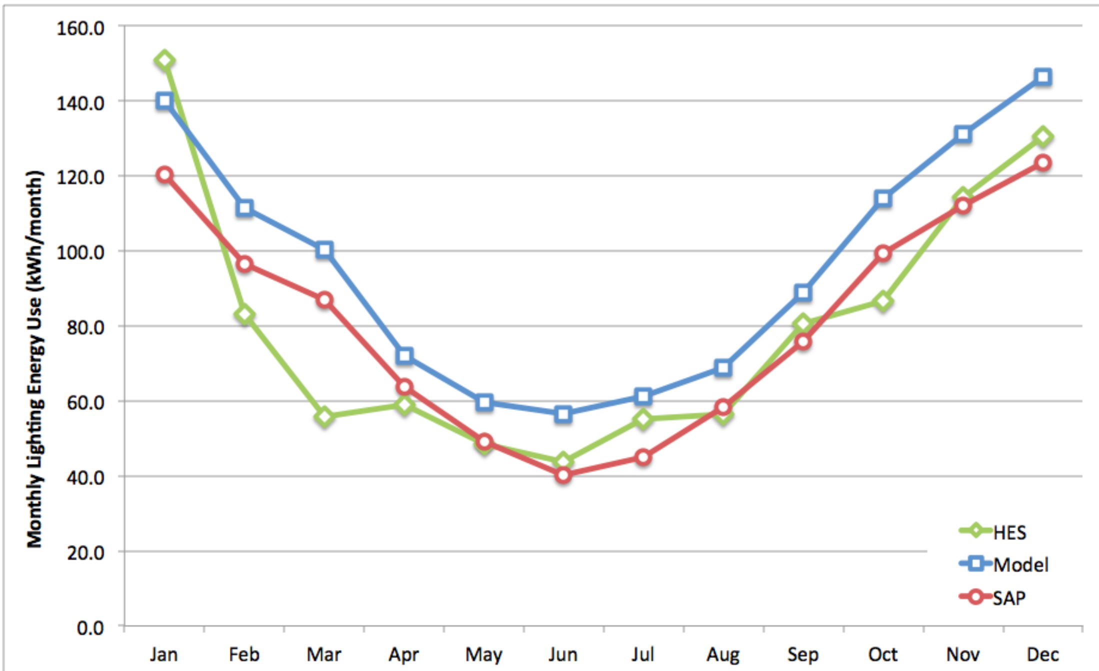


Part of the 'error' between estimates and measured energy is caused by the fact that large deviations from 'typical' behaviour/design cannot easily be accounted for under simple models, which rely on assumptions of typical behaviour. While SAP does not explicitly consider user behaviour in its calculations, this is an implicit part of the relationship assumed relating occupancy and floor area to lighting demand.

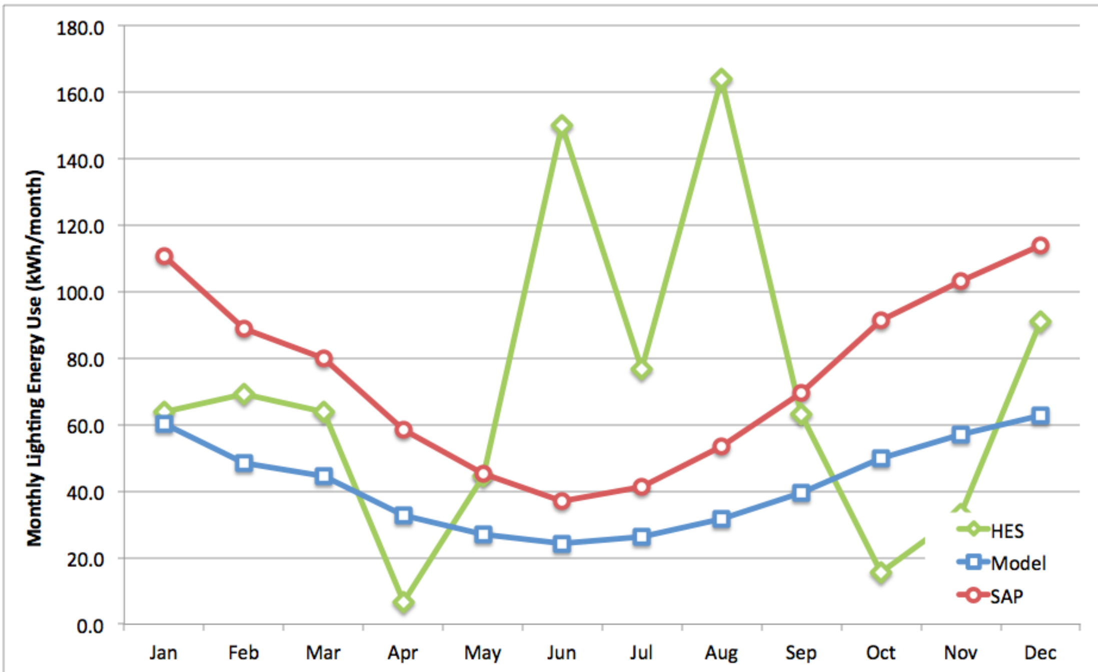
The graphs below show the *monthly* breakdown of lighting consumption for three example houses through the year. This is an output from SAP that is seldom used.



Example result: Two occupants, no children, 100m^2 floor area, part-time employment.



Example result: Four occupants, no children, 130m^2 floor area, full-time employment.



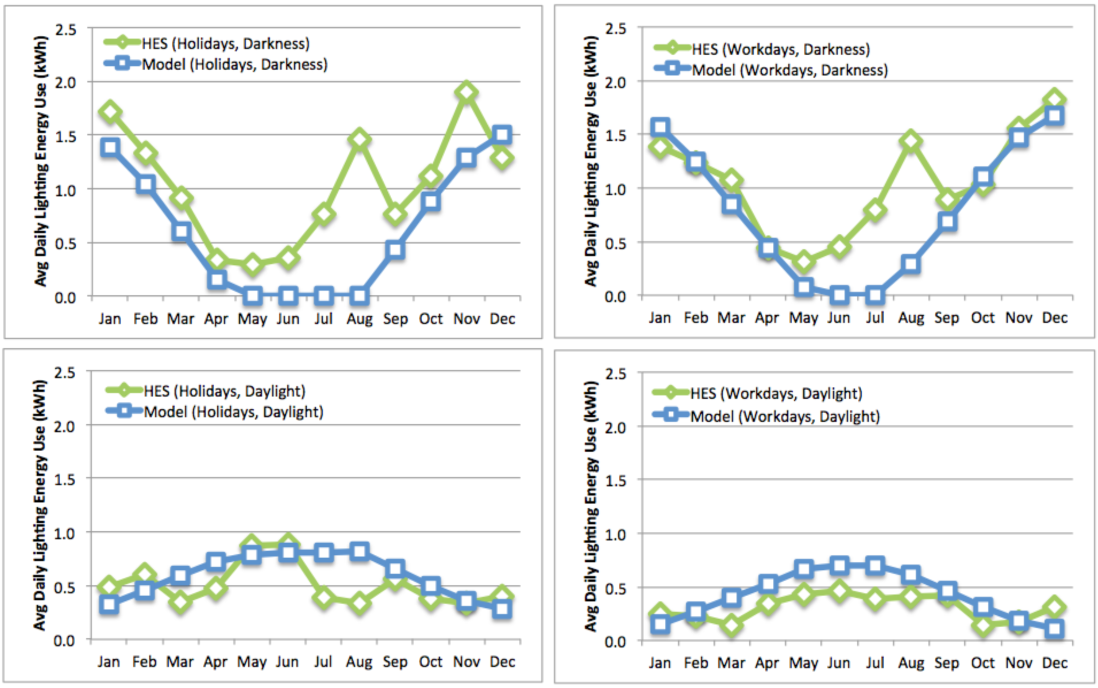
Example result: Six occupants, with children, $120m^2$ floor area, full-time employment.

A few of the sample households had lighting energy use peaks during the summer (see figure immediately above, and that below), which may be due to changes in behaviour during this time. Part of the reason may be an increased use of outdoor lighting in the summer. However, installed external lamp power in the HES sample households is typically a small proportion of the total household installed lamp power (the mean outdoor lighting is 11%), and there are instances of summer peaks in houses with little or no outdoor lighting, so this is unlikely to be the key factor. Other possibilities are temporary changes in occupancy patterns, such as children being off school or allowed to stay up until later, or occupants spending more time at home on holidays. Unfortunately, the HES lighting use monitoring did not cover specific lamps (see earlier in this report for details) and occupancy diaries were not collected, so determining the true reason for this was not feasible.

The Lighting Tool spreadsheet we have developed to support this work allows readers to create their own graphs comparing modelled and actual energy use for lighting, month-by-month, for the HES households. The spreadsheet is available here:

www.tiny.cc/HES-Lighting-Tool

The Lighting Tool allows readers to look specifically at average daily lighting consumption on work days or holidays, and/or further split by hours of darkness (sunset to sunrise) and hours of daylight (sunrise to sunset). There are four example plots from the tool below, showing energy use for lighting in a household of two people in part-time employment. (This more detailed breakdown is not calculated in SAP, so we did not include SAP estimates for this part of the Tool.)

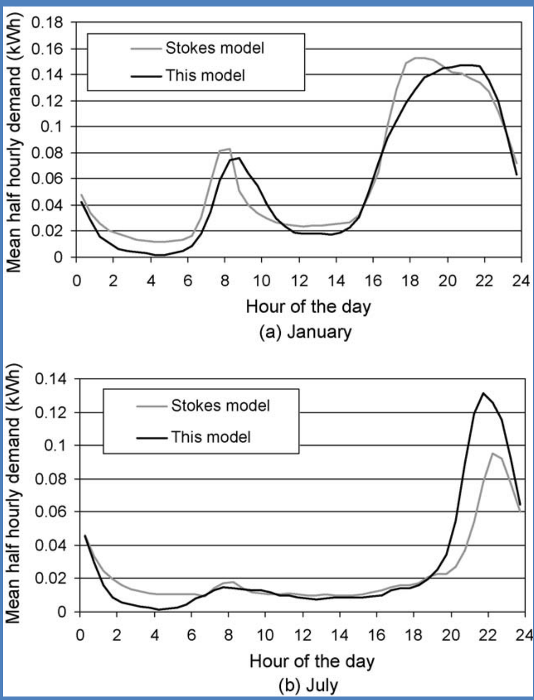


Example result: Two occupants, no children, $100m^2$ floor area, part-time employment.

Other Work on Lighting Energy Models and Use Profiles

We were unable to find any published research that included lighting use profiles over the year, but we did find two research projects that examined the 24-hour profile of electricity use for lights. First, the Electricity Association Load Research Group measured lighting consumption data from 100 homes in 1996-97, and this was used to build the Stokes domestic lighting model[24]. The model predicted an average load profile at half hourly intervals for both lighting circuits and portable lamps. The model showed two distinct peaks (morning and evening), which change according to the time of year. The morning peak is between 8:00am and 9:00am but the evening peak varies considerably through the year between 6:00pm (December) and 10:00pm (June). Occupant behaviour was found to be an important driver of the variation in time of use for lighting, but averaged over the whole sample the seasonal solar variation was a more significant influence.

A second model used household activity based on the Time Use Survey and the level of natural light entering buildings to estimate lighting demand[25]. Although this model was not based on measured consumption data, its outputs are similar to those described in the Stokes model above (see graphs below).



These graphs compare Stokes' and Richardson's model estimates of mean lighting demand.

[26] Stokes, M., Rylatt, M. & Lomas, K. (2004) A simple model of domestic lighting demand. Energy and Buildings 36, 103–116.

[27] Richardson, I., Thomson, M., Infield, D. & Delahunty, A. (2009) Domestic lighting: A high-resolution energy demand model. Energy and Buildings 41, 781–789.

Observations and recommendations

The use of some simple assumptions in this section means that the results should be treated with caution. However, this suggests that it is possible to improve the reliability of lighting energy use estimates in SAP for total energy across a sample of households, based partly on the HES data. (Conversely, the work suggests that it is very hard to improve on the reliability of lighting algorithms in SAP for individual dwellings.) Further, it is not a trivial task to improve the estimates even for samples of dwellings, and some important input data is still missing, including validation data (lighting energy use could only be checked at the house-scale, rather than room scale). A study monitoring lighting use in individual rooms, alongside occupancy behaviour diaries, may help to improve the assumptions used here, and identify the reasons for the unexpected energy use profiles that were observed in some of the households. Further validation work and larger samples would be worthwhile if DECC wishes to improve aggregate lighting energy estimates.

Nevertheless, the bottom-up transparent approach outlined here provides two possible advantages over existing statistical-based approaches (like SAP and BREDEM[28]): it enables subtle differences between households to be included in the calculation process, and make it easier to analyse the impact of changes. Whether this is possible or practical for large numbers of homes is a legitimate question, but when this sort of data is collected for other reasons, it may be possible to use this form of modelling as a basis for lighting estimates.

While this level of detail may not be necessary for Building Regulations purposes, it may also be helpful in unusual cases, where a number of ‘typical’ profiles could be used to account for different likely uses (e.g. a typical retirement home profile, or typical profiles for student accommodation, etc.).

Readers should note that the data used for this model is not identical to that collected in the English Housing Survey. (This means it cannot easily be inserted into stock models like the Cambridge Housing Model or the National Household Model.) However, many of the variables used here have analogues to the EHS dataset, meaning it may be feasible to use a *similar* approach for the EHS analysis. We were not able to test this because the HES homes were not included in the English Housing Survey.

[28] BRE (2013) BREDEM 2012: A technical description of the BRE’s Domestic Energy Model v1.0. Watford: BRE. http://www.bre.co.uk/filelibrary/bredem/BREDEM-2012-specification.pdf

External Lighting

Our information on installed lighting was collected using a questionnaire and it lists the bulbs in each house, giving room, type and wattage. We identified 318 outside lights from the installed lamp data, across 142 households. This gave us the opportunity to assess energy use for outdoor lighting, but the opportunity was imperfect because the HES did not record energy use for individual light fittings – rather, the lighting circuit in each household was monitored. Instead, we concentrated on the type of external lighting, which is a very good indicator of energy use per unit of light (watts per lumen), and which was well documented in the HES.

Analysis

The first stage of the analysis studies the presence of outside lights within the HES homes. 245 homes were included in the questionnaire and 318 outside light bulbs were recorded. The table below present summary statistics on the presence of outside lights, with figures given for each of the six light bulb types recorded in the questionnaire and for all light bulb types combined. Overall 58% of the HES homes (142 homes) had at least one outside light present. 37% of homes had at least one incandescent outside light bulb present, 27% had at least one halogen outside light bulb and 15% had at least one compact fluorescent bulb outside.

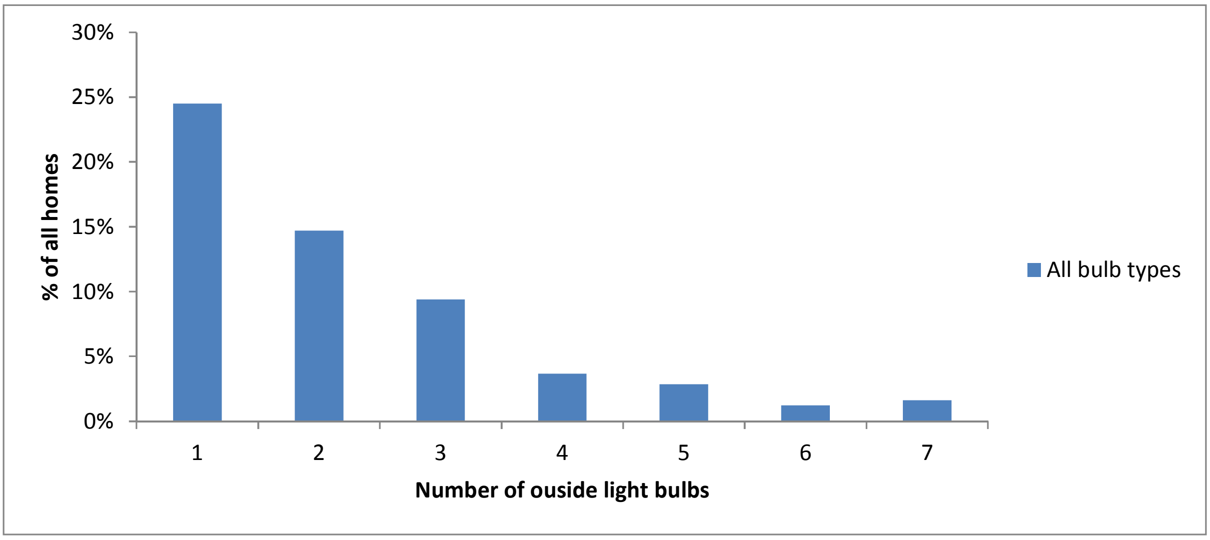
None of the homes had LED outside lighting and only a small proportion (1.6%) had halogen low voltage or standard fluorescent lights. Of the 318 outside light bulbs present, nearly half (49%) were incandescent bulbs and around a third (30%) were halogen bulbs. The 245 homes had an average of 1.3 outside light bulbs per home. For the 142 homes which had outside lighting, the average number of outside bulbs was 2.2. For those homes with incandescent outside lighting, the average number of incandescent light bulbs was 1.7. The maximum number of outside light bulbs per home across the sample was seven.

Summary statistics for outside lights: different bulb types

Outside light bulb type	% of homes with outside light bulbs	Proportion of outside light bulb type across sample	Average number of outside light bulbs (for all homes)	Average number of outside light bulbs (for those homes with at least one outside light of the same type)	Maximum number of outside light bulbs per home
Incandescent	37.1%	48.7%	0.63	1.70	7
Halogen	27.3%	29.6%	0.38	1.40	4
CFL	15.1%	17.0%	0.22	1.46	3
Low Voltage Halogen	1.6%	2.5%	0.03	2.00	4
Fluorescent	1.6%	2.2%	0.03	1.75	3
LED	0.0%	0.0%	0.00	0.00	0
All bulb types	58.0%	100.0%	1.30	2.24	7

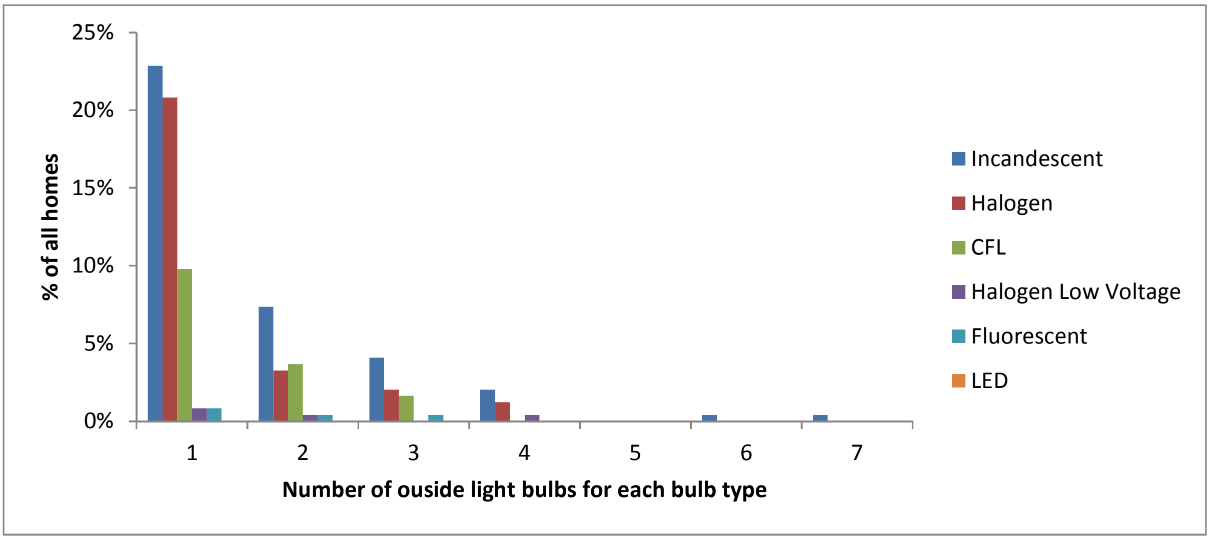
Base: Households that responded to the lighting questionnaire (n = 245).

The number of outside lights per home varied between zero and seven. Of the 245 homes that answered, 24% had one outside light, 15% had two outside lights and 19% had more than two. 2% of the homes had seven outside lights, the maximum amount recorded in the questionnaire.



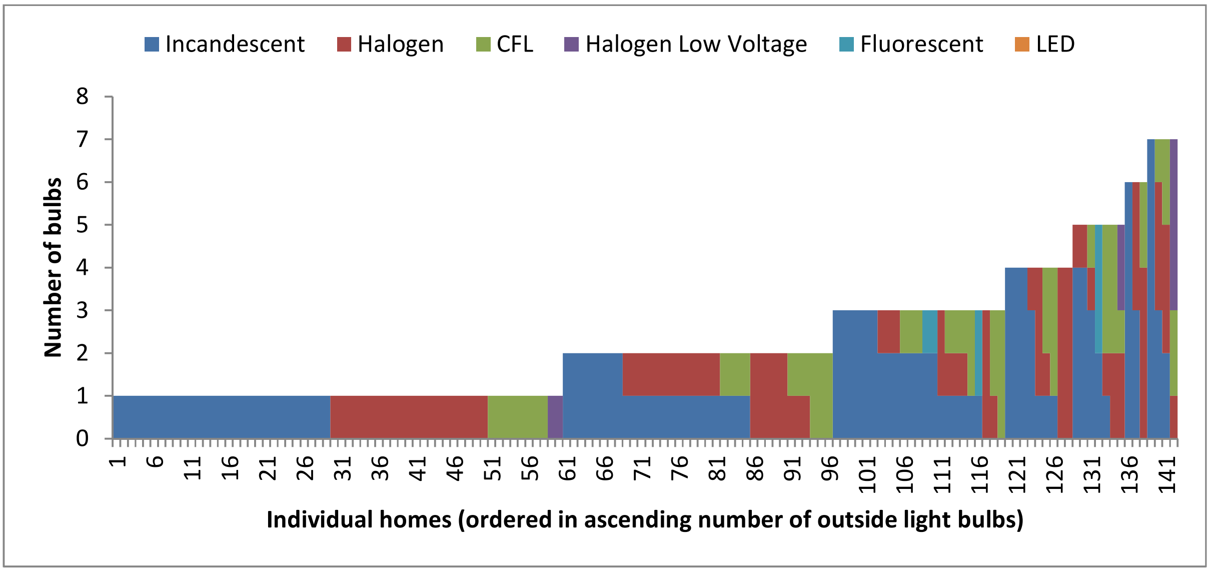
Distribution of the number of outside light bulbs, shown by the percentage of all homes against the number of outside light bulbs [Base: All homes, n=245]

For incandescent outside lights, 23% of homes had only one incandescent bulb, 7% had two incandescent light bulbs and 7% had more than two. Halogen outside lights were slightly less prevalent, with 21% of homes having only one halogen outside light bulb, 3% of homes having two halogen bulbs and 3% having more than two. Compact fluorescent outside light bulbs (CFLs) were the next most prevalent outside lighting choice, with 10% of homes having one CFL bulb and 5% of homes having more than one.



Distribution of outside light bulbs by outside bulb type, shown by the percentage of all homes against the number of outside light bulbs [Base: All homes, n=245]

The 142 homes with outside lighting had a variety of outside light bulb combinations at each home. The figure below shows the combination of light bulb types for each home. Incandescent outside lighting is most prevalent throughout, and combination of incandescent, halogen and CFL lighting being the most common.



The number and combination of outside light bulb types for each home [Base: All homes with at least one outside light bulb, n=142]

The second stage of the analysis studies the power (wattage) of the outside lights within HES homes. For the 318 outside light bulbs surveyed in the questionnaire, the wattage of each light bulb was recorded. The table below presents summary statistics on the wattage of outside light bulbs, with figures given for each of the six light bulb types recorded in the questionnaire, and for all light bulb types combined. Overall there was 41 kW of outside light bulb wattage recorded in the 245 homes, with nearly three quarters of this due to halogen outside lights (29 kW). The average total outside light wattage for all homes (n=245) was 168 W, and 289 W on average for homes with outside lighting (n=142).

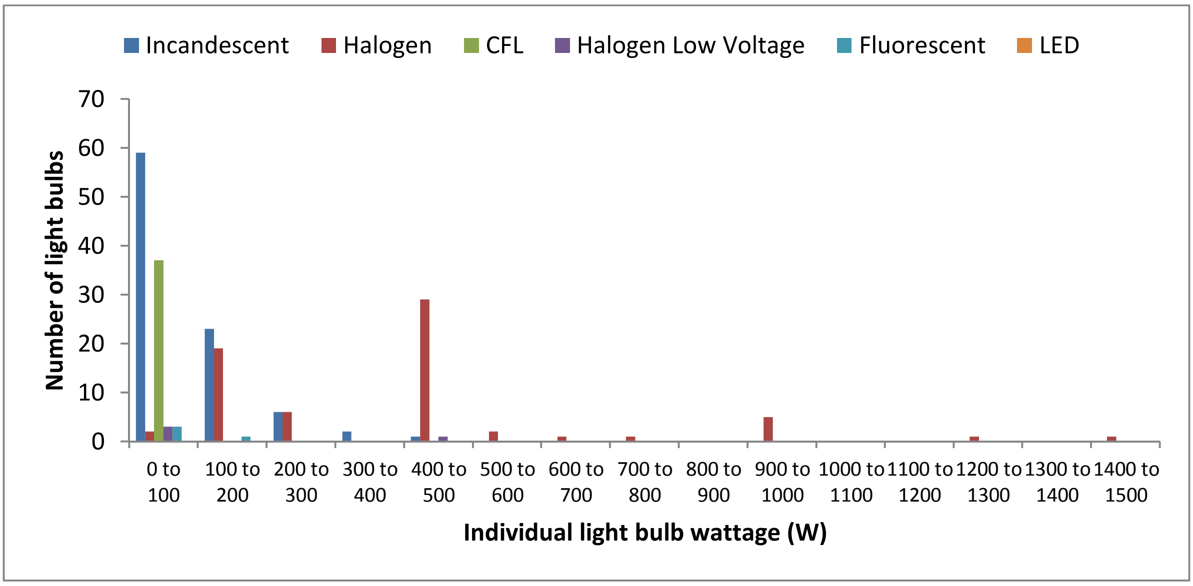
For the bulbs, the average wattage across all bulb types was 129 W, with halogen bulbs highest at 312 W. The maximum outside light wattage for an individual home was 1,500 W, attributed to a home with only halogen external lights.

Summary statistics for outside lights: power

Outside light bulb type	Total wattage of outside light bulbs (W)	Average wattage of outside light bulbs per bulb (W)	Average wattage of outside light bulbs per home (all homes) (W)	Average wattage of outside light bulbs per home (for homes with at least one outside light of the same type) (W)	Maximum wattage of outside light bulbs per home (W)
Incandescent	10,028	64.7	40.9	110.2	420
Halogen	29,370	312.4	119.9	438.4	1500
CFL	716	13.3	2.9	19.4	58
Halogen Low Voltage	601	75.1	2.5	150.3	500
Fluorescent	320	45.7	1.3	80.0	145
LED	0	0.0	0.0	0.0	0
All bulb types	41,035	129.0	167.5	289.0	1500

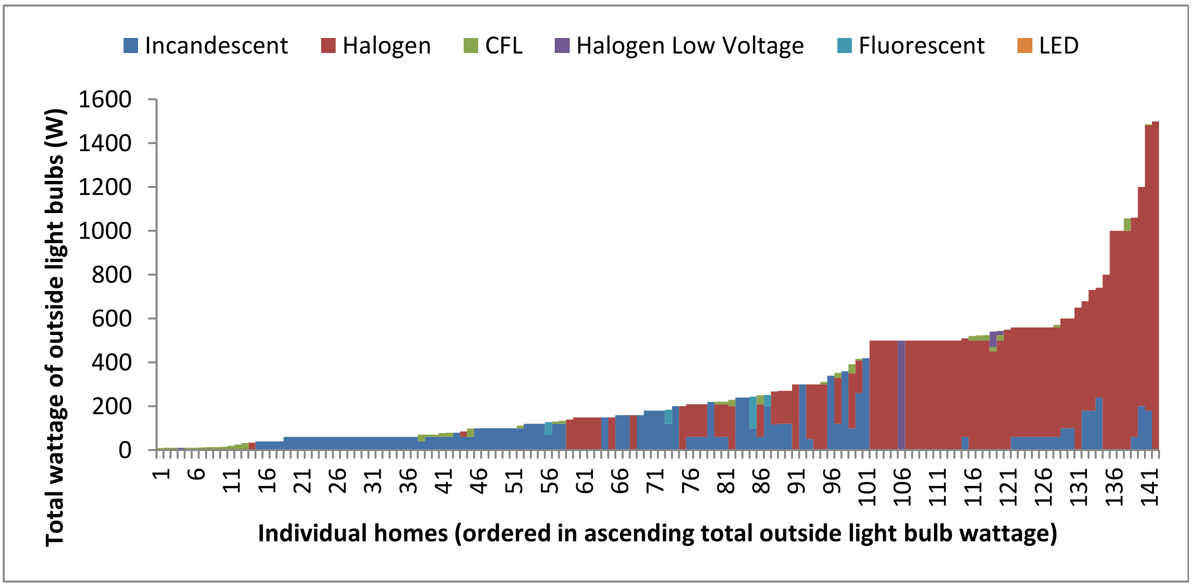
Base: Households included in the lighting questionnaire (n = 245)

The variation in the wattage of individual outside light bulbs is shown in the figure below. Almost all incandescent outside lights have a wattage below 300 W, with the majority less than 100 W. All CFL outside light bulbs have a wattage below 100 W. Halogen outside light bulbs are reported to have considerably higher wattages, with a large proportion between 400W and 500W, and several instances in the range 500 W to 1500 W.



Wattage of individual outside light bulbs by bulb type, shown by the number of light bulbs against wattage (in bins of 100W) [Base: All outside light bulbs, n=318]

The total wattage and contribution of different outside light bulb types for each of the 142 homes with outside lighting is shown in the figure below. The total wattage across all homes is dominated by incandescent and halogen outside lighting.



The total wattage and combination of outside light bulb types for each home [Base: All homes with at least one outside light bulb, n=142]

Observations and recommendations

For external lighting, a majority of lights are inefficient bulb types. 49% of outside lights are incandescent bulbs and 30% are halogens. These two light bulb types have high wattages (an average of 65W for incandescents and 312W for halogens), so there are potential savings from replacing these with more efficient light bulb types such as CFLs or LEDs.

The Eco-design Directive sets out a timeline for improving the energy efficiency of both directional and non-directional lighting (see[29, 30]). Since September 2012, incandescents with power above 7W and halogens above 40W have not been allowed to enter the EU or European Economic Area supply chains (i.e. no manufacture in or import into the EU or EEA countries).

Some retailers have stockpiled the old lamps, which explains why these lamps are still available in shops. However, over the long term, inefficient lamps will disappear from the European supply chains. This will necessarily improve the energy efficiency of outdoor lighting.

[29] European Commission (EC) (2009) No 244/2009 of 18 March 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps. Brussels: EC.

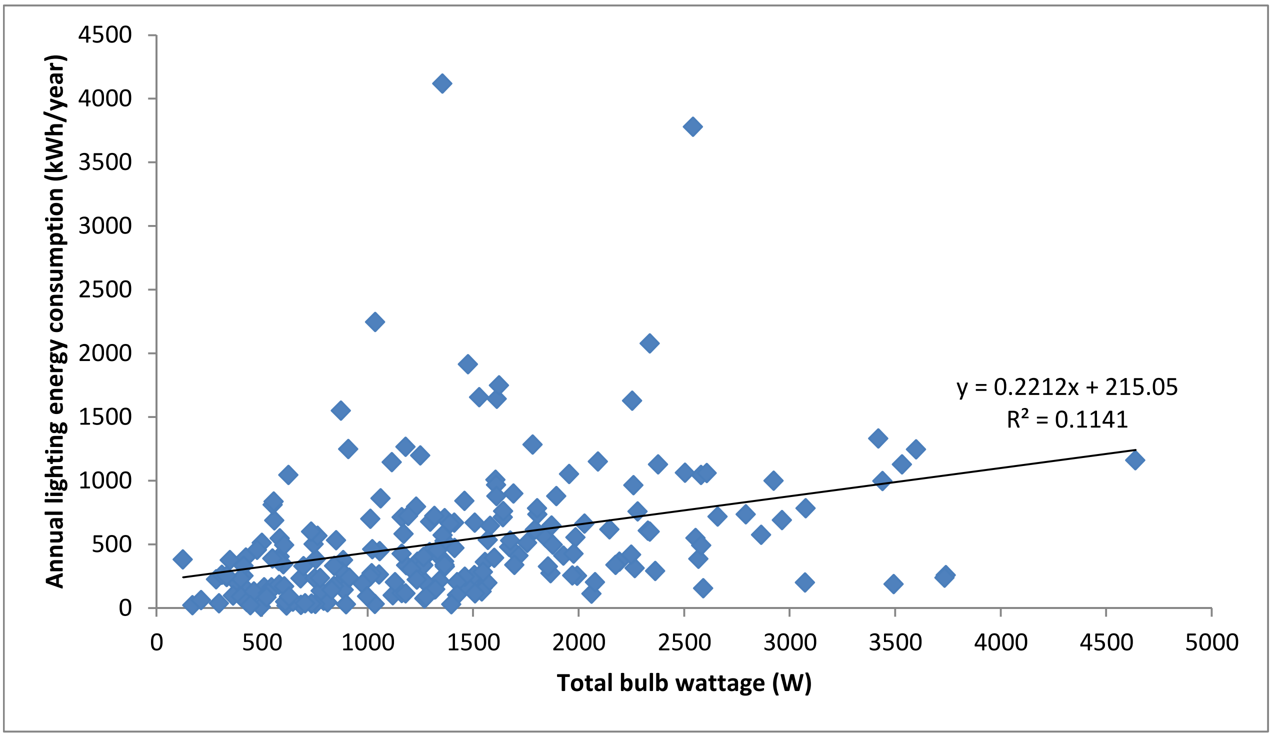
[30] European Commission (EU) No 1194/2012 of 12 December 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, light emitting diode lamps and related equipment. Brussels: EC.

Projections of overall lighting energy use over next 10 years

Overall energy use for lighting is expected to change over the coming years due to technology and behaviour changes. Annual lighting use for all UK homes is influenced by the number of dwellings and households, the types of light bulbs used in the homes, and how long electric lights are in use. We tried to use the best data available in the HES to explore how lighting energy use might change over the next 10 years. Like all projections, there is considerable uncertainty in the projections, and we had to make some big assumptions because of limited data and unknowns that could affect household lighting use.

Analysis

This section of the report assesses the impacts of replacing light bulbs with more efficient models. Firstly the total wattage of lighting in each home was calculated and compared with the annual lighting energy use. The lighting wattage was recorded as part of the questionnaire survey and the annual lighting use was calculated from electricity measurements of lighting circuits. We found a weak positive correlation between total wattage and annual lighting energy use (annual lighting energy use increased as total wattage increased). The wide variation can be attributed to the number of hours the lights are used and the choice of which lights are in use.



Total bulb wattage vs. annual lighting energy consumption for all homes [Base: All homes with total wattage and lighting electricity use recorded, n=209]

Secondly we calculated the number of hours of lighting use over a year. Here we assumed that each household used all light bulbs for the same amount of time. This was necessary as the electricity consumption of individual light bulbs was not measured during the HES survey, but the whole lighting circuits were measured instead. From the monitoring of lighting circuits, with potentially many different light bulb types and wattage on each circuit, it is not possible to determine hours of use at the individual light bulb level. Without knowing how long each light bulb in a home is used for, it is a reasonable and practical assumption to state that all light bulbs are used for the same amount of time. Clearly this will not be the case in practice and this introduces some uncertainty into the analysis. For example, if any homes use higher wattage light bulbs more often they will save more by replacing these light bulbs with more efficient bulb types. Conversely homes that use higher wattage light bulbs less often will have lower savings.

Annual hours of use for lighting, per household, was therefore given by the annual lighting energy consumption (in Wh) divided by total bulb wattage (in W). The average household lighting hours of use is 431 hours/year (4.9% of a year) for the 209 homes in the analysis. This is comparable to assumptions of between 394 hours/year and 562 hours/year for incandescent light bulb used in previous modelling studies[31].

Thirdly, the reduction in total light bulb wattage was calculated, as light bulbs are replaced with more efficient bulb types. We assumed that, as light bulbs are replaced with more efficient models, the requirement for lighting levels still remains and so any new light bulbs will be chosen to deliver the same lighting level, or luminous flux (measured in lumens, lm), as the original bulbs. The luminous efficacies of light bulbs types are assumed to have the values as below[32]. CFL light bulbs (60 lm/W) are assumed to be four times as efficient as incandescent light bulbs (15 lm/W) and three times as efficient as halogen light bulbs (20 lm/W).

Luminous efficacy for different light bulb types

Light bulb type	Luminous efficacy (lm/W)
Incandescent	15
Halogen	20
CFL	60
Halogen Low Voltage	20
Fluorescent	60
LED	60

Using the reported light bulb types and their associated wattages, total luminous flux (the light power emitted by a light source) was calculated for each home. The average household luminous flux was 30,644 lm. Once the total household luminous flux was known, we could determine the change in total bulb wattage through replacing light bulbs with more efficient bulb types.

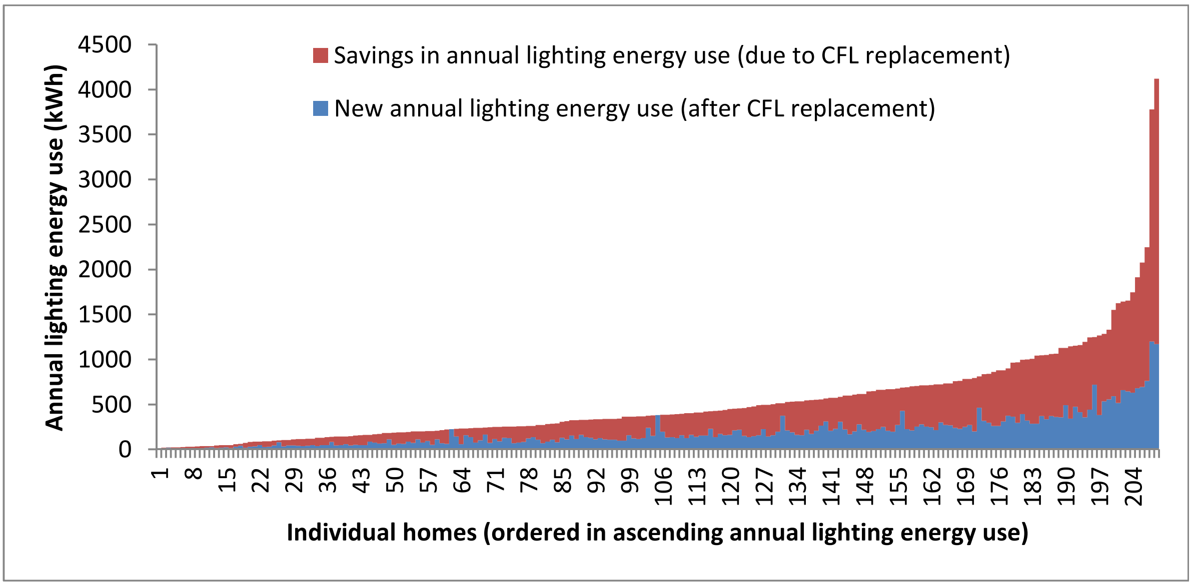
For example, a house with an annual lighting energy use of 1,197 kWh/year had a total bulb wattage of 1,250 W from a combination of incandescent, halogen and CFL bulbs. The total hours of lighting use were estimated as 957 hours/year and the total luminous flux was estimated (using the luminous efficacies above) as 22,400 lm. If all the non-CFL bulbs in this house were upgraded to CFL bulbs with the same luminous flux (60 lm/W), then the new total bulb wattage would be 373 W. Multiplying this new total bulb wattage estimate by the number of hours of lighting use (373 W x 957 hours/year) gives a new lighting annual energy use of 357 kWh/year.

For the 209 homes in this analysis, we estimated that replacing all non-CFL bulbs with CFLs (at 60 lm/W) would reduce average annual lighting energy use from 524 kWh/year to around

[31] Market Transformation Programme (2010). BNDL01: Domestic Lighting Government Standards Evidence Base 2009: Key Inputs. http://efficient-products.defra.gov.uk

[32] These values are based on the values reported here http://www.rapidtables.com/calc/light/how-watt-to-lux.htm

190 kWh/year. This is a saving of some 330 kWh/year and a percentage saving of about 60%. If the HES homes are taken as representative of the English housing stock, then replacing all bulbs in English homes with CFL light bulbs is estimated to result in national domestic lighting energy use dropping to 37% of its current value. Across the 209 homes in the HES sample the energy savings are seen for both homes with low and high annual lighting energy use. The amount of energy saved will depend on the number of light bulbs in the home, the proportion of light bulbs already in place, and the number of hours of use of the light bulbs.

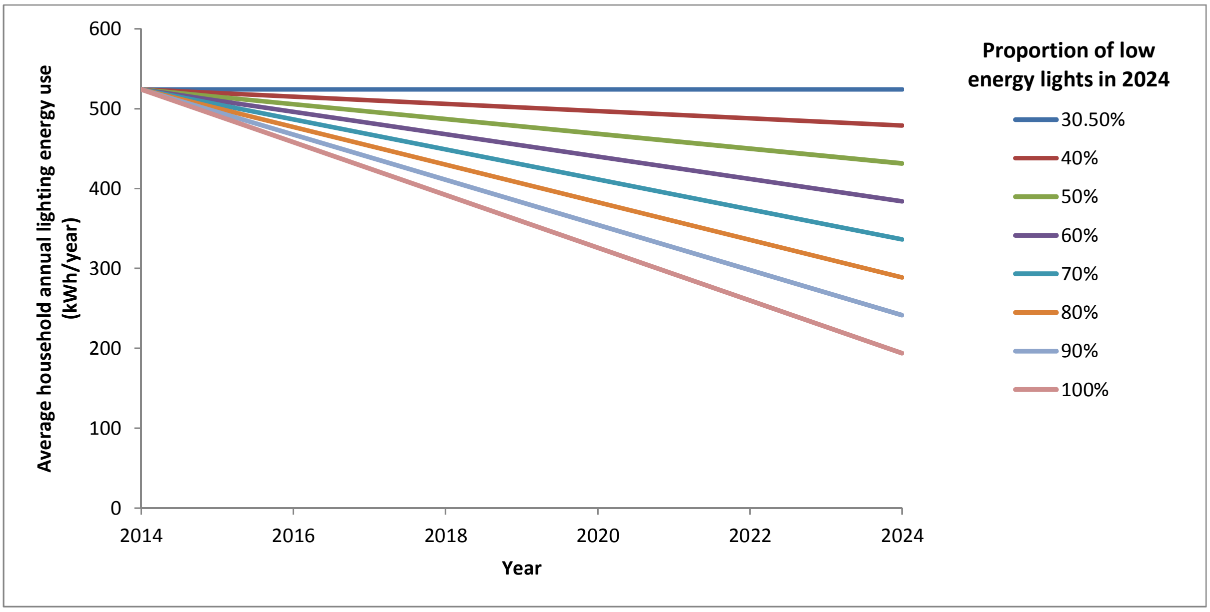


Annual lighting energy use after CFL replacements, and the savings from replacement, for each home [Base: All homes with total wattage and lighting electricity use recorded, n=209]

In projecting lighting use for the next 10 years, the determining factors are the rate of upgrading existing light bulbs from inefficient models to efficient models, and the rate of new dwellings being constructed. Using the analysis method above, the replacement of inefficient lighting (incandescent and halogen lighting) with low energy lighting (CFLs, fluorescents and LEDs – all at 60 lm/W) can be modelled for different proportions of overall replacement. In 2024 overall reductions in annual lighting energy use are modelled for 30.5% of low energy lights installed (the proportion in the HES study) up to 100% in steps of 10%. Replacement rates are assumed constant for each year between 2014 and 2024, and the results below show the reduction in annual lighting energy use for existing homes only.

In the Market Transformation Programme projections of future lighting use, the 'Reference Scenario' estimated that in 2020 low energy lights would represent around 60% of the overall light bulbs in use[33]. This rate of replacement, if it continued until 2024, would result in an 80% proportion of low energy lights in place in 2024 and a new average household annual lighting energy use of around 290 kWh/year, or a saving of around 230 kWh/year per home on average.

[33] BNDL01: Domestic Lighting Government Standards Evidence Base 2009: Key Inputs, Market Transformation Programme, 2010, http://efficient-products.defra.gov.uk



Projected average household annual lighting energy use for existing homes only, based on different replacement rates of low energy lights [Base: All homes with total wattage and lighting electricity use recorded, n=209]

This chart shows linear reduction in lighting energy over time, due to our assumption that all lights have the same pattern of use. In practice some lights will be used more than others and these will need to be replaced before the ones that are rarely used. Therefore, in practice the energy consumption will reduce more quickly in earlier years and flatten off, though the end point will be the same.

The expected increase in the numbers of new-build homes in England to be constructed over the next ten years can be estimated as 221,000 new homes per year, based on the Department of Communities and Local Government projections of households[34]. The total number of homes in England in 2011 is given as 22,102,000. The assumption made here is that new-build homes will contain 80% low energy lights, and so (using the above analysis) new homes are assumed to have an average household annual lighting energy use of 289 kWh/year.

Combining the impact of new-build homes with the results for existing homes, and assuming the 209 HES homes are representative of the wider English housing stock, gives an indicative projection of total household annual lighting energy use for England over the next ten years. The initial estimate of 11.9 TWh/year for domestic lighting compares well with existing modelling predictions[35]. If no changes are made to the light bulbs in the existing 2014 housing stock, then the new-build housing results in annual lighting energy of around 12.5 TWh/year, an increase of 5.4% on the 2014 value. As the light bulbs in the existing 2014 housing stock are replaced with low

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[34] 'Household Interim Projections, 2011 to 2021, England', Department of Communities and Local Government, 2013. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190229/Stats_Release_2011FINALDRAFTv3.pdf

[35] For example, see Palmer J, Cooper I (2014). Housing Energy Fact File 2013. London: DECC. This gives household energy use for lighting in 2011 as 14.0 TWh/year. This is around 17% higher than the value derived from the HES homes in this analysis (11.9 TWh/year). Possible reasons for the difference in estimates could include the population considered (UK vs. England, and the HES sample contained owner occupied homes only) and the difference in the approaches used (e.g. modelling vs. measurements).

energy lights, the annual lighting energy falls. The best case of 100% low energy light replacement in the existing 2014 housing stock results in a 2024 annual lighting energy use of around 5 TWh, which is a saving of around 6.8 TWh, or 60% compared, to 2014.

Projected total lighting energy demand in English homes, based on light bulb replacement and increased household numbers due to new-build construction

	Total English household annual lighting energy use (TWh/year) in the year:										
Percentage of low energy lights installed across the existing stock in 2024	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
30.50%	11.9	11.9	12.0	12.1	12.1	12.2	12.3	12.3	12.4	12.4	12.5
40%	11.9	11.8	11.8	11.8	11.7	11.7	11.6	11.6	11.6	11.5	11.5
50%	11.9	11.7	11.6	11.4	11.3	11.1	11.0	10.9	10.7	10.6	10.4
60%	11.9	11.6	11.4	11.1	10.9	10.6	10.4	10.1	9.9	9.6	9.4
70%	11.9	11.5	11.2	10.8	10.4	10.1	9.7	9.4	9.0	8.6	8.3
80%	11.9	11.4	10.9	10.5	10.0	9.5	9.1	8.6	8.1	7.7	7.2
90%	11.9	11.3	10.7	10.2	9.6	9.0	8.4	7.9	7.3	6.7	6.1
100%	11.9	11.2	10.5	9.8	9.2	8.5	7.8	7.1	6.4	5.7	5.1

Observations and recommendations

Considerable potential energy savings still exist from replacing inefficient light bulbs in homes with low energy light bulbs. Estimates in this work suggest that replacing all inefficient light bulbs in homes with low energy lights would results in an overall energy savings for all English homes of around 6.8 TWh (a saving of around 60% of total lighting energy use in 2014).

A potential policy implication of these findings is the opportunity to further reduce overall lighting energy use by reducing the overall wattage of light bulbs in homes, in particular by replacing inefficient bulb types with low energy lights. Accelerating the replacement of inefficient light bulbs with low energy lights would deliver these savings sooner, resulting in lower household energy bills and less greenhouse gas emissions.

Over the next 10 years the additional lighting energy use from new build homes will be minimal (an increase of around 5% in lighting energy use over 10 years), provided new build homes are equipped with low energy lights.

Other Projections of Lighting Energy Use

Johnston et al's 2005 analysis of the potential for making improvements to the UK housing stock[36] suggested that under a 'business as usual' scenario, average lighting consumption per dwelling could increase by almost 20% between 1996 and 2050. However, the same study suggested that with significant uptake of low-energy lighting, energy use could decrease by around 50% during the same period.

The Market Transformation Programme[37] estimated the energy use for domestic lighting in 2020, based on three scenarios . The reference case predicted that domestic lighting would use 19.2 TWh in 2020 (This compares to DECC figures from 2009 of 15.2 TWh). Accounting for an increase in domestic dwelling and lamp ownership, the 'Policy' and 'Early best practice' scenarios saw a 35% and 46% reduction, respectively, on the reference case.

In September 2009 the European Union announced that incandescent light bulbs were to be phased out[38]. The proportion of low energy lighting in the housing stock is an important driver of household electricity use and forms part of the calculation for Energy Performance Certificates. Data from EPCs could provide a significant insight into the proportion of low energy lighting in the domestic stock, but is not currently available to the general public.

In 2006 the Energy Saving Trust estimated[39] that if half of the rooms in homes undergoing major electrical work were fitted with low energy lighting (including new build), the energy savings would be equivalent to nearly 230 million kWh in the first year, and would cut energy bills by over £18 million .

[36] D Johnston et al (2005) An exploration of the technical feasibility of achieving CO2 emission reductions in excess of 60% within the UK housing stock by the year 2050. Energy Policy 33(13) pp1643-1659.

[37] Market Transformation Programme (2008) BNDL01 : Assumptions for energy scenarios in the domestic lighting sector. 1–10, Department for Environment, Food and Rural Affairs, London.

[38] European commission (2013) Energy-saving light bulbs – web reference accessed 21st June 2013 http://ec.europa.eu/energy/lumen/index_en.htm

[39] Energy Saving Trust (2006) Energy efficient lighting – guidance for installers and specifiers, The Energy Saving Trust, London.