Study on Energy Use by Air-Conditioning: Annex D: Monitored Consumptions

BRE Client Report for the Department of Energy & Climate Change, HPR218-1001 - June 2016

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This report provides supporting information and explanation to the DECC Report "Study on Energy Use by Air-Conditioning: Final Report" (BRE Client Report HPR218-1001 The views expressed in this report are those of the authors, and not necessarily those of the Department of Energy and Climate Change (nor do they reflect Government policy).

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Annex D: Monitored Consumptions

This Annex reports the analysis of monitored data from 32 air conditioning systems. It includes annual consumptions, monthly weighting factors, peak power levels, “operational hours” (equivalent full-load hours) for the monitored systems, and also shows the variation of these variables by region. The main conclusions are summarised below.

Annual consumption. Standardising results to the London climate, the median annual electricity consumption for cooling in offices was 40.5 kWh/m^2. Industry benchmark values for “typical consumption” are between 30 and 40 kWh/m^2, and for “good practice between” 15 and 20 kWh/m^2. 14% of cooling consumption was at weekends, although most of the offices were unoccupied at weekends.

The range of standardised annual consumptions was high - between 6 and 270 kWh/m^2 - and showed no consistent pattern between different types of system or size of conditioned space. By contrast, the standardised average consumption for the region with the highest consumption (London) was only 30% higher than that for the lowest (Belfast). This suggests that consumption is largely determined by other factors such as building design and use, and system efficiency.

Throughout the year there is often ancillary consumption by equipment that is not directly associated with the provision of cooling. (This type of consumption is included in ErPD energy labelling and minimum performance metrics).

Peak electricity demand. In general the (standardised) peak electricity demands are significantly smaller than the connected loads in the sample. In other words, the installed cooling power seems to be higher than the observed maximum half-hourly demands. This implies that the cooling capacity of the monitored systems exceeded that actual peak demands.

Peak demand varies with outdoor temperature onto which are superimposed the effects of other variations of heat gain. An increase of the maximum mean daily outdoor temperature of 1 deg C increased the standardised peak electricity demand by 4% for London weather. The peak demand varies with the value of the frequency of occurrence of extreme demands chosen as a criterion. When the "exceedance" threshold was changed from 5% to 1%, the standardised peak power levels increased by 16% on average from 31.3 to 36.4 W/m^2 (for London weather).

Because of the temperature dependency, the calculated mean peak values vary by location. The highest value, for London, is 17% higher than the lowest, for Newcastle, reflecting the effect of the different values of outdoor temperature used. However, the locations with low peak demands do not necessarily have the lowest annual consumptions.

Product policy modelling. In general, systems with high peak power demands also tend to have high annual consumptions: the ratio being known as the "equivalent full load hours" value – which is one of the key inputs to DECC's product policy model. The measurements provide empirical values for this parameter.

The monitored data also provided monthly consumption profiles for each system and location.

1. Objectives

1.1. Identification of buildings for which existing cooling demand and electricity data from air-conditioning systems can be obtained and analysis of this data.

1.2. Making recommendations to update the key inputs to DECC's existing model of electricity demand from air-conditioning.

1.2.1. In particular relating to the peak and monthly electricity demand and the "operational hours" of air-conditioning in the UK.

2. Overview of the Monitored Systems

2.1. The measured consumption data were originally collected as part of a collaborative project between BRE, Cardiff University and National Grid between 2001 and 2003. The principal "as measured" results showing the variability of measured annual consumption between buildings and differences between types of system have previously been published.[A] These results were for the combined energy use by each air conditioning system for cooling, air handling (where this was measured) and heating (if the system is reversible). The present study reanalysed the raw data in order to separate out the different components of consumption and to address the required objectives.

2.2. All the buildings are offices occupied by private sector businesses, mainly in the Southern part of England. Details of the buildings are provided in the results sections. The sample of 32 systems included several different types of air conditioning system. These are summarised below. In summary, six main types of are represented. Each system is identified by a reference number from the original data set (for example WSA 100):

2.1.1. Water/air systems with fan coils and chillers. These are systems that provide mechanical ventilation. The cooled air satisfies part of the cooling demand but is supplemented by chilled water fan coil units which also provide local control. One of the systems has a reversible chiller that also provides winter heating

2.1.1.1. Systems WSA 100 (reversible); WSA 500; WSA 600; WSA 900; WSA 1000; NGC 1000.

2.1.2. Chilled ceilings or chilled beams. These are systems that usually provide mechanical ventilation. The cooled air satisfies part of the cooling demand but is supplemented by a chilled ceiling (cc) or by "passive" chilled beams (pcb) which provide additional surface area and cooling power. One system uses "active" chilled beams (acb) in which the supply air is provided through the beams rather than separately. This further increases the cooling power, albeit at the expense of needing more fan power. None of the chillers are reversible.

2.1.2.1. Systems WSA 1100 (cc); WSA 1200 (pcb - also has ice storage); WSA 1300 (pcb, naturally ventilated); WSA 1400 (acb); WSA 1500 (pcb)

2.1.3. Variable Refrigerant Flow (VRF) systems. In these systems, the chilled water room terminals are replaced by direct expansion room units which are connected to an outdoor cooling generator by refrigerant pipework. Mechanical ventilation may also be provided or the spaces may be naturally ventilated. All the systems are reversible.

2.1.3.1. Systems WSA 200; WSA 300 (naturally ventilated); WSA 400; WSA 700; WSA 1600; WSA 2000; WSA 2400; NGC 1000.

2.1.4. All-air variable air volume (VAV) system with chillers. These systems handle sufficient cooled air (some of it recirculated) to meet the peak cooling demands. This avoids the need for additional terminal units. Local control is achieved by varying the volume of cooled air supplied to each space. None of the chillers are reversible.

2.1.4.1. Systems WSA 900; NGC 1500; NGC 2000; NGC 2100; NGC 2200; NGC 2400.

2.1.5. Individual room air conditioners. These are mostly “split systems” comprising a single indoor terminal and an associated outdoor cooling generator connected to the indoor unit by refrigerant pipework. They may be cooling-only or reversible. They are generally used with natural ventilation. One of the systems comprises two split systems within the same space. In addition there is one single-room packaged “rooftop” unit which provides both mechanical ventilation and cooling.

2.1.5.1. Systems WSA 1700; WSA 1800; WSA 1900; WSA 2100 (reversible) WSA 2200 (reversible) WSA 800 (packaged unit)

2.1.6. Water loop heat pump system. This type of system comprises a reversible air to water heat pump in each conditioned space, rejecting heat to a water loop that runs throughout the building. Heat pumps operating in heating mode extract heat from the water loop. The net heating or cooling requirement is then satisfied by a central chiller.

2.1.6.1. System. NGC 2300

2.2. Other types of air conditioning systems exist, mainly as “legacy systems” in the existing stock. These include constant volume all-air systems, terminal reheat systems, and dual duct systems. All of these can be expected to have higher annual consumptions than the systems monitored.

2.2.1. Since all the systems date back to at least 2001, they do not include products that were introduced to the market after this date – including high-efficiency products. European minimum performance requirements were introduced in 2013 for products of cooling power up to 12 kW and similar requirements will apply to larger products from 2017. Products complying with the new regulations will be approximately 40% more efficient than typical earlier products although small numbers of highly-efficient products were already on sale before these deadlines. About 30% of the stock of smaller-capacity products should now comply. (The National Measurement Office is responsible for enforcement).

2.3. A general background to building heat balance and cooling demand is presented in the main report.

3. Overview of the Data Collection and Analysis Methodology

3.1. In order to break down the consumptions into cooling, air-handling and heating elements and to adjust them to a common basis in terms of outdoor temperatures, the data have been used to generate “energy signatures” for each system. Energy signatures were produced for the cooling energy for all systems and for heating or air-handling for those systems for which data were available.(Only a minority of the systems provided heating by reverse-cycle operation of the cooling generator, some systems do not provide mechanical ventilation. Where mechanical ventilation was provided there was rarely sufficient data to produce detailed energy signatures for air handling – however, for fixed speed fans, annual consumption can be estimated from the motor power and estimated hours of use). The energy signature process is essentially the inverse of that used in the algorithm for use with the current DECC model and therefore also serves to develop a better understanding of its strengths and weaknesses. The energy signatures are then used to:

- Separate the energy use for cooling, heating and other purposes –notably fans, pumps and terminal units (as far as possible given the extent of monitoring, which varied between systems).
- Adjust the “as measured” consumptions to standard annual and monthly outdoor temperature profiles
- Differentiate between weekday and weekend consumption patterns (and between Saturday and Sunday patterns)
- Identify the times of use of the systems and compare them to the stated occupation times of the buildings (where known)
- Identify changes in consumption patterns over time (presumed to result from differences of building or system operation)
- Determine standardised peak energy demands
- Extract monthly patterns of consumption (for use with the existing DECC model)
- Determine “load factors” or “operating times” in the form of annual “equivalent full-load hours” (for use with the existing DECC model)

- Explore how the consumption levels, monthly consumption patterns and load factors change when derived for temperature profiles for different parts of the UK

3.2. The analysis process overlaps considerably with the methodology of the algorithm developed to extend the scope of the current DECC air conditioning model, which is described in Annex E.

3.3. In each of the buildings energy consumption was measured at sub-hourly (generally 15 minute) intervals over a period of at least one year – longer in most cases. The consumption data always included the “cooling generator” (commonly a set of chillers) and, where possible, the energy used by fans. The combined consumption of the fan and cold generator was measured for packaged units where the fan is integrated into the unit. In several systems fan energy was estimated from spot measurements of power input combined with reported operating times – these data are clearly less reliable than those obtained from continuous measurements. Consumption by other system components such as terminal units was recorded only in a few systems. Outdoor air temperature was recorded at the same time intervals, as was air temperature at one point within the conditioned space.

3.4. For this contract, the data files were retrieved and the sub-hourly values converted into the half-hourly and daily values needed for the required analysis. These were inspected for significant gaps and improbable values.

3.5. The consumption analysis focussed on determining “energy signatures” for each of the monitored systems and components. The principles, structure and use of daily energy signatures for air conditioning systems are described in Annex E. The key steps are to describe how daily air conditioning energy consumption varies with 24-hour mean outdoor temperature, and to quantify the remaining day to day variability.

3.6. The analysis procedure for each system had the following steps:

- Scatter diagrams of daily consumption versus outdoor temperature were produced and inspected for each system and each component for which separate measurements were available.
- These diagrams showed that the consumptions on each weekday followed the same pattern but that Saturdays and Sundays differed significantly from weekdays, and sometimes from each other. Data for weekdays were therefore combined but Saturdays and Sundays were each considered separately.
    - In some buildings the relationship between consumption and temperature changed, usually abruptly, during the monitoring period, reflecting changes in the operation of the system. In these cases, separate energy signatures were produced for each period. (And

applied to weather data for a whole year to generate annual consumptions that reflect each pattern of operation).
  - Some scatter diagrams showed that reversible systems were also providing a heating service in cold weather.

- Regression techniques were used to identify the influence of daily mean outdoor temperature on daily consumption.
  - Regressions were piece-wise linear, as this was the form of relationship expected. Other forms, notably polynomial regressions were considered, but did not provide a significantly better fit.
  - The regression equations were used to generate energy signatures (tables of average daily consumption at each outdoor mean temperature), which were compatible with the structure of the algorithm. (Ideally, the energy signatures would have been created from mean consumptions at each temperature, but there were too few data points to permit this, especially at higher temperatures.)
- Each energy signature was applied to each month of standard weather data (from CIBSE Test Reference Years) for different locations. The monthly consumptions were used to produce:
  - Values of standardised annual consumption.
  - Weighting factors to allocate annual consumption between months.
- Standardised ½ hourly peak power demands were determined by following the procedure described in Annex E: selecting a suitable (warm) external daily mean temperature and using the energy signature to determine the daily mean electricity consumption on such a day; selecting a value for an extreme but feasible value for the difference between daily mean consumption and peak half-hourly electricity consumption (the half-hourly residual value) and adding the values. Two reference temperatures were used for Heathrow: 21.6 ^{o}C for normal “comfort cooling” such as offices and shops where a degree of occasional overheating is considered acceptable and 28.2 ^{o}C for more demanding applications such as operating theatres.
- “Equivalent full-load hours” values were determined by dividing the standardised annual consumption by the standardised peak power. (The annual load factor is obtained by dividing this value by 8760 for a non-leap year)

4. Analysis: Cooling

4.1. Cooling Energy Signatures – general issues

4.1.1. Consistency over monitoring period.

4.1.1.1. Some systems exhibited abrupt changes in the relationship between their consumption and outdoor temperature, presumably because of changes in system or building operation. In some cases the monitoring reports noted that the building occupants had altered control settings, typically in relatively new buildings. Commonly this resulted in a more consistent pattern of energy consumption.

4.1.1.2. Where changes of operation took place at clearly defined dates, the later – generally more consistent - pattern was analysed. When the change of operation did not coincide with a specific date, this was noted and a regression was fitted to all the data. This resulted in a poorer fit than if the data had been split into two samples simply on the basis of apparent clustering.

4.1.1.3. Two systems appeared to be operating only in a heating mode. One of these was a “change-over” system which would require intervention to controls to change between heating and cooling operation.

4.1.2. Non-temperature related variations

4.1.2.1. The energy signature describes how daily consumption is related to outdoor air temperature. Consumption is not completely determined by outdoor temperature (and day of the week): there are other, more or less random, day to day variations. Although some individual residual variations are quite large, the root mean square residual for each system is always less than the equivalent of 1 degree C change of outdoor temperature – and often substantially less. The outliers are conjectured to result from solar gains: the frequency distribution of which in the UK is skewed, with daily solar radiation in clear sky conditions typically three times the monthly average. The distribution of half-hourly variations is discussed later in the context of peak power.

4.1.3. Caveats

4.1.3.1. The energy signatures are treated as being unchanging throughout the year. This implies that occupation patterns are also similar throughout the year. A few individually controlled room air conditioners appeared to be unused for much of the year: this is not captured by the energy signature. (Periods when systems are known to be out of use can, in principle, be modelled by overriding the consumption calculation).

4.2. Variations between systems

4.2.1. Results are shown below for London weather. Similar features occur for other locations (the general effects of location are discussed later).

4.2.2. Figure D1 shows the variation of standardised annual electricity consumption for cooling for London weather.

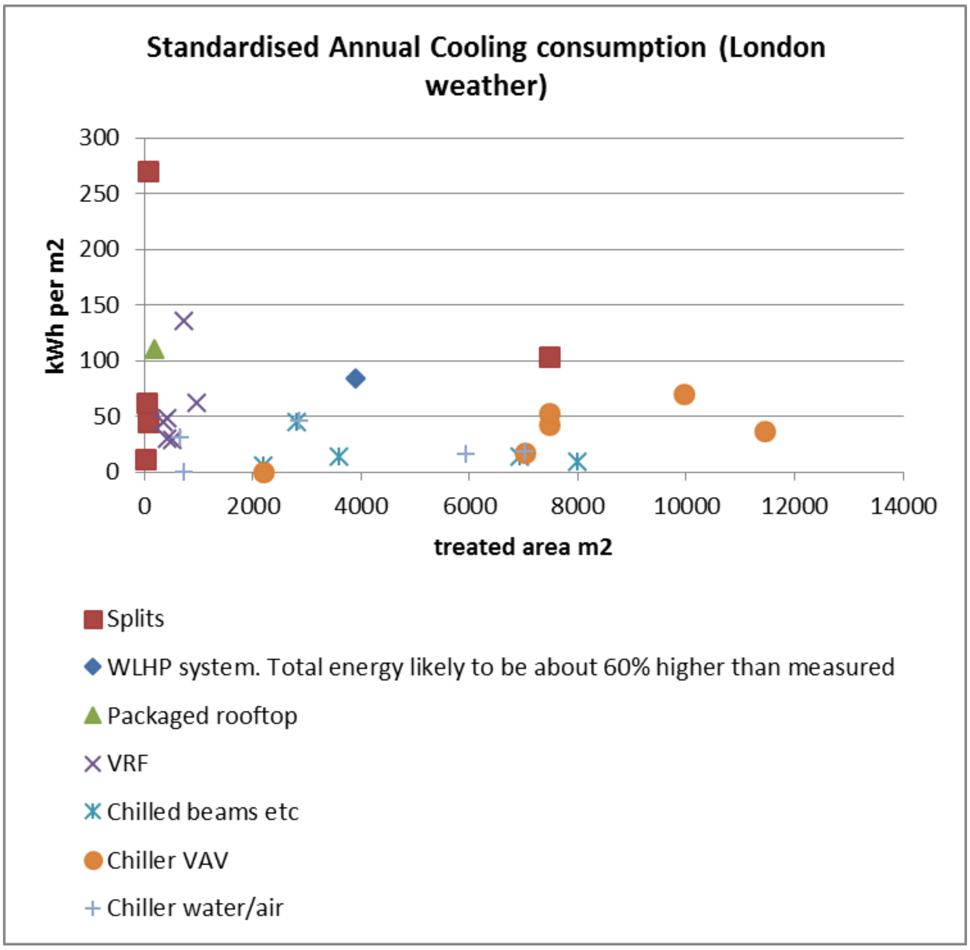


Figure D1: Standardised Annual Cooling Consumption (London weather)

4.2.3. Several general points apply to results for all weather locations:

4.2.3.1. Two reversible systems did not operate in a cooling mode during the monitoring period: they are included in the chart.

4.2.3.2. The outlying split system with the apparently very high consumption level was located in an industrial space and used very intermittently and only at times when the outdoor temperature was high. It is conjectured that under these conditions it may have had high heat gains from the adjoining space. The standardised consumption shown on the figure reflects the observed relationship between consumption and outdoor temperature when the system was in use applied to whole-year weather.

4.2.3.3. The consumption of the terminals (which are heat pumps) of the water loop heat pump was not monitored. We estimate that the total cooling consumption is likely to have been about 60% higher than that reported.

4.2.4. The average mean annual electricity consumption for cooling, weighted by system is 50.2 kWh/m2 (the median is 43.6 kWh/m2).

Weighted by treated floor area it is 40.5 kWh/m2. The lowest value observed was 6.3 kWh/m2 for a chilled ceiling system and the highest was 270.6 kWh/m2, which was for a split system. These figures may be compared to the industry “benchmark” figures of 31 to 36 kWh/m2 for “typical” systems and 14 to 21 kWh/m2 for “good practice”.

4.2.4.1. Treated area does not appear to have a significant influence on consumption per m^2.

4.2.4.2. On average 14% of consumption was at weekends, ranging from less than 1% to 35%. The highest value was associated with a system that was in use at weekends, apparently with a significant load. In general, some of the weekend consumption was associated with a base level of consumption not associated with outdoor temperature (and, from the diurnal profiles, probably not with day of the week); but many systems appeared to be in operating mode during some - sometimes most - weekends. When weekend consumption is removed, average consumption falls to 43.0 kWh/m^2. (Although systems were operating, consumptions were lower than on weekdays, presumably reflecting lower heat gains from the absence of occupants and the resulting lack of energy use by lighting and equipment)

4.2.4.3. It appears that chilled ceiling and beam systems may have consistently lower consumptions than other types of system. However, these systems are not suitable for use in spaces with high heat gains so any such difference may result from the choice of applications rather than system efficiency (although there are technical reasons why these systems may have higher efficiencies).

4.3. Monthly distribution of consumption: London

4.3.1. The monthly weighting factors are shown in figure D2. (The horizontal axis numbers represent months of the year from January to December).

4.3.1.1. There is significant variation from one system to another.

4.3.1.2. The outlying system is a split system serving a small office. Cooling was not provided unless the average outdoor temperature was 19 ^{0}C or above: at other times the system absorbed no power – it was presumably switched off at the mains.

4.3.1.3. Consumption in winter months is “base consumption” not associated with the provision of cooling.

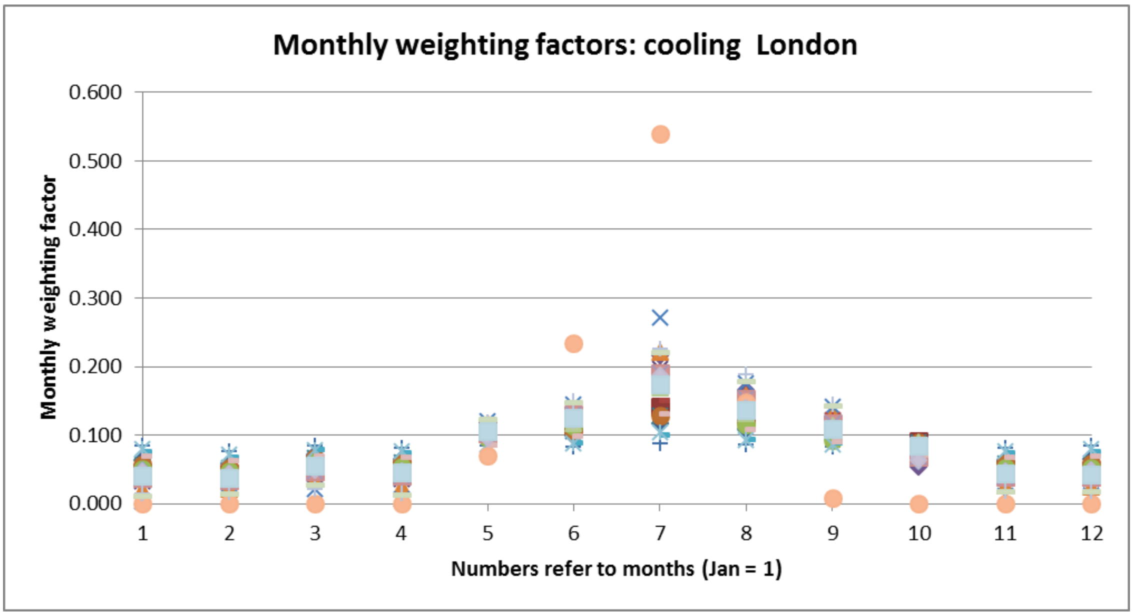


Figure D2 Monthly weighting factors for cooling energy: London weather

4.3.2. Variation with system type; floor area

4.3.2.1. Figure D3 shows the range of weighting factors for July. There is no apparent variation with system type or floor area treated. A water loop heat pump system comprises individual heat pumps in each space connected to a central chiller and boiler. The heat pumps extract heat from, or reject heat to, a common water loop. A central chiller and boiler provide cooling or heating to the common loop. Only the electricity use by the central chiller was monitored and it is estimated that the total electricity used for cooling would have been about 60% higher than this.

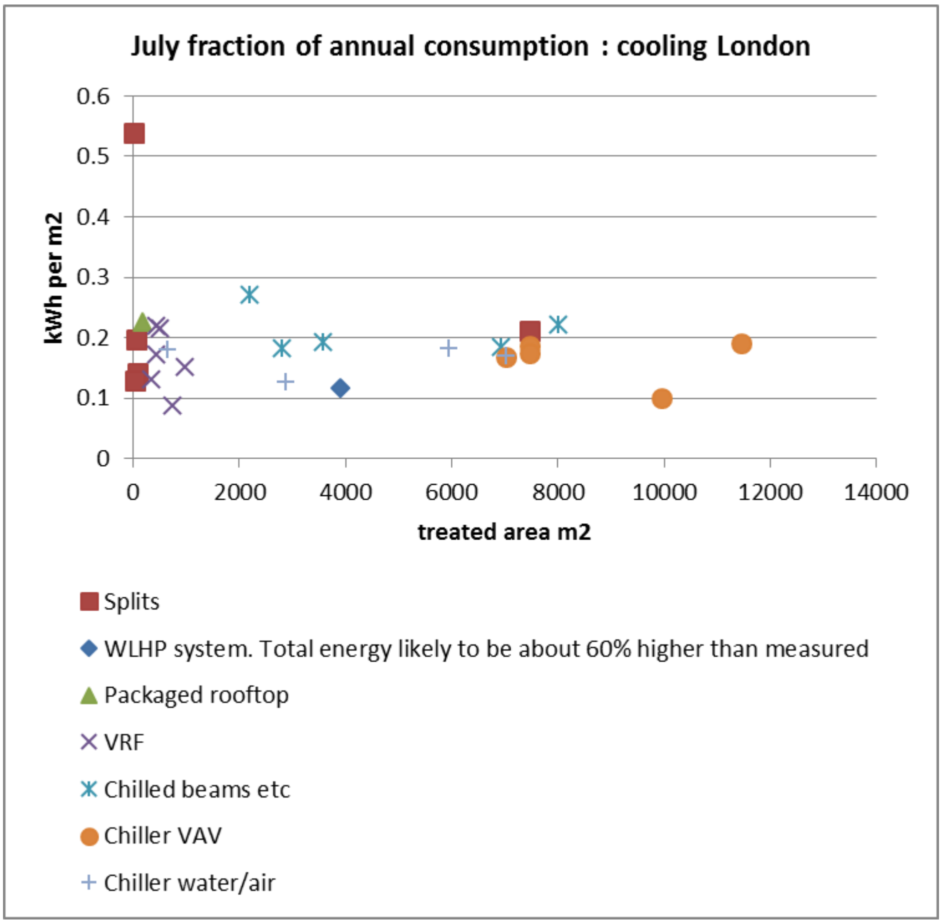


Figure D3 July fraction of annual cooling energy: London weather

4.4. Standardised peak power demand

4.4.1. The procedure for determining standardised peak power is described in annex E dealing with the calculation algorithm. The peak power is the sum of two components:

- The daily mean power associated with a high daily mean external temperature. The value of this temperature for each location was based on the relationship between air conditioning normal design hourly temperatures and corresponding daily mean temperatures. This relationship was based on CIBSE Summer Design Year weather data.

- A term that reflects the difference between half-hourly power input and the mean power input (on a weekday) of the chosen mean outdoor temperature. This second term reflects short-term variations of power requirement caused by heat gains that are uncorrelated with daily outdoor temperature (or by other time-of-day effects such as changing levels of occupancy and variations in solar heat gain). For each system, its value was determined from a frequency analysis of the differences between the observed half-hourly power consumptions and the mean daily power consumption as calculated from the combination of the energy signature and the chosen mean outdoor temperature (the half-hourly “residuals”). It was initially set as the value which was exceeded for 5% of the time. The choice of this value was somewhat arbitrary and it was subsequently changed to a 1% exceedance level for the reasons described below.

- The temperature component therefore varies with location and with the thermal characteristics of the building, while the second component differs between buildings - and possibly with other factors (and is taken to be essentially independent of location).

- For normal comfort cooling (e.g. for offices) occasional increased indoor temperatures are normally considered acceptable and systems are conventionally designed to be capable of meeting the peak cooling demand cooling when the 24 hour mean temperature is 21.6 ^{o}C (for Heathrow). For more demanding applications, such as in parts of hospitals, increased indoor temperatures may not be acceptable and the air-conditioning system is designed must be capable of meeting peak cooling demand even when the daily mean temperature is higher - for Heathrow, 28.2 ^{o}C.

4.4.2. Determination of peak power levels

4.4.2.1. As the criteria for standardisation of peak power levels were selected somewhat arbitrarily, two sensitivity tests were carried out and the standardised peaks were compared to the (absolute) peak power levels that were actually observed.

4.4.2.2. An increase of the maximum 24-hour mean outdoor temperature of 1 deg C increased the average standardised peak electrical power by 4% for London weather

4.4.2.3. When the exceedance was changed from 5% to 1%, the standardised peak power levels increased by 16% on average from 31.3 to 36.4 W/m^2 (for London weather). (The annual “equivalent full-load hours - EFLH - values decreased accordingly). Differences for individual systems ranged from zero to over 50%, showing that the nature of the distributions varies significantly between systems.

4.4.2.4. The standardised peaks were compared to the maximum values observed during the monitoring period for the 26 systems for which this was possible. For an exceedance of 5%, only 4 of the standardised values were within +/- 20% of the (generally higher) observed peaks. With an exceedance of 1%, this proportion increased to 19, with another 4 being within 30%. The remaining systems exhibited consumption patterns which combined extensive periods during which cooling consumption was relatively low and shorter periods when it was much higher. It is speculated that these differences may correspond to changes of use. The consequence of this is that the observed peak power levels have low probabilities over the entire monitoring period and are not captured by the exceedance criterion. It is evident that the shape of the frequency distribution of the half-hourly values can differ significantly between buildings and systems.

4.4.2.5. There are other reasons why standardised and observed peaks may differ:

- The weather conditions during the monitoring period may not be representative

- Peak heat gains may be not be representative of normal operation if, for example, windows are left open in warm weather. There were two systems where this appears to be a possibility: the peak powers were concentrated into one or two days of warm but not extreme weather and persisted at night (and in one case into a weekend).

- In reversible systems, the observed peak power may be for a heating demand. 7 systems had heating peaks that were comparable or slightly higher than cooling peaks, and in one system the observed peak was significantly higher than the cooling peak.

- Measurement error. In 11 systems, the observed peak power input exceeded the reported power input of the cooling generator(s), sometimes by a significant amount. At least one of these seemed likely to be a measurement error, since it was with an isolated, single very high value. (The other instances had other possible explanations, discussed later).

4.4.2.6. Since the use of an exceedance of 1% resulted in better agreement with observed peak powers, the associated peak power and EFLH values have been preferred and are shown in the following results. This does not imply that 1% is necessarily the optimum value to use. That will depend on the purpose for which the peak power is required.

4.4.2.7. The regression analyses used to define the energy signatures reported the root mean square values of the deviations of observed daily consumption from the regression. These can provide an (approximate) indication of the relative importance of day-to day variations (represented by the regression deviations) and the within-day variations (represented by the half-hourly residuals). There is a noticeable distinction between different types of system with day to day variations being dominant for most chilled ceiling and fan coil systems and within-day variations for most split and VRF systems. The two elements were of approximately equal importance for most VAV systems. This might reflect a combination of the ability of different types of system to respond quickly to changes in cooling load or to their being typically used in applications where such changes are more common (such as highly glazed spaces).

4.4.3. Variation of peak power between buildings (London weather data)

4.4.3.1. Figure D4 shows the variation of standardised peak power per square metre of treated floor area with system type and floor area. It is noticeable that the chilled ceiling systems have low peak demands. This may reflect the fact that such systems are unlikely to be used in spaces with high heat gains. Apart from this, there is no apparent systematic variation with system type of treated floor area.

4.4.3.2. Although the standardised peaks are somewhat larger in terms of W/m^2 than similar figures from the European iSERVcmb study (median peak power for cooling generator of 19 W/m^2), most of them are significantly lower than the nominal installed demand of the cooling generator(s).

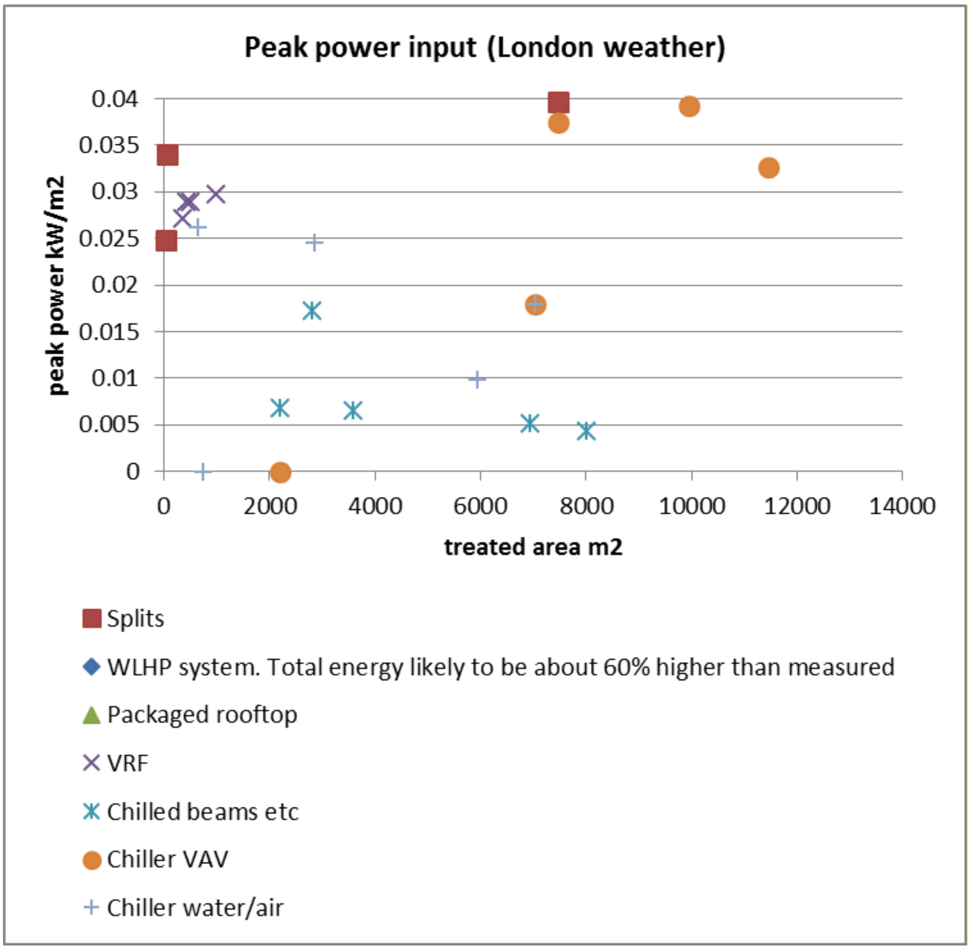


Figure D4 Peak power per unit area: London weather

4.4.3.3. Figure D5 plots standardised peak power against standardised annual consumption. Load factor (EFLH) is the ratio between the two. Although there is some scatter, there is a signiicant correlation.

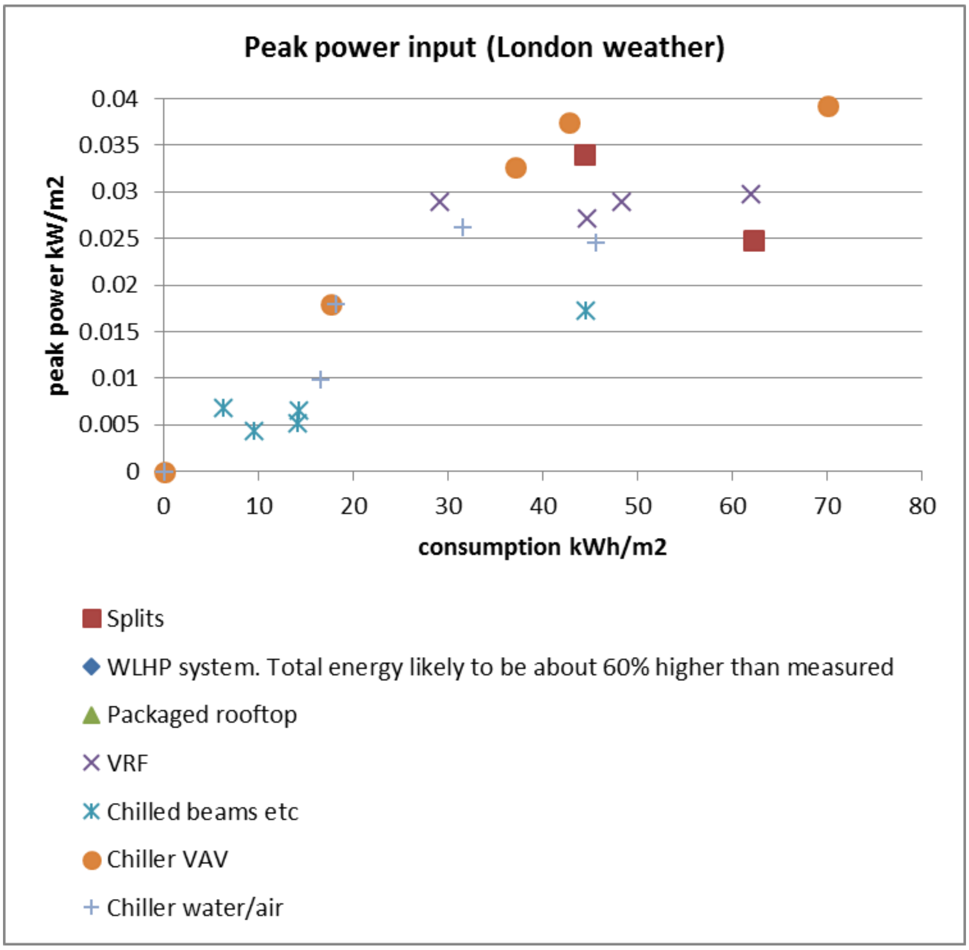


Figure D5 Peak power versus annual consumption: London weather

4.4.4. Peak power and connected load

4.4.4.1. For 14 of the systems we know the connected electrical power of the cooling generator(s) and for most of the others we can estimate it approximately from the nominal cooling capacity and an assumed efficiency (EER) value. Figure D6 compares the values for both 1% and 5% exceedance assumptions.

4.4.4.2. In general the (standardised) peak demands are significantly smaller than the connected loads. In other words, the installed cooling power seems to be higher than the observed maximum half-hourly demands.

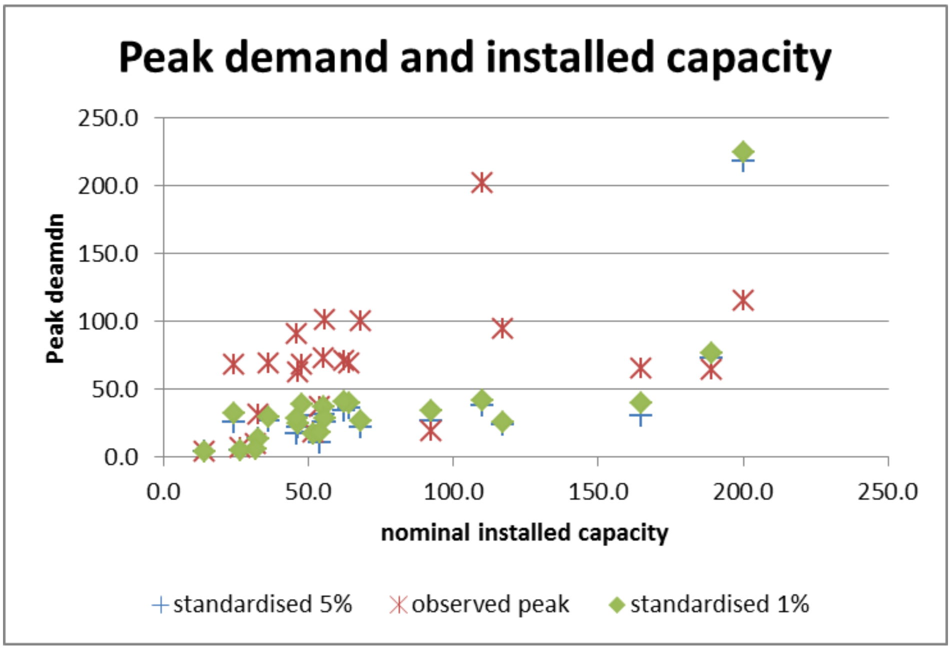


Figure D6 Peak demand and installed capacity

There are several possible explanations for this apparent oversizing, (which are not mutually exclusive.)

- Spare cooling capacity may be deliberately provided to provide resilience against changes in building use, extreme weather conditions or equipment breakdown.
- Excess cooling power may be provided in order to guard against uncertainties in load calculations. In addition to the issues noted above, these could include uncertainties relating to the properties of materials, unaccounted losses in distribution or from simplified calculation methods.
- Load calculations may be conservative – for example, by ignoring the smoothing effects of building thermal capacity.
- The capacity of the air conditioning system's distribution system (chilled water or air) limits the amount of cooling that can be delivered.

4.4.4.3. The nominal power input of the cooling generator(s) was reported for 18 systems and was imputed from the nominal cooling capacity and an assumed "typical" EER value for the remainder. These are also shown on figure D6. In 11 systems, the observed peak power input exceeded the reported power input of the cooling generator(s), sometimes by a significant amount. The possibility of measurement error for one of these has already been discussed. Smaller differences may have resulted from discrepancies between the assumed and actual EER values.

4.4.4.4. The installed power figures were not a good predictor of observed or standardised peak power. Even with a 1% exceedance level the standardised peak was, on average, only 53% of the estimated installed capacity.

4.4.4.5. Whatever the explanation for apparent oversizing, if this is typical, (and it is in line with anecdotal reports), it has consequences for the use of energy consumption models based on installed cooling capacity, including the current DECC product policy model, when applied to air conditioning systems. The total installed cooling capacity (usually estimated from historical sales figures net of estimated replacements) is likely to exceed the physical requirement for cooling (except perhaps for the most extreme assumptions) and an allowance for this is needed.

4.4.5. Variation with location

4.4.5.1. Figure D7 shows how the standardised mean peak values vary by location. The highest value, for London, is 17% higher than the lowest, for Newcastle, reflecting the effect of the different values of outdoor temperature used.

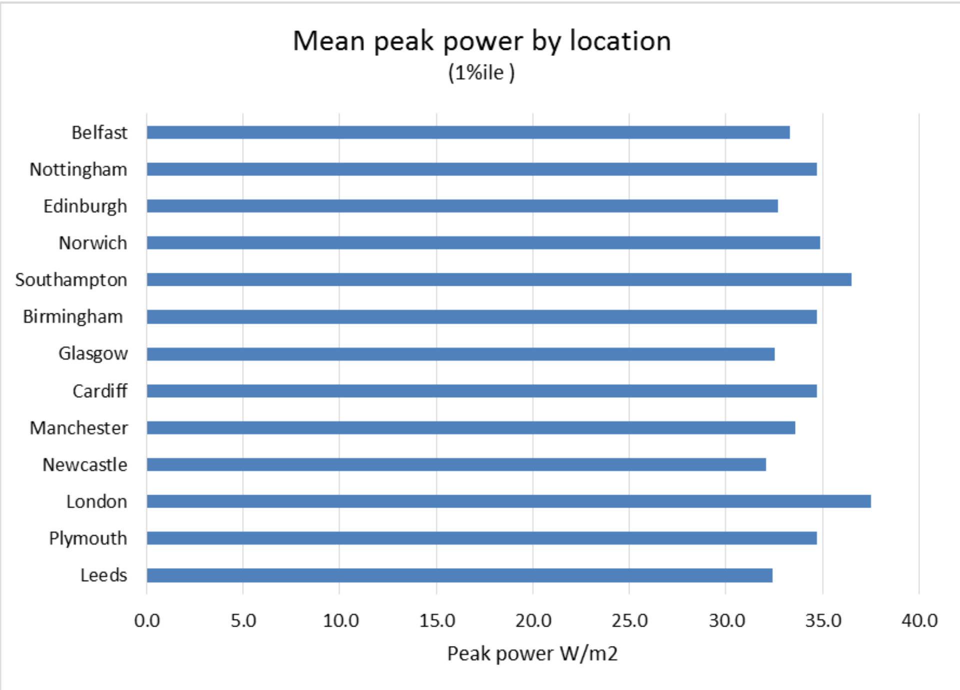


Figure D7. Mean peak power by location

4.5. Standardised “Operational Hours” (EFLH)

4.5.1. Standardised “operational hours” are obtained by dividing the standardised annual consumption by the standardised peak power demand. In this study, both the consumption and the power are electricity inputs to the cooling generator, but the same principles can be applied to generate an equivalent figure for thermal heat extraction from the treated space. Figure D5 showed that there is a broad correlation between standardised peak power and standardised annual consumption for different systems, but the ratio (EFLH) varies.

4.5.1.1. Variation of peak power between buildings (London weather data). Figure D8 shows that the annual EFLH figure is largely independent of treated area, although there is slightly more variation between systems for small areas (and for the split and VRF systems that are commonly used to cool them). The average value of 1630 hours is considerably higher than the figures reported in the literature search from simulation studies, which are typically between 200 and 600 hours and the "default" figure of 1000 used in the product policy model.

4.5.1.2. The coefficient of variation of EFLH is only about 40% of that for consumption per square metre of floor area, showing that EFLH is a significantly better predictor of annual consumption.

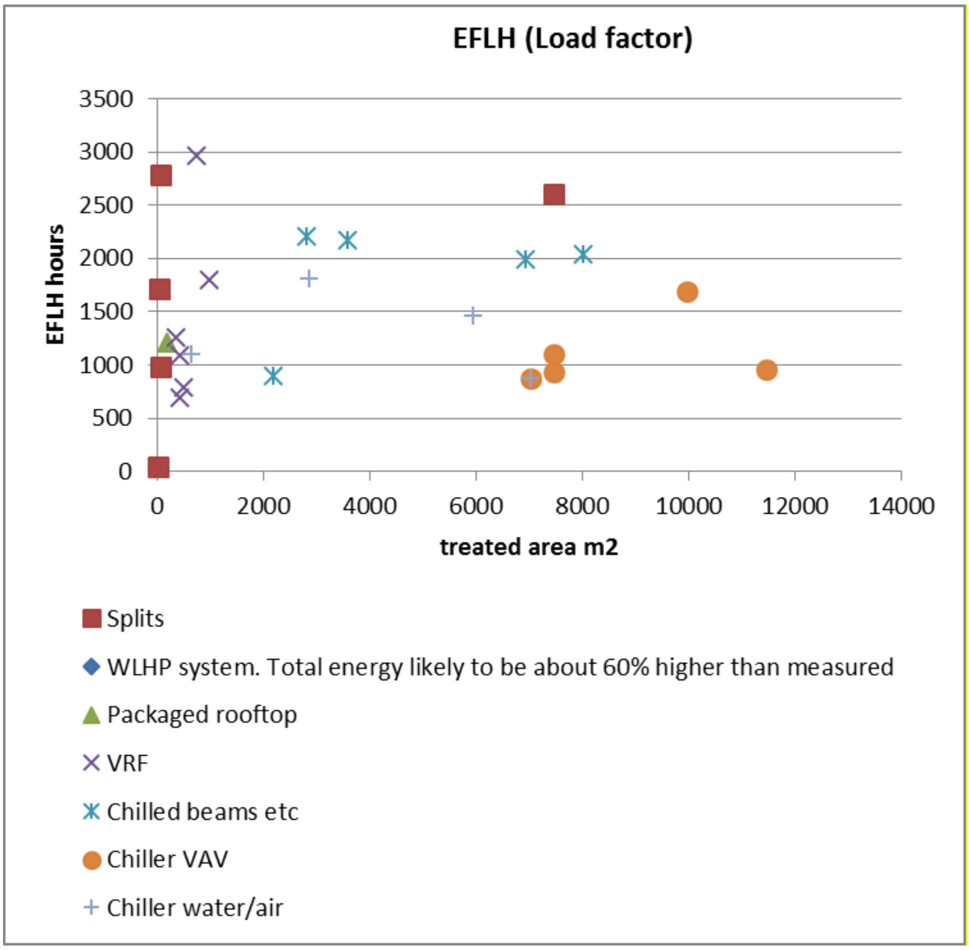


Figure D8 EFLH by system, London weather

4.5.2. Variation with location

4.5.2.1. The frequency distribution and range of daily outdoor temperatures differ with location, meaning that the EFLH value will also vary – though the nature of the change is not very intuitive. Figure D9 shows the relationship between peak power and annual consumption.

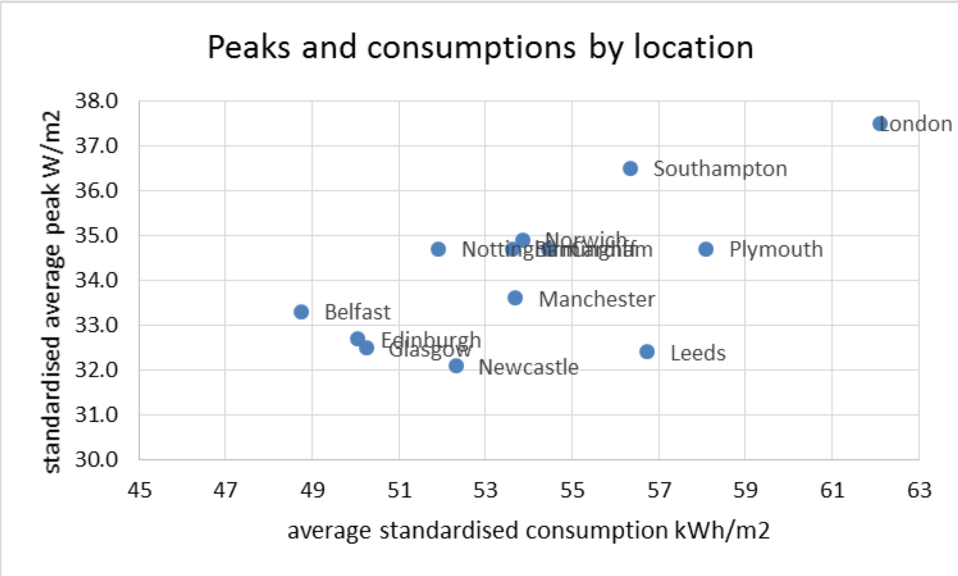


Figure D9 Mean values of standardised peak power and standardised consumption by location

4.5.2.2. Figure D10 shows the mean value of EFLH for the monitored systems for each location. The highest value (Leeds) is 20% greater than the lowest (Belfast).

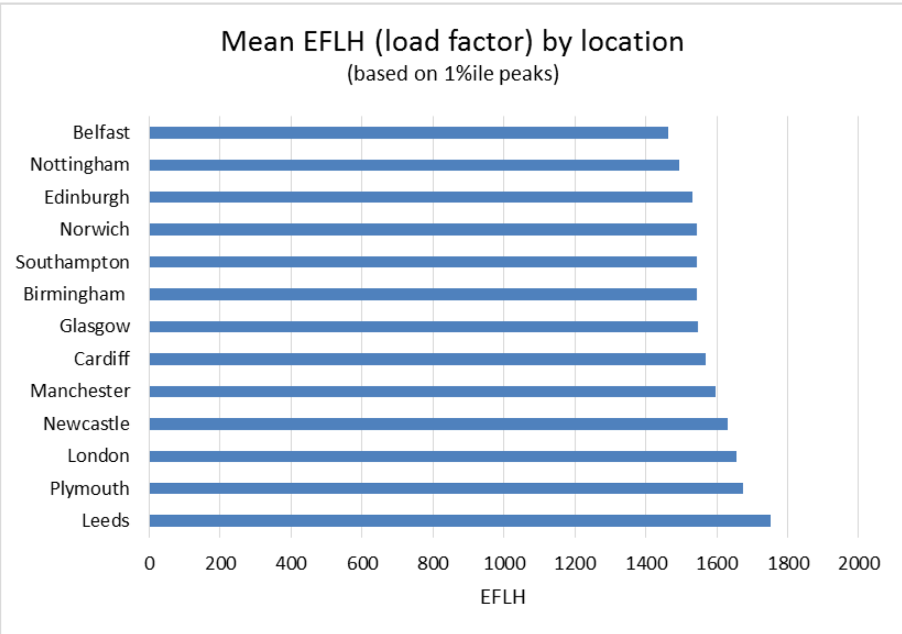


Figure D10 Mean EFLH by location

4.6. Consumption factor

4.6.1. The DECC product policy model estimates annual consumption from estimates of total installed cooling power by dividing by the assumed SEER and multiplying by the "operational hours" (aka EFLH). As already discussed, in principle it should modify the installed load figure to take account of the installed spare capacity (or modify the EFLH figure to be consistent with the uncorrected power). We can make a direct comparison between the monitored results and the published default assumptions of the model by computing the ratio between cooling power (kWc/m2) and annual electrical consumption (kWhe/m2). This metric has the unit of hours but includes the efficiency of the cooling generator.

4.6.2. Taking the default model values as: 1000 hours EFLH, and SEER of 2.3 (actually varies between 2.25 and 2.39 according to technology)[B], and making no allowance for surplus capacity results in a value of 435 hours.

4.6.3. The equivalent values for the monitored systems and London weather are shown in figure D11. These are based on the reported installed cooling capacity of each system. The mean value is 340 hours (median 215 hours) with a range from 77 to 808 hours.

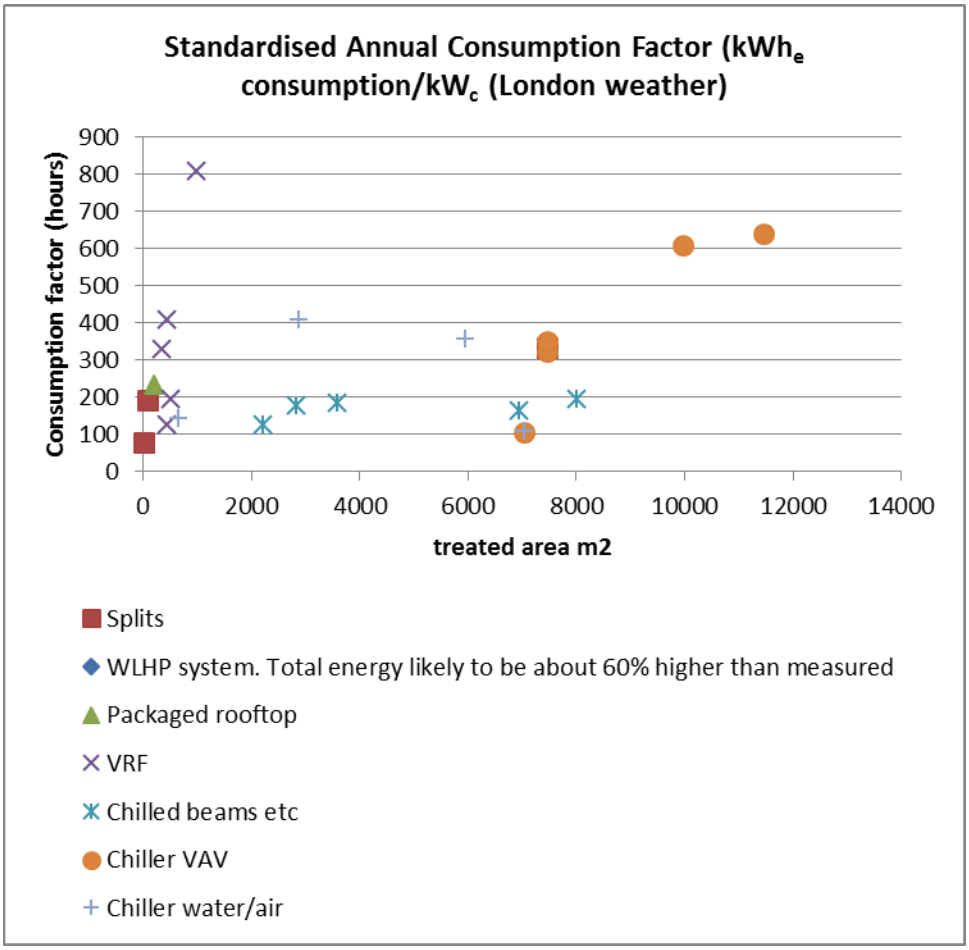


Figure D11: Standardised annual consumption factor, London weather

5. Analysis: Energy consumption by "rest of system"

5.1. Energy consumption for heating by reversible cooling generators (that is, heat pumps) was estimated in the same way as for cooling, using the energy signatures.

5.2. Data from 12 of the monitored systems included detailed energy consumptions for some of the system components additional to the cooling generator - fans, pumps, terminal units, controls - to which fans would be expected to make a substantial contribution. Fan energy consumptions based on installed power and assumed operation times were available for two systems, while five systems - and possibly another three –(mainly split systems) were used in naturally ventilated spaces which would have no fan energy use (other than that used by fans contained in the cooling generator which are included in that component's measured consumption). Unfortunately, most of the measurements did not define which components were included in the monitoring, being defined as "motor control cabinet" "HVAC board" or in similar terms. Meaningful analysis is therefore rather difficult. Figure D12 summarises the information that was obtained, for London weather

5.3. The "rest of system" figures can be compared to published benchmarks: 30 to 40 kWh/m^2 for "good practice" (0.12 to 0.16 kWh/m^2 per working day for 5 day per week operation) and "typical" values of 60 to 70 kWh/m^2 (0.16 to 0.19 kWh/m^2 per day for 7 day operation). [C]

- 7 systems have daily average consumptions of 0.11 kWh/m2 per day or more – therefore within the range of benchmarks noted above. Of these, 3 have values of 0.28 or higher – well above the "typical" benchmarks (but the figures may include consumption by components other than fans)
- Another 5 have values between 0.06 and 0.08 kWh/m^2 per day which, while below the benchmark figures, could reflect current good practice (the benchmarks were produced before there were regulatory constraints on specific fan power which should reduce fan energy consumption significantly). Published values based on simulations cover a similar range. [D]
- There does not appear to be any consistent relationship with system type.

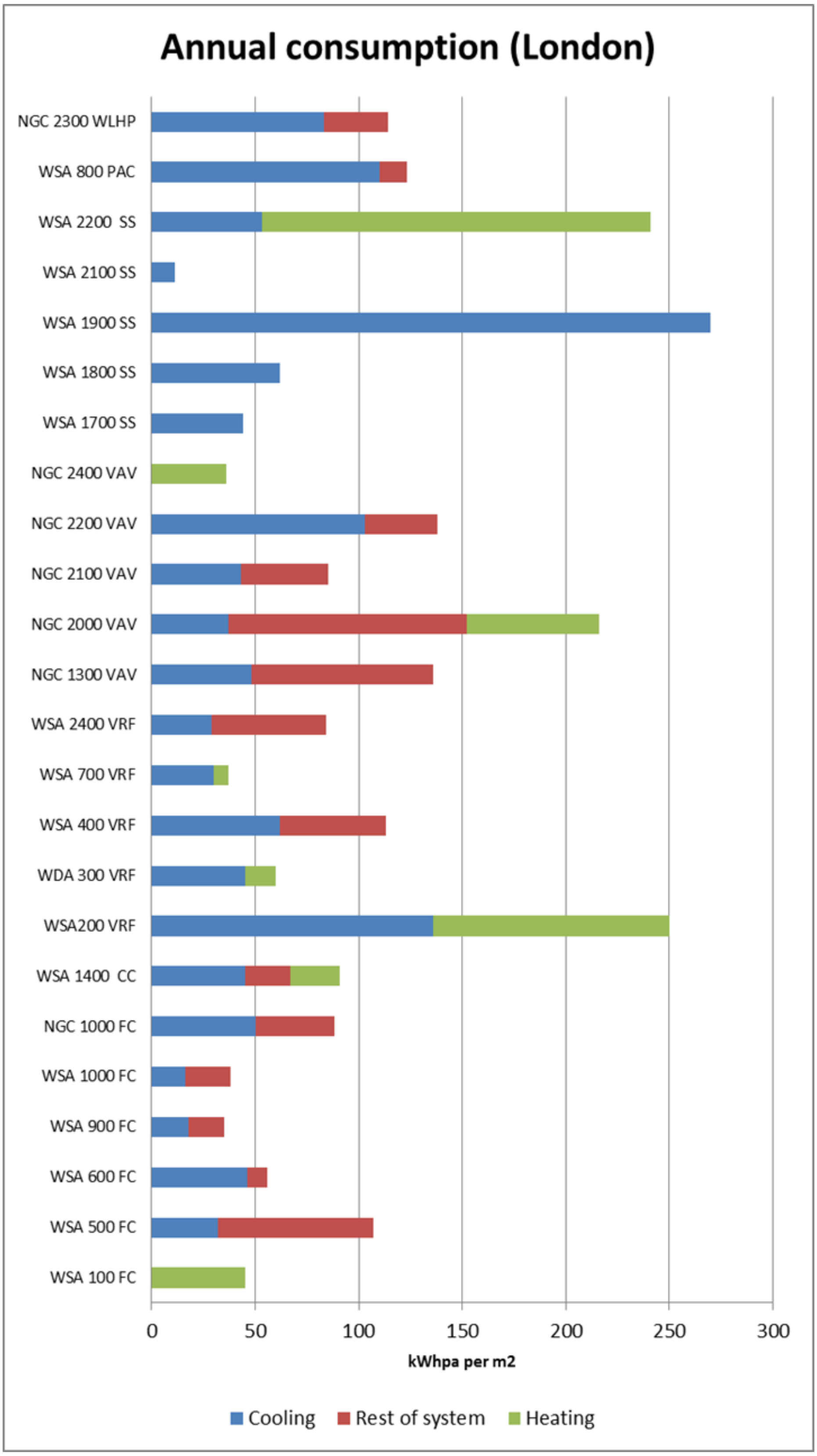


Figure D12 Monitored values of consumption by "rest of system"

Summary of standardised consumptions (London weather)			
	Cooling	**Heating**	**Rest of System**
Mean electricity consumption kWh/m^2	50.2	75.6	57.4
Median electricity consumption kWh/m^2	43.6	45.3	52.0
Range kWh/m^2	6.3 to 270	7.2 to 187.5	17.4 – 114.9
Notes	Excludes 2 systems that never provided cooling	10 systems provided reverse-cycle heating	10 systems. Scope of measurements is not always clear - assumed to include fans

Table D1 Summary of standardised consumptions (London weather)

6. Patterns of Use of Systems: reported occupancy and observed system operation times

6.1. Data on reported occupancy times was collected for 21 of the offices at the time of monitoring.

6.1.1. On weekdays, the expected core occupancy time is 9 am to 5 pm. However, this is the actual reported occupancy period for only two buildings. Reported occupancy usually either starts earlier or ends later (and sometimes both). Several buildings explicitly reported working by some staff until well into the evening. Where occupancy by cleaners was explicitly reported, it was commonly (seven buildings) before the main occupancy period or during the main occupancy period (five buildings). Occupancy by security staff was not explicitly reported. In one or two cases it was reported that the HVAC system was switched off during periods of low (but non-zero) occupancy.

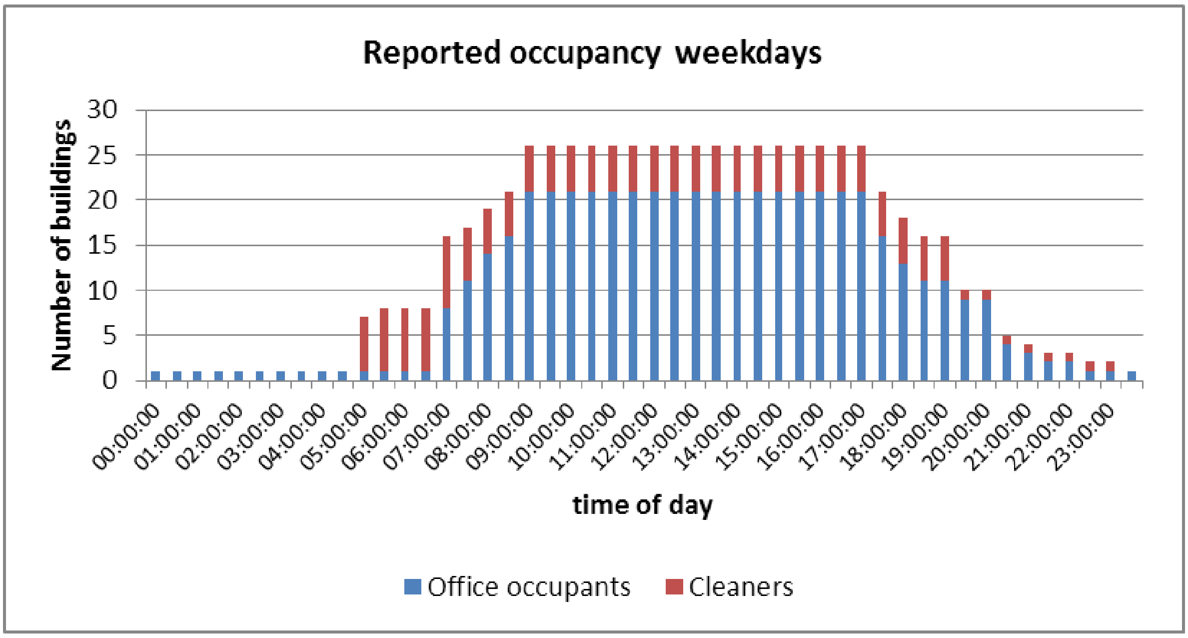


Figure D13 Reported weekday occupancy

6.1.2. Eleven buildings reported some occupancy on Saturday mornings, usually only by a proportion of staff. Of these seven buildings, four also reported occupancy on Saturday afternoons. Reported cleaning occupancy was similar to weekdays.

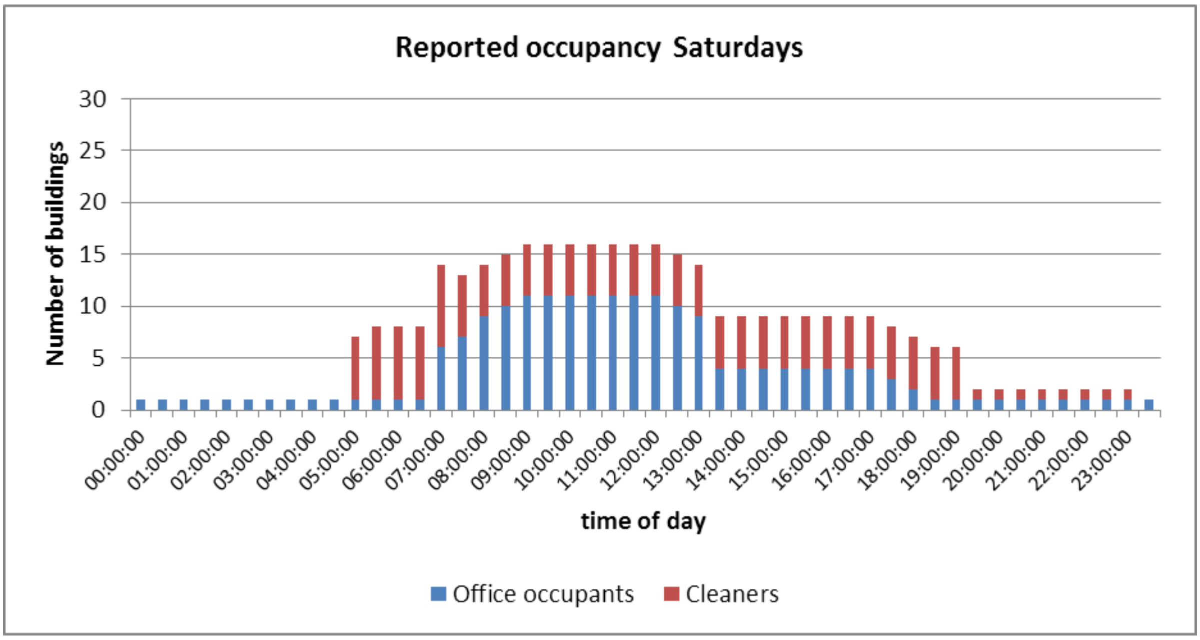


Figure D14 Reported Saturday Occupancy

6.1.3. One office operated 24 hours seven days a week, though with reduced staffing at night and weekends. In two buildings cleaners were reported to work on Sunday mornings.

6.2. Observed system operation times are more difficult to interpret.

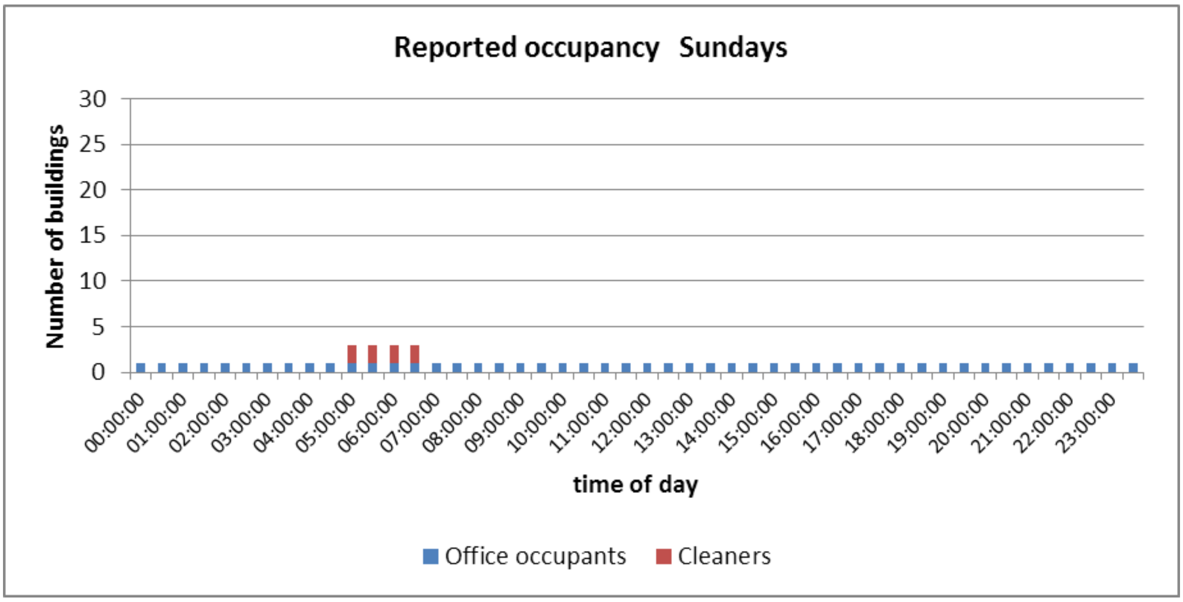
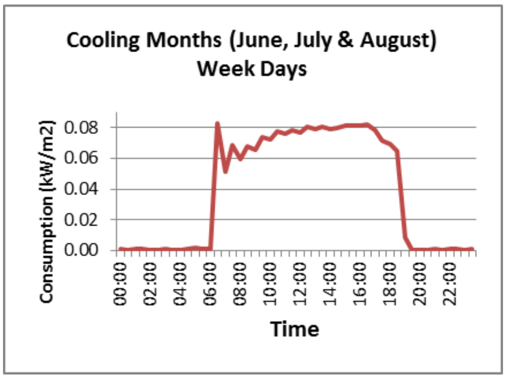


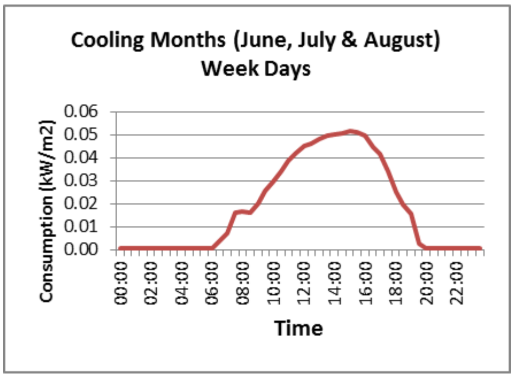
Figure D15 Reported Sunday Occupancy

6.2.1. Half-hourly profiles of observed system demand were produced for each system for each month, for both weekdays and weekend days.

6.2.2. We have good data for operation of the chiller (or other cold generator), but many of the data on fan energy do not represent direct measurements of operating periods but have been produced by extrapolating spot measurements. The analysis of operating periods therefore focused on the aggregate consumption at the same time of day for each system during June, July and August, when cooling loads – and therefore chiller operation – are largest and most frequent.

6.2.3. The charts below illustrate typical weekday profiles. As can be seen, it is sometimes difficult to distinguish between times of day system may have been "live" but there was no cooling load and times when the system was switched off.



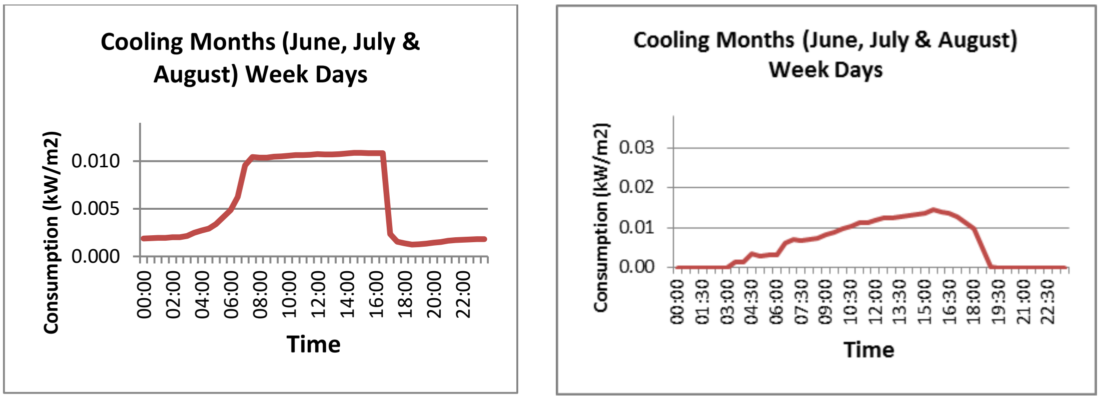


WSA 0500: well-defined switch-on time

well-defined switch-off time

NGC 0700: unclear switch-on time

unclear switch-off time



NGC 240: unclear switch-on time well-defined switch-off time

WSA 1300: unclear switch-on time well-defined switch-off time?

Figure D16 Examples of profiles

6.2.4. Notwithstanding this uncertainty, the operation times inferred from the charts rarely match the reported occupancy periods. In particular, systems are often operating well before the start of reported occupancy (even allowing for cleaning times). This could be deliberate, in order to ensure that the building is comfortable before occupants arrive, but there must be a suspicion that some systems are continuously “live” and that the early morning consumption reflects solar gains during the long hours of daylight in early summer and late spring. This interpretation is somewhat supported by inspection of month by month changes in consumption patterns. The early morning consumption is relatively small compared to levels during working periods but is, nevertheless, additional consumption.

6.2.5. Weekend patterns of cooling were inferred from the daily load profiles and the form of the daily energy signatures. They can be categorised into four classes (recalling that, where there is weekend occupation, it is generally Saturday morning occupancy by a proportion of users). In 11 buildings the weekend system operation appeared to be consistent with reported occupancy: either system operating and occupants present or no occupants and no system operation. In the other 8 buildings for which the comparison was possible, the system operation was not in line with reported occupancy.

	Number of sites	
	Weekend occupancy	No Weekend occupancy
System operating (generally for weekday hours)	4	4
System not operating	4	7

Table D2 Reported and observed occupancy

6.3. Consumption pattern for system with storage

6.3.1. One monitored system includes phase-change thermal storage in the form of ice. This is an established technology to reduce running costs by avoiding consumption at times when electricity is expensive (at the expense of energy losses in the storage cycle) but is rarely considered economical in the UK. The operational pattern suggests a cooling need between 8 am and 5 pm and illustrates the apparent operation of the storage system.

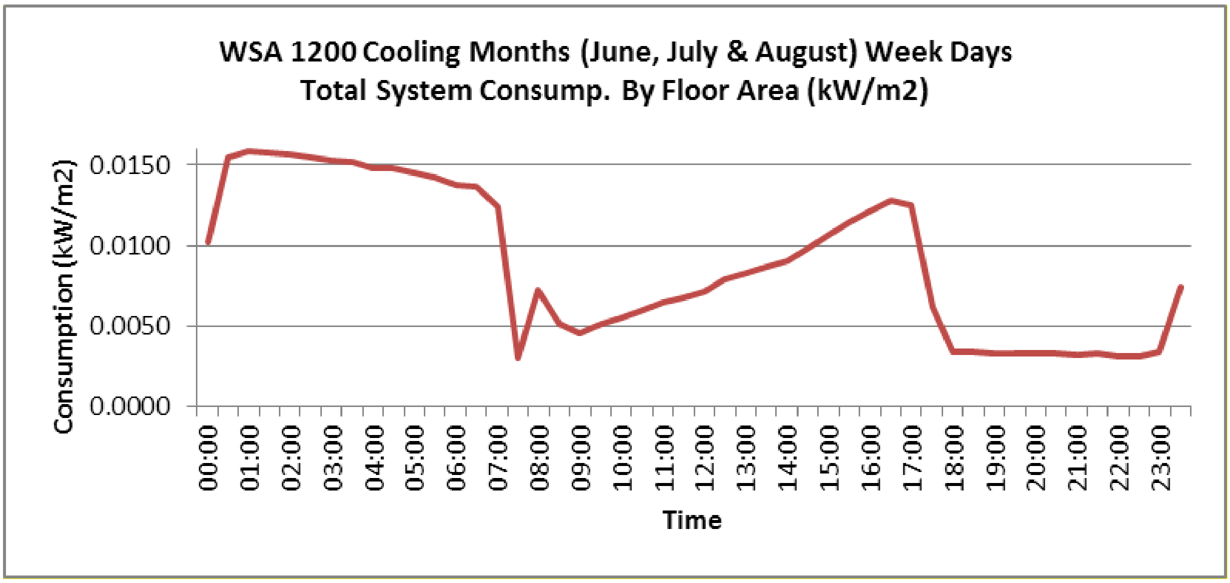


Figure D17 Weekday profile of system with ice storage

6.3.2. The storage appears to be charged during off-peak hours, as one would expect. During the day the storage alone appears to be inadequate to meet the cooling demands, as the chillers are progressively called into operation. One can speculate that peak prices will probably be in mid to late afternoon, in which case there could be financial benefits in managing the use of storage to reduce chiller use during those hours – if the system design allows this. With a suitable control system this thermal storage system would seem to have the capacity to provide short-term (several hours per day) of demand management.

Appendix: Buildings Data Quality Report

1. The objective of this appendix is to establish whether the data are of good enough quality and sufficient quantity to render it fit for purpose within the scope of this project. In particular, it is to check that the data are sufficiently complete, whether the values of each parameter within the collected data are within an allowable expected range and whether they compare reasonably to established patterns (where such patterns exist).

2. The data set comprises raw data from monitoring activities undertaken in 32 buildings. The raw consumption and temperature data are sometimes accompanied by derived consumption values, monitoring notes and – for most buildings - responses to a building survey. The building survey contains general building information, some information on the building design and layout and the reported building occupancy and operation. This section considers all of this data and comprises the following techniques:
   - Data visualisation
   - Data validation
     - Timestamp check
     - Spike check
     - Duplicate check
     - Completeness/gap check
     - Constraints check

   It would be usual to calculate the measurement accuracy of the data in addition to examining its validity; in this instance we do not have sufficient information on the monitoring equipment to do this. (However, the equipment is known to have been typical of that used for energy consumption research and was installed and operated by an experienced university department).

3. Notes accompanying the data provide some information on the calculated "maximum margins of error as a percentage of the total for any time interval” for each site, see Table D2 below. In some cases, these errors are large and result from estimated consumption for components for which only instantaneous power measurements were available. In these cases, electricity consumptions (typically for fans or pumps) were estimated assuming that the component in question was operating, when it may not have been. At times of low cooling demand, this results in high percentage errors. This can result in the calculated annual system consumptions being high, though the impact will be attenuated by the inclusion of periods when cooling components are in operation. Consumption by cooling generators (generally designated as “chillers”) was always measured at sub-hourly time steps without operating time assumptions being necessary. In a number of buildings, there are believed to be electricity-

consuming system components – mainly terminals – which were not monitored. As a result, while the measurement uncertainty is low for data needed to calculate electricity consumption for cooling, the reliability of consumption values for other components varies between buildings from non-existent to good, depending on the data collection methodology employed. The reported results of the analysis identify and reflect this.

Site	System Type	Error (+/-)
1	Packaged rooftops	1.0%
2	Chiller VAV	0.8%
3	Chiller VAV	1.0%
4	Chiller VAV	0.3%
5	Chiller VAV	0.6%
6	Chiller VAV	0.6%
7	Chiller VAV	0.5%
8	Chilled beams etc	84.4%
9	Chilled beams etc	5.2%
10	Chilled beams etc	1.0%
11	Chilled beams etc	9.5%
12	Chiller water/air	0.9%
13	Chiller water/air	0.9%
14	Chiller water /air	51.7%
15	Chiller water /air	0.6%
17	VRF	1.0%
18	VRF	1.0%
19	VRF	0.9%
20	VRF	0.7%
21	Splits	1.0%
22	Splits	1.0%
23	Chilled beams etc	51.0%
24	VRF	1.0%
25	Splits	1.0%
26	Splits	1.0%
27	Splits	1.0%
28	Chiller water/air	0.6%
29	VRF	1.0%
30	VRF	1.0%
31	VRF	1.0%
32	WLHP system	16.6%

a: Site 8 - energy use by distribution pumps estimated from instantaneous readings

b: Site 14 - energy use by fancoil units, Primary, Secondary and condenser pumps estimated from instantaneous readings

Table D3: Margins of error for measured energy consumption per site

4. Data were available from 32 sites in the original study. Monitoring periods varied by site. Table D4 below shows when and for how long monitoring took place on each site. A minimum of 13 months of data was collected on each site, with each monitoring period spanning at least one cooling season. The measurement periodicity varied between sites and in eight cases within the site. Measurements were taken at intervals of 10, 15 and 30 minutes. Final working data sets were consolidated to intervals of 30 minutes and one day to match the needs of the subsequent analysis. A combination of environmental and consumption data was measured at each site. Details on what was measured at each site are provided in Table D5. Site 19, shaded out in grey, is the only site not to have any measured external temperature data. This will severely limit the analysis that can be undertaken for this site.

Site	System Type	From	To	Duration (months)
1	Packaged rooftops	September 2000	October 2002	26
2	Chiller VAV	June 2001	November 2002	18
3	Chiller VAV	February 2001	December 2002	18
4	Chiller VAV	February 2001	December 2002	19
5	Chiller VAV	February 2001	December 2002	19
6	Chiller VAV	February 2001	December 2002	19
7	Chiller VAV	April 2001	December 2002	16
8	Chilled beams etc	March 2000	August 2001	18
9	Chilled beams etc	May 2000	September 2001	17
10	Chilled beams etc	March 2000	September 2001	19
11	Chilled beams etc	March 2000	July 2001	17
12	Chiller water/air	December 2000	April 2002	17
13	Chiller water/air	December 2000	April 2002	17
14	Chiller water /air	March 2000	April 2002	26
15	Chiller water /air	September 2000	October 2001	14
17	VRF	September 2000	January 2002	17
18	VRF	August 2001	August 2002	13
19	VRF	June 2000	October 2002	29
20	VRF	September 2000	December 2002	23
21	Splits	December 2000	October 2002	23
22	Splits	March 2001	July 2002	17
23	Chilled beams etc	May 2000	May 2001	13
24	VRF	December 2000	December 2002	25
25	Splits	March 2001	November 2002	21
26	Splits	May 2001	May 2002	13
27	Splits	May 2001	June 2002	14
28	Chiller water/air	December 2000	December 2002	25
29	VRF	September 2000	April 2002	20
30	VRF	September 2000	October 2002	26
31	VRF	March 2001	December 2002	22
32	WLHP system	March 2001	December 2002	17

Table D4: Monitoring period for each site

Site	System Type	External Temp	External RH	Internal Temp	Other Env[1]	"Chiller"	Other consum[2]
1	Packaged rooftops	X	X	X		X	
2	Chiller VAV	X		X		X	X
3	Chiller VAV	X				X	
4	Chiller VAV	X				X	X
5	Chiller VAV	X				X	X
6	Chiller VAV	X				X	X
7	Chiller VAV	X				X	X
8	Chilled beams etc	X		X	X	X	
9	Chilled beams etc	X		X	X	X	X
10	Chilled beams etc	X		X	X	X	
11	Chilled beams etc	X		X	X	X	X
12	Chiller water/air	X	X	X		X	X
13	Chiller water/air	X	X	X		X	X
14	Chiller water /air	X		X	X	X	
15	Chiller water /air	X	X	X		X	X
17	VRF	X	X	X		X	X
18	VRF	X	X	X		X	X
19	VRF			X		X	
20	VRF	X				X	X
21	Splits	X	X	X	X	X	
22	Splits	X	X	X		X	
23	Chilled beams etc	X		X	X	X	X
24	VRF	X	X	X	X	X	
25	Splits	X	X	X	X	X	
26	Splits	X	X	X		X	
27	Splits	X	X	X		X	
28	Chiller water/air	X	X	X	X	X	X
29	VRF	X	X	X		X	

[1] Other environmental measures include: internal RH, supply air temperature, heating flow temperature, heating return temp, cooling flow temperature and cooling return temperature.

[2] Other consumption measures are described as being for: fancoils, pumps, air handling units, control panels, distribution boards and mechanical ventilation.

Site	System Type	External Temp	External RH	Internal Temp	Other Env[1]	"Chiller"	Other consum[2]
30	VRF	X	X	X		X	
31	VRF	X	X	X	X	X	
32	WLHP system	X				X	X

Table D5: Data available for each site

5. At sites 8, 9 and 11 some of the 'other consumption' data (pump, other loads and pumps respectively) is presented as a 7 day average, resulting in some loss of granularity and sensitivity for those measures. Notes associated with each site provide varying quantities of information on the system being monitored and its operation. For some sites information has been provided which directly relates to the quality and accuracy of the data being measured and/or to changes to operation that will affect system performance. An example extract from Site 18's monitoring notes demonstrating this can be seen in Figure D18. Example of the monitoring notes from Site 18.
6.

DX Split Energy Consump Highly confident in the quality and accuracy of this data over the entire monitoring period

Mech Vent Energy Consump Highly confident in the quality and accuracy of this data over the entire monitoring period

Interior Temp's Gap in data from 24/12/01 to 10/01/02

Exterior Temp +RH: Gap in data from 26/12/01 to 10/01/02

Subject to local building conditions and possible interference from building fabric and equipment

Particularly on peak summer temperatures which appear high.

Figure D18. Example of the monitoring notes from Site 18.

7. Information from the monitoring notes pertaining to data quality and accuracy has been collated and reviewed. As a result of this review, where possible, measures have been allocated a level of confidence in data accuracy and/or quality. Further to that some portions of measured data have been flagged up to be excluded from analysis. In nearly all cases it is external relative humidity data that is flagged for exclusion from analysis. (It is not required for the subsequent analysis).
8. Data cleaning was conducted to identify and remove clearly erroneous values, duplicates, etc. and create a clean time stamp. This process included the removal of data that had been identified in the monitoring notes as incorrect as well as other data where clear errors could be identified. E.g. Site 28 where some external relative humidity values were duplicated under "external temperature".
9. Following the data cleaning process, the data validation process began with visual examinations of a series of plots of each measure. These revealed issues such as spikes and gaps in the data, as well as indicating trend over time. Figure D19: AC Load at Site 3 before removal of outliers shows the consumption data for the VAV chiller system at Site 3. It reveals a spike in the data in the early part of the monitoring and a large gap in the middle of the monitoring period. The gap

corresponds to information found in the monitoring notes. While the gap is relatively large it does not span a cooling season. In addition, during the full monitoring period, there are data present in other years that cover those missing months of operation, therefore it would still be possible to get an idea of the typical pattern of consumption over a year.

Data validity for each measure was calculated based on the following equation:

$$Data\ validity\ = \frac{Number\ of\ data\ values - Number\ of\ outlier\ values}{Number\ of\ data\ values}$$

Outlier data values were identified and removed from the data series as is shown in Figure D19: AC Load at Site 3 before removal of outliers and Figure 3: AC Load at Site 3 after removal of outliers

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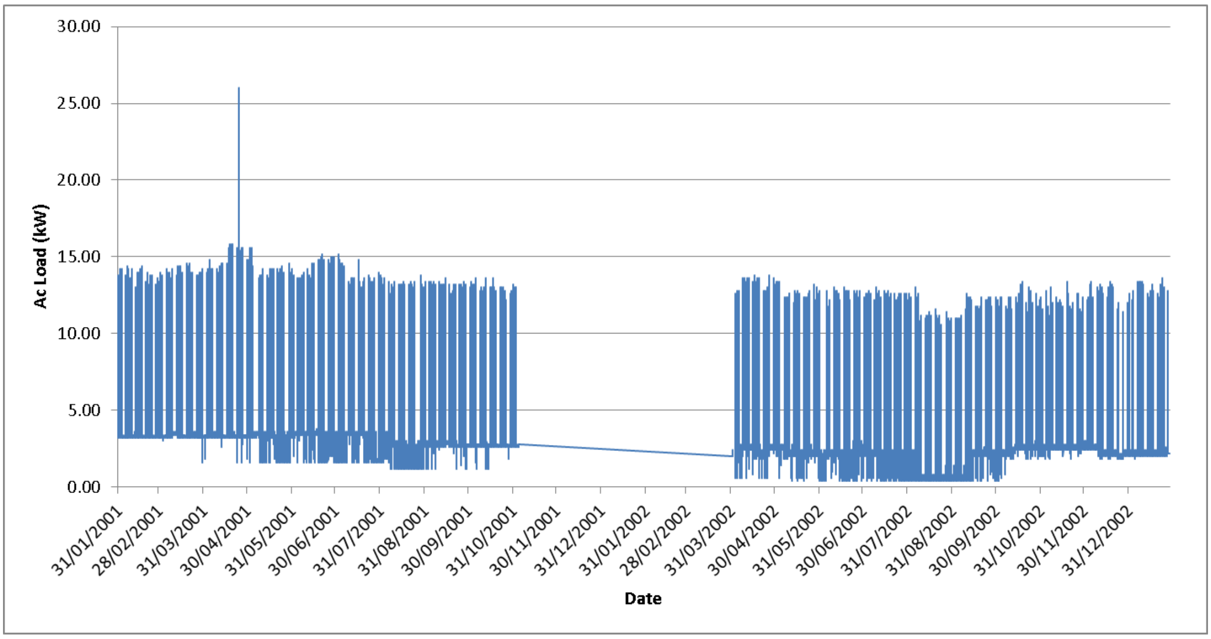

Figure D19: AC Load at Site 3 before removal of outliers

10. Data cleaning was conducted to identify and remove clearly erroneous v Potential data outliers / extreme values were identified in a number of ways; a visual inspection of the plotted data, flagging values plus or minus three standard deviations away from the mean (for those data which are approximately normal in distribution) and flagging values outside the expected ranges of operation given context, e.g. internal compared to external temperature, and a review of the monitoring notes. Few values were identified as legitimate outliers and fewer still removed from the data set, resulting in data validity ranging between 99.95% and 100.00% for each variable examined. The impact on the planned analysis of those values that were not removed from the data set but were flagged should be very small as much of the work is being undertaken on data aggregated to one day

intervals. Where analysis is planned of the half hourly interval data, the option remains to remove these flagged values if it is deemed appropriate.

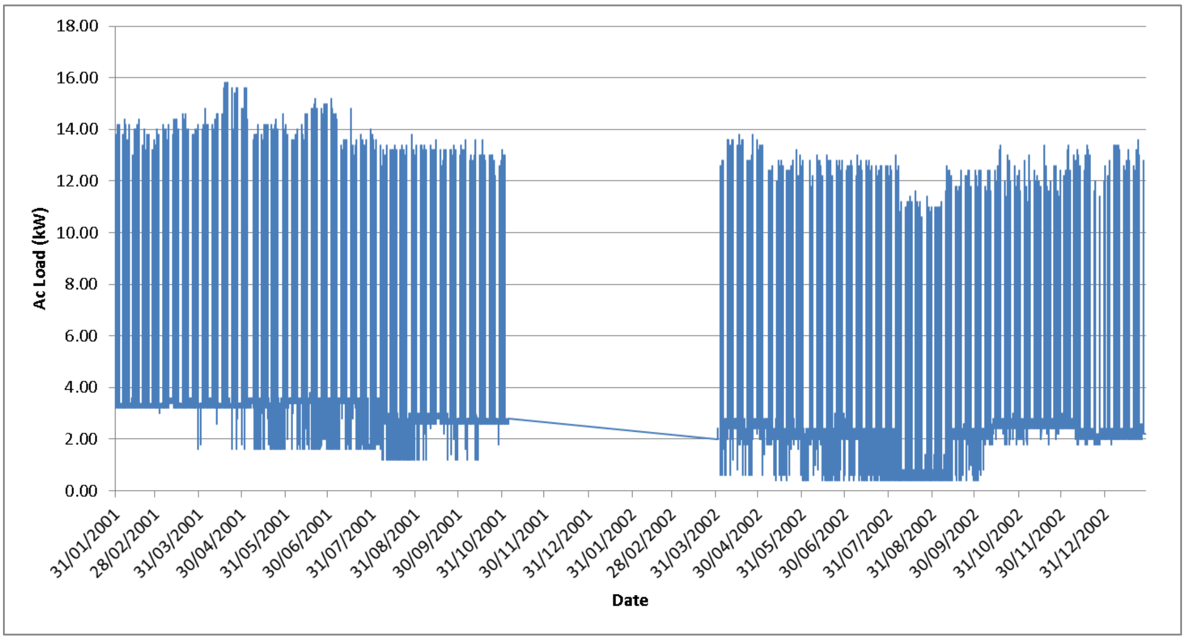

Figure 3: AC Load at Site 3 after removal of outliers

11. Data cleaning was conducted to identify and remove clearly erroneous v Outcomes from the data quality review are presented in the form of

- Number and per cent of valid data points
- Number and per cent of missing data points
- Number of valid monitoring days
- Accumulated days of missing data
- Measured data validity and descriptive statistics
- Monitoring notes of significance

A sample summary of the findings for Site 3 is presented in **Error! Reference source not found.**. Full summary tables for each site can be found in a separate spreadsheet.

All Data	**O/S Temp** (Deg °C)	**AC Load** (kW)
Number valid	24288	27792
Per cent valid	87.2%	99.8%
Number missing	3552	48
Per cent missing	12.8%	0.2%
Total	27840	27840

Cooling Period Only (Jun to Aug**)**		
Number valid	8832	8832
Per cent valid	100.0%	100.0%
Number missing	0	0
Per cent missing	0.0%	0.0%
Total	8832	8832

Number of Days		
Min number of days data	506	579
Min number of cooling days data	184	184
Max number of missing days	74.0	1.0
Max number of missing cooling days	0.0	0.0

Descriptive - all data		
Minimum	-5.00	0.40
Maximum	41.25	26.00
Average	13.92	5.72
Standard deviation	6.73	4.66

Measured data validity	100%	99.99%

Table 3 Summary data quality information for Site 3

Monitoring Notes
VAV Energy Consumption Data collected by EA therefore WSA do know if all "loads" are accounted in this data.
Interior Temp Temperature loggers appear to have been installed in stairwells NOT office areas

Exterior Temp +RH: Subject to local building conditions and possible interference from building fabric and equipment Particularly on peak summer temperatures which appear high. Relative Humidity Data should be disregarded as the recorded profile appears to be highly unlikely to be accurate (Unknown Reason)

12. Data cleaning was conducted to identify and remove clearly erroneous values. It can be seen that for Site 3 both internal and external environmental measures were made. The external relative humidity data and internal temperature have been excluded in this summary based on the monitoring notes. The monitoring notes state that it is unclear whether “AC load” includes all “loads” and the measurements may therefore understate consumption. (From inspection of the consumption patterns, the consumption appears to be simply the chiller). There are gaps in the temperature data, but none during the cooling season. There appears to be a sufficient number of days of data to conduct the planned analysis. The descriptive statistics for the data seem reasonable and, in respect of external temperature, reflect the information in the monitoring notes regarding ‘high peak summer temperatures’. The overall measured data validity was good.

13. In summary**:**

a. The data have been cleaned, validated and aggregated into files of 30 minute and daily intervals ready for the main analysis phase. Visual examinations of the data show that the mode of operation (such as operating times) of some systems changes part-way through the monitoring period. Unsurprisingly, operation on some sites differs at the weekend from that on weekdays. Although of interest, these are not data quality concerns per se, but rather points for consideration in the main analysis phase.

b. The data validation process has revealed that the collection of the air-conditioning system electricity consumption data for cooling was more reliable than that of the environmental data, or of consumption data for other system components. The cooling consumption data contained very few gaps of note and few anomalies. As a result very little of this data has been trimmed, or manipulated in any way. Certain values, which by themselves may not look out of the ordinary but, taken in association with the outdoor temperature, tend towards the unusual, have been identified as potential influencers. If it were considered appropriate, these could be filtered out in the main analysis as a means of determining the size of their impact.

c. In contrast to the consumption data, there are more sites where sizable gaps could be observed in the external temperature data. In addition, there were issues with external relative humidity data measures on some sites, as well as a few questionably high outdoor air temperature values. In a small number of instances this led to trimming of the temperature data. Where higher than expected external temperatures occur, it is often at around the same times each day, perhaps implying that these values may be dependent on the position of the monitoring equipment (which might, for example, be exposed to solar radiation at certain times of day). These values were identified as potential influencers but not removed.

d. Site 19 has no environment data measures and therefore will be of restricted value in the main analysis phase. Other than Site 19, only one site has a sizable amount of missing external temperature data (60.4% of data missing) during the cooling season. However, the analysis process is fairly robust for such gaps and the remaining data was judged to be sufficient. For all other cases there is clearly a sufficient quantity of temperature data present to carry out the intended analysis.

e. While the quantity of available data is constrained by data gaps, especially for valid outdoor temperature data, overall there are sufficient data available to undertake the analyses. However, the number of examples of each type of air-conditioning system is small and comparisons should be considered as indicative rather than definitive.

f. The extent, values, continuity, and consistency of the data were examined. After removing a few isolated outliers and examining the duration and frequency of data gaps, and accompanying monitoring notes. It was concluded that the data were acceptable for the planned analysis.

References

[A] Knight, I and Dunn, G. Measured energy consumption and carbon emissions of air-conditioning in UK office buildings, BUILDING SERV ENG RES TECHNOL May 2005 vol. 26 no. 2, 89-98.

[B] Market Transformation Programme Briefing Note, BNCAC01: Central Air Conditioning Plant, Government, Standards Evidence Base 2009: Key Inputs, Version 1.1 http://efficient-products.ghkint.eu/spm/download/document/id/871.pdf (accessed March 2016)

[C] Energy Consumption Guide 19: Energy Use in Offices, 1998, http://www.cibse.org/pdfs/ECG019.pdf

[D] EDSL, Comparative energy consumption of air conditioning systems: simulation study BRECSU 07/0 2001 (unpublished)