Study on Energy Use by Air-Conditioning: Annex A Literature Search

BRE Client Report - for the Department of Energy & Climate Change, HPR218-1001 Annex A

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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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1. Introduction

1.1. This Annex reports the results of the literature search (Work Package 1) of the "Study on Energy Use by Air-Conditioning" (DECC Tender Ref 874/09/2014). The review identified over 200 papers and other information sources of interest, which are tabulated in the Appendices. The annex reports the numbers of sources that were found that were relevant to the questions posed by the project definition, summarises the extent to which they appear to address these questions and highlights the general content.

1.2. A set of research questions was identified at the outset of the project as being relevant for increasing our understanding of energy use by air conditioning systems in the UK. A template was devised to reflect these questions and resulted in the following set of distinct questions and accompanying information requirements:

- Estimates of usage, e.g. annual full load equivalent hours, benchmark comparisons .
- Comparisons between measured and calculated consumption for a range of non-domestic premises (for either individual buildings or markets).
- Variation of air-conditioning usage with external temperature (usage meaning periods of use).
- Usage patterns (all types of non-domestic buildings).
- Technology (especially efficiency).
- The proportion of UK office space and other non-domestic buildings which is air conditioned.
- The geographical variation within the UK of air-conditioning installations and operation.
- Trends in cooling loads imposed on systems (if possible).
- Operational improvements (if possible).
- Assumptions on peak temperature.
- Duration of high temperatures.
- Impact of energy prices on consumption .
- Lifetime of air conditioning systems and components.
- Breakdown of data by at least one of:
  - Economic sector;
  - System type;
  - System size;
  - Age.

1.3. Some of the subject areas cover work that is not usually formally published in peer-reviewed journals (although often available in the wider public domain). The results of the review include both peer-reviewed published papers and "grey" literature from other sources. A small number of important references relate to unpublished work.

1.4. It is important to note that this report is concerned with identifying data sources which can potentially be used to inform the recommendations for improving the current DECC model of energy use for air conditioning. The contents have been used in other parts of this study, where relevant.

1.5. There are various ways of classifying cooling systems; for example based on how the system components are packaged, the distribution and heat rejection medium, and the basic system configuration. Some features are present in all cooling systems; for example cool generation, transfer of "coolth" into a room, removal of heat from the room and heat rejection. A simple approach is classification into three broad classes of cooling system which are:

- Moveable units. These are appliances bought over the counter or through internet suppliers and do not generally require any installation expertise.
- Room air conditioners/Packaged systems. These are series-produced self-contained units or systems comprising a unit that conditions a single room. They should generally be installed professionally.
- Central systems. These are larger systems that serve more than one room (often large numbers of rooms). They are generally bespoke systems designed for specific buildings, but are largely composed of standardised component products.

This study is concerned with the latter two classes of cooling systems. For the purpose of examining the potential for improving energy efficiency, a more detailed breakdown of each class is appropriate and descriptions of some of the more common system configurations are shown in Table A1.

Room air conditioners	
Window/Wall Units	Both sides of the refrigeration cycle are housed in a single unit which is installed through a window or wall so that the heat rejection side of the system is on the outside of the building and the cooling side is on the inside. There is a fan in each side of the unit to facilitate the transfer of heat into the refrigerant on the inside, and into the air on the outside. This category also includes fixed dual duct systems which are functionally very similar, except that the unit is housed wholly within the building and is connected to the outside via an inlet and an outlet duct.
Single Split Systems ≤12kW	The single split system has an outdoor unit which contains the condenser and compressor, and discharges heat to the outside air. This is linked via the refrigerant pipework to a single indoor unit which contains the evaporator and a fan which delivers cooling within the room and can be ducted or non-ducted.
Central plant systems	
Larger Split Systems	This category comprises both larger >12kW single splits systems and multi-split systems. Multi-split systems are similar to single split systems except that there are multiple indoor units which serve separate rooms or zones. These are individually connected to a single outdoor unit via refrigeration pipework. The system may either operate only in cooling only mode have a heat pump mode for heating.
VRF	VRF (Variable Refrigerant Flow) multi split systems are a more sophisticated version of the multi-split system. These system supply heating and cooling and can have 2 pipe refrigerant pipework, or a 3 pipe refrigerant pipework system that enables heat to be transferred from a room that requires cooling to another within the same building that requires heating. A variable speed compressor allows the system capacity to be varied to accurately match the building heating and cooling loads.
Rooftops	These are packaged units where both sides of the refrigeration cycle are housed in a single unit which is located on the outside of the building (often on top of the roof) together with an air handling unit (AHU) which supplies the conditioned air to the building via ducts.
All Air Constant Volume (CAV)	These systems provide a constant volume air supply at a single temperature. Cooling of the air is normally provided by a chilled water or direct expansion (DX) cooling coil in an AHU which distributes the cooled air to rooms via ductwork. The AHU is usually able to vary the proportion of fresh to recirculated air to meet the ventilation requirements of the building and to minimise cooling requirements. Some systems also include terminal reheat coils to allow different air supply temperatures in different rooms or zones.
All Air Variable Air volume (VAV)	As above but different cooling requirements of individual rooms or zones can be accommodated by varying the volume of air supplied to each room or zone. The AHU fan speed is varied to match the overall supply air flow rate and therefore significant fan energy savings are possible when the overall cooling requirement is low.
Water based fan coil unit (FCU)	Chilled water (and sometimes also hot water) is circulated around the building to supply terminal units in the rooms where a fan blows room air over a cooling coil. Most fan coil systems are also supplied with conditioned fresh air from a central AHU. The room air and ducted fresh air are mixed at the inlet to the FCU.
Water based induction	Similar to the above except that a minimum quantity of conditioned fresh air from an AHU is injected through nozzles to induce a flow of room air over a chilled water coil before the mixed air flow is supplied to the room.
Heat Pump Loop	This system is based on a constant temperature water loop circulated around the building with self-contained heat pumps providing either heating and cooling of individual rooms or zones by transferring heat from or to the water loop. These systems are sometimes referred to by their historical trade name “Versatemp”. Some versions are also fed with ducted conditioned fresh air from an AHU which is mixed with room air at the inlet to the unit. The water loop is kept cool by a central chiller, cooling tower or dry air coolers.
Chilled Ceiling/Passive chilled beam/other construction embedded cooling	High temperature chilled water is circulated through embedded cooling pipes, passive coils or cooled ceiling panels to provide cooling by conduction and natural convection.
Active chilled beam	As with passive chilled beams, high temperature chilled water is circulated within cooling coils but room air flow is induced through the coils by a minimum quantity of conditioned fresh air. The air is supplied from a central AHU and injected through nozzles but at a lower pressure than with induction units.

Table A1: Description of common cooling system types

2. Description of the procedure

2.1. The initial literature search comprised two elements. The first was a formal search by a professional BRE information specialist. Sources included the BSRIA Library catalogue/database, the British Library catalogue (which includes theses and conference papers, as well as articles and reports), internet databases of journal articles through publishers such as Science Direct/Elsevier/Wiley, and Google Scholar (looking for articles in institutional repositories). This was augmented by the addition of less visible – sometimes unpublished – sources of information of which the project team was aware. During the course of the work additional references came to light, or appeared in the press.

2.2. The literature search focused on UK sources and data for the past 10 years, but included studies from other countries where these addressed pertinent issues for which UK sources could not be found.

2.3. Following an initial screening to rate sources as “apparently relevant”; “possibly relevant” and “not relevant”, those deemed to be apparently or possibly relevant were mapped against the questions of interest initially defined by DECC using a template agreed with DECC. The template also identifies whether the source is the full paper (or equivalent document), an abstract or accessed via the internet. Abstracts were available for almost all relevant sources. Full papers were obtained (or already in our possession) for many of the most relevant. The information included in the completed template is presented in the Appendices to this Annex. A spreadsheet version of the template is also provided.

2.4. The search identified a substantial number of documents which relate to the specific areas of interest for this study and which are relevant to the UK. Many of them contain information from the last 10 years and many comprise studies of air conditioning energy consumption, mainly through calculation. However, in some areas only a small proportion is directly applicable to the research questions posed by the project.

2.5. The success of the literature search in relation to the topics identified as being relevant for this study is identified in Table A2.

Research Area	Number of references	Directly relevant references
Estimates of usage, e.g. annual full load equivalent hours, benchmarks.	Good	Good
Comparisons between measured and calculated consumption for a range of non-domestic premises.	Limited	Limited
Variation of air-conditioning usage with external temperature.	Moderate	Limited
Usage patterns (All types of non-domestic buildings).	Limited	Limited
Technology (especially efficiency).	Good	Good
The proportion of UK office space and other non-domestic buildings which is air conditioned.	Moderate	Limited
The geographical variation, within the UK, of air-conditioning installations and operation.	Limited	Limited
Trends in cooling loads imposed on systems (If possible).	Moderate	Moderate
Operational improvements (if possible).	Moderate	Limited
Assumptions on peak temperature.	Very limited	Very limited
Duration of high temperatures.	Limited	Limited
Impact of energy prices on consumption.	Good	Limited
Lifetime of air conditioning systems and components.	Moderate	Moderate

Table A2 Summary of coverage

2.6. The following sections of this report summarise and comment on what was found, following the structure of this template. Extracts from selected papers and reports are presented in the following sections order to provide an insight into the scope of the results. Where appropriate, more detailed results will be cited in the final project report and compared with information from other parts of this study

3. Estimates of usage, e.g. annual full load equivalent hours, benchmark comparisons

Number and Scope of References

3.1. 44 references were located that had relevance to this issue, of which 35 had materially relevant content. However, many of these provide only a limited amount of useful information. Almost all the references were based on calculations and related to offices.

3.2. The energy consumption of air conditioning systems is known to vary with system type; the efficiency of individual components within the system; the building design and use; weather; and the quality of the energy management and maintenance. The very large number of possible permutations means that statistically robust site measurements require large sample sizes and are expensive to carry out. For this reason, empirical benchmarks are rare and calculated comparisons that change one parameter at a time are more common.

3.3. Annual energy consumption can be expressed in several ways, the most common being per unit of conditioned floor area, and per kW of cooling required (or installed). The second metric is independent of floor area and is actually an annual load factor. It is conventionally expressed in units of "equivalent full load hours".

Floor area based measurements and benchmarks: mainly empirical

3.4. The key UK source for benchmarks of annual energy consumption for air conditioning is Energy Consumption Guide (ECG) 19[1] [22], the figures from which are repeated in CIBSE guide F [51]. They are believed to be mainly based on observed consumptions, but the detailed methodology behind them is not entirely clear. Since the benchmarks were produced, there have been changes to the types of system installed, the efficiency of their components, Building Regulations and, in some cases building use patterns. As a result, it is unlikely that the benchmarks are appropriate for newer installations.

3.5. ECG 19 (also known as ECON 19) dates from 1998 but is based on analyses from at least 10 years earlier.[2] It does not distinguish between locations or types of system. Since then, new types of air conditioning system have become more common and minimum performance requirements have been introduced into Building Regulations for some products and aspects of system performance. Heat gains from lighting and equipment have changed and patterns of use may have altered.

3.6. A published review of the TM46 benchmarks (derived from ECON19) compared them to the energy usage reported in DECs and concluded that for most building types (including offices) the overall energy consumption benchmarks are still valid. However, this is because higher electricity demand is offset by reduced heating energy consumption.[3]

3.7. An analysis of Display Energy Certificates for public buildings, based on measured annual energy consumption, provided indirect estimates for air conditioning in offices by comparing the median values of three groups of offices: naturally ventilated with no cooling; mechanically ventilated with no cooling; cooled (and presumably mostly mechanically ventilated). The inferred consumptions were consistent with the benchmarks, bearing in mind that the three samples probably differ in other characteristics.

3.8. Table A3 shows the ECG 19 energy benchmarks for cooling three office building service levels[4].

[1] Reference numbers refer to the listing in Appendix A

[2] These benchmarks are acknowledged to be based on limited measured data combined with "technical" benchmarks built up based on expected energy use for specific end uses.

[3] This paper makes recommendations for updating the current benchmarks based on both statistical and technical data sources.

[4] These categorisations were devised for EGC 19 and have become commonly adopted for benchmarking purposes.

Office Type	**Annual energy consumption kWh/m^2 pa**	
	Cooling	**Fans, pumps and controls**
	Typical	
Type 2 Naturally ventilated open-plan	4	8
Type 3 Air–conditioned standard	31	60
Type 4 Air-conditioned prestige	36	67
	Good Practice	
Type 2 Naturally ventilated open-plan	1	2
Type 3 Air–conditioned standard	14	30
Type 4 Air-conditioned prestige	21	41

Table A3: Air conditioning energy benchmarks for offices ECON 19 2002 [22]

3.9. Reported direct UK measurements are limited to those reported by Knight, Dunn et al. [63] This study measured the annual air conditioning consumption of 32 office buildings with different types of air conditioning system. The published papers report annual figures for different types of system consumption levels but do not explore the reasons for the different consumptions. Table A4 summarises the published results. These figures do not distinguish between measurements that include or exclude fan energy or heating provision, or between constant-volume and variable-volume all-air systems.

System type and sample size	Annual energy consumption kWh/m^2 pa		
	Mean	**Minimum**	**Maximum**
	Cooling-only systems		
All-air (7)	81.9	36.0	164.4
Chilled ceilings and beams (4)	17.5	6.8	23.3
Fan coil systems (5)	91.1	38.1	151.6
Direct Expansion (DX) split system (6)	46.3	23.0	69.4
Unitary system (1)	98.2	-	-
	Reversible systems providing heating and cooling		
Chilled ceilings and beams (1)	70.5	-	-
Fan coil systems (1)	104.5	-	-
DX split system (3)	173.0	128.3	230.3
Variable Refrigerant Flow (VRF) Heat Recovery (HR) systems (4)	121.4	92.6	159.0

Table A4: Measured energy consumptions for 32 offices [63]

Floor area based measurements and benchmarks: simulations

3.10. There are several studies that compare annual calculated air conditioning energy consumption for office buildings using simulation tools that represent the air conditioning system in some detail. Notable examples are an unpublished study carried out for Building Research Energy Conservation Support Unit (BRECSU) in 2002 [66]; a smaller, more recent study carried out at De Montfort University (DMU) [112]; and a European study that considered three different climates, including the UK [3]. Table A5 summarises these results.

	London office simulations				
	Annual consumptions kWh/m^2 pa				
System	**Cooling**	**Fans**	**Pumps**	**Terminals**	**Total**
Large packaged units	8.0	0.4	0.0	8.4	16.8
Multi-splits	8.0	0.4	0.0	8.4	16.8
Splits	8.0	0.4	0.0	8.4	16.8
Small packaged units	8.0	0.4	0.0	8.4	16.8
VRF	3.9	7.9	0.0	11.7	23.5
WLHP	7.5	2.6	0.1	10.1	20.3
Single duct units	9.5	0.4	0.0	9.9	19.8
Water cooled chiller, water distribution	7.8	8.1	2.3	18.2	36.4
Air cooled chiller, water distribution	10.0	7.9	1.4	19.2	38.5
Outside water and water distribution	6.2	7.9	4.9	19.0	38.0
Two loops and chiller	4.1	7.9	4.9	16.9	33.8
Rooftops	7.8	22.3	0.0	30.1	60.2
Water cooled chiller, air distribution	7.5	22.6	1.7	31.8	63.6
Outside water and air distribution	5.9	22.3	4.4	32.6	65.2
Air cooled chiller, air distribution	9.7	22.3	0.8	32.8	65.6
Outside water, air distribution and humidity control	9.7	24.8	1.7	36.3	72.5
Water cooled chiller, air distribution and humidity control	7.7	24.5	4.4	36.6	73.2
Air cooled chiller, air distribution and humidity control	12.6	24.5	0.8	37.9	75.8

Table A5: Calculated annual consumptions from Ref [3]

3.11. The BRECSU study covered several building designs and UK locations and a range of system types. For some combinations, the impacts of oversizing and extended use were investigated. It is clear that consumption can easily be twice that calculated assuming perfect design and operation, which is in line with the (rather limited) empirical results reported above. The simulation work is now nearly 15 years old and does not include all current types of system, nor buildings constructed to current building regulations. Selected results are shown in Tables 6, 7 and 8 - a more extensive review will be contained within the final report and the tables will be made available as spreadsheets.

	kWh/m² Southeast location					
System	Building 1		Building 2		Building 3	
	cooling	fans + pumps	cooling	fans + pumps	cooling	fans + pumps
ECON 19 type 3 Good Practice	14	30	14	30	14	30
VAV[5] + reheat	19	17	16.5	18	19	16.5
Fan-coil	16	18	13.5	20.5	14.5	16.5
Induction	22.5	25.5	18.5	32.5	17	22.5
Constant volume	39.5	35	Not simulated	Not simulated	Not simulated	Not simulated
Dual duct	44.5	41	56	49	55.5	54
Chilled ceiling + floor supply	11	13	5	13.5	9.5	12
Passive chilled beams + floor supply	16.5	14	8	14	14	12.5
Active chilled beams	12	15.5	7.5	17	11	13.5

Table A6: Selected calculated consumption results from [112]

[5] Variable Air Volume

	Cooling EFLH (Southeast location)		
System	**Building 1**	**Building 2**	**Building 3**
ECON 19 type 3 Good Practice	191	154	168
VAV + reheat	259	182	228
Fan-coil	218	149	174
Induction	307	204	204
Constant volume	539	Not simulated	Not simulated
Dual duct	607	616	666
Chilled ceiling + floor supply	150	55	114
Chilled beams + floor supply	225	88	168
Active chilled beams	164	83	132

Table A7: Selected calculated equivalent full load hour figures from [112]

Calculated impact of imperfect design and operation (expressed as % change of carbon emissions compared to base level for the same system type)			
System type	Fan-coil	VAV with reheat	Constant volume
Sized well *Normal use* *Good care*	56.8 $kgCO_2eq/m^2$	60.1 $kgCO_2eq/m^2$	89.1 $kgCO_2eq/m^2$
Sized well Normal use Good care	100%	100%	100%
Sized well Normal use Poor care	121%	121%	109%
Sized well Extended use Good care	160%	151%	163%
Sized well Extended use Poor care	192%	185%	174%
Over-sized Normal use Good care	112%	105%	156%
Over-sized Normal use Poor care	140%	138%	158%
Over-sized Extended use Good care	174%	160%	241%
Over-sized Extended use Poor care	223%	213%	254%

Table A8: Impact of imperfect design and operation from [112]

3.12. The figures in Table A5 may be compared to similar ones in Table A4 from the European study [3] which use a different simulation tool, a different design of office building (and probably different assumptions about component performance). This study provided a more detailed breakdown of the energy use by system components.

3.13. The UK's report to the European Commission on cost-optimal building regulations included energy consumptions for example buildings from different sectors (and from new and existing versions of these buildings) calculated using the Simplified Building Energy Model (SBEM) [59]. Table A9 summarises the results of most relevance to the present project and Figure A1 shows this information graphically. Note that "auxiliary energy" is not simply fans and pumps in air conditioning systems but also includes ventilation fans, heating pumps etc. The report does not define the type of air conditioning system but it is believed to be a fan coil system.

	Calculated annual consumption (kWh/m² pa)							
Building type	**New Buildings**				**Existing**			
	England, Wales, & N. Ireland		Scotland		England, Wales, & N. Ireland		Scotland	
	Cooling	Auxiliary	Cooling	Auxiliary	Cooling	Auxiliary	Cooling	Auxiliary
AC Office	9	14						
Hospital	15	15	15	15	36	26	29	19
Hotel	7	39	4	29	17	73	13	63
Distribution centre	0	1	1	3				
Retail warehouse	13	21	18	29	40	47	39	47

Table A9: Calculated annual consumptions (SBEM) from Ref [59]

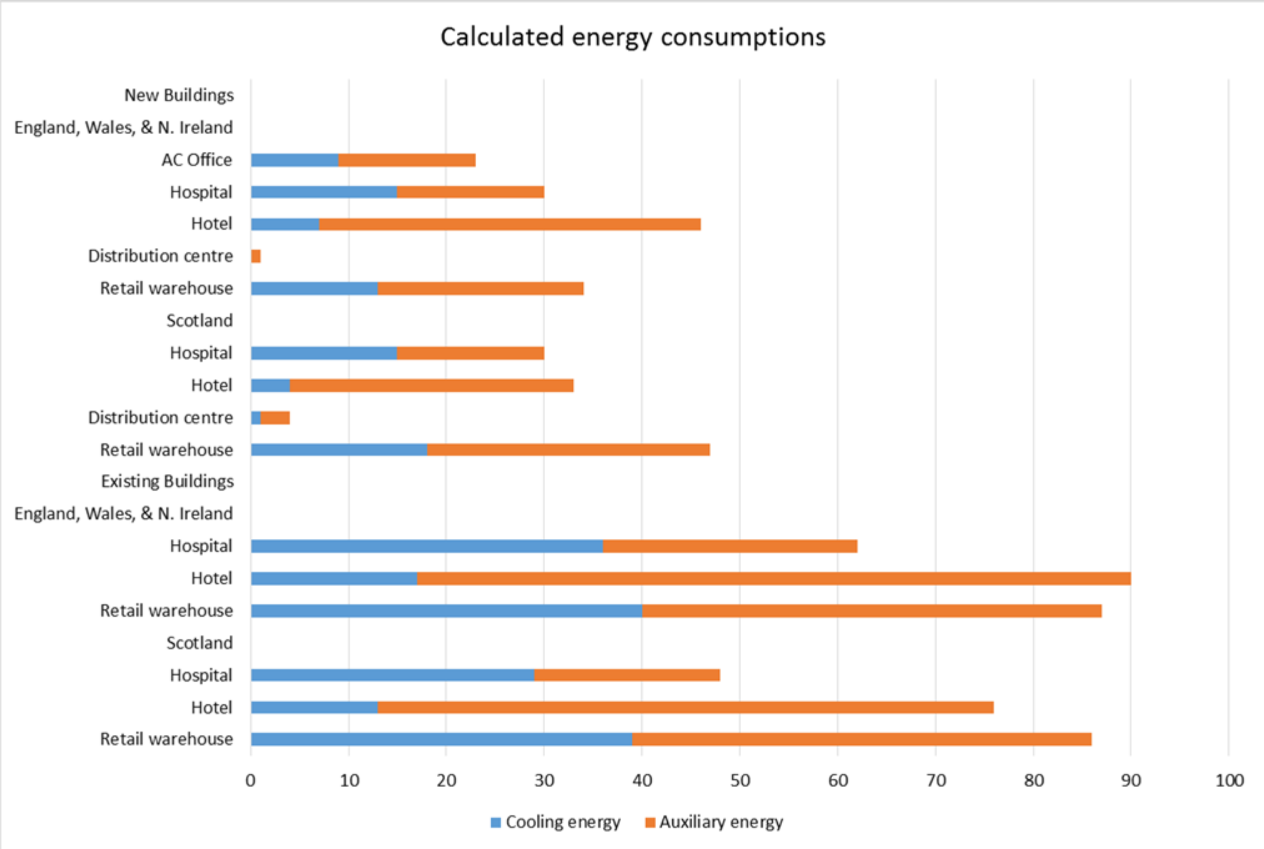

Figure A1: Calculated annual consumptions (SBEM) from Ref [59]

3.14. Each of the simulation studies compared consumptions for the same building using different systems. None of them formally reported daily or hourly consumptions or outdoor temperatures, though these must have been calculated. The BRECSU study included a range of assumptions about building use, and the DMU study considered the same office building in both open-office and cellular office layout. Only the BRECSU study reported annual load factors - equivalent full load hours (EFLH).

3.15. Preparatory Studies carried out in support of the Energy-related Products Directive [4, 84] used EFLH figures (for demand) calculated by the University of Athens – a subsequent BRE study applied these to a simplified HVAC system model. [85, 86]

4. Comparisons between measured and calculated consumption for a range of non-domestic premises. (For either individual buildings or markets)

4.1. Only 7 references were located that directly compared measured and calculated energy consumptions for air conditioning, and only one of these used detailed simulations [101]. None of these were in the UK.

4.2. The detailed comparison applied to a Swedish building and the remainder to work by a group at the University of Liege [8, 9, 10, 29, and 30] who have attempted to calibrate building and system models against measured consumptions in order to be able to better quantify the potential savings from revised operation or system modifications with limited success.[6]

[6] This is a difficult task to carry out reliably since there are usually several sets of conditions that can lead to the same observed consumption patterns.

5. Variation of air-conditioning usage with external temperature. (Usage meaning periods of use)

5.1. 21 references were located that had a bearing on this issue, but only 2 had materially relevant content. This mostly related to the variation (or expected variation) of air conditioning consumption with climate (or climate change) or urban heat island effects without providing details of how meteorological changes had been translated to variations in cooling energy. 5 of the references related to the UK (sometimes as one of several countries). Other references that identified specific countries related to Austria, Netherlands, Belgium, Spain, Slovenia, USA and Japan.

5.2. The concept of energy signatures relating consumption to temperature (but not explicitly to occupation hours) is well-known in connection with heating [76, 92] but much less so for air conditioning. A few examples relating to cooling demand (ignoring system effects) were located [56, 60, 79, 107,197] but very few [56, 117] were based on actual energy consumption. It appears that energy signatures for cooling have rarely been considered and when they have, the impact of the type of air conditioning system on the temperature dependency of consumption has almost always been ignored.

6. Usage patterns. (All types of non-domestic buildings)

6.1. 7 references were located that had a bearing on usage patterns, and only 3 had materially relevant content. The most comprehensive data set is the standard (assumed) patterns of use that underpin Energy Performance of Buildings Directive (EPBD) related energy calculations in the UK. [58]. These are based on rather variable amounts of evidence for different activities. It is known from studies of consumption and system inspections that actual patterns of use can vary considerably between buildings of apparently similar intended use [107].

6.2. A limited amount of information on retail premises is provided by small-scale surveys carried out by University College London (UCL) [36, 37]. These papers report the results of informal surveys (mostly from the street) of 600 shops in London, Leicester, Stamford and Chesterfield. Overall, 50% of the shops had air conditioning, with more located in city centres, large premises and chain stores; for example, in the London sample 73% of the shops had air conditioning. There is little further information beyond observations on summer door opening. For the air conditioned shops (and excluding shops in malls) 71% had open doors; 3% had closed doors; 21% had air curtains but they were not in use; and the remainder (4%) had air curtains in use. The paper does not report the outdoor temperatures. It notes that the air curtains would only be useful in summer if the outdoor temperature was above the indoor temperature and calculates that the likely air conditioning energy savings (allowing for the energy used by the air curtains) in a UK summer would be minimal – between £3 pa and £15 pa.

7. Technology (especially efficiency)

7.1. This category had the most numerous results with 70 references most of which had materially relevant content. The reference are predominantly of two types:

- analyses (sometime case studies) of unusual cooling technologies such as desiccant systems, solar-assisted cooling, thermal storage, evaporative cooling, ground pre-coolers, or ground source systems; or
- assessments of how mainstream products fall short of readily achievable performance levels that are cost-effective from a life-time perspective.

(The first category also includes a number of references to studies or proposals for advanced controls.)

7.2. The most important example of the second type is the study carried out in support of the Energy-related Product Directive [150] which quantifies the potential savings and costs for different levels of performance (and proven technology) for the products considered. The recommended minimum seasonal energy efficiency ratio is based on an analysis of the best currently available products. This performance level can be achieved in a number of ways, typically including variable-speed twin-rotor compressors and/or twin refrigerant circuits; flooded shell and tube or falling film evaporators; variable –speed Electronically Commutated (EC) fan motors and sometimes micro-channel condensers.

8. The proportion of UK office space and other non-domestic buildings which is air conditioned.

8.1. 20 references were located that related to market penetration by air conditioning, but only 4 related directly to the UK market for large systems. Three of these related to work carried out in support of the Energy-related Product (ErP) Directive [84, 86, 150] or are derived from this work. While country-specific figures were estimated, these were not reported in the literature . The remaining reference reports data for 1994 [212].

8.2. Most of the remaining references either address the drivers for market penetration or relate to smaller, room air conditioners.

8.3. The most comprehensive data [212] relates to 1994 and is summarised in Table A10 for England and Wales (E&W). Estimates for the ErP Directive [84, 150] based on sales and replacement figures suggest that the installed cooling capacity in the UK in 2009 was about 250% of that in 1994. However, the mean operational life for the best-fit model was over 30 years, which is significantly higher than the conventional assumptions, so the overall growth may be lower than this. Commercial floor space increased by about 20% over the same period. The bracketed figures in Table A11 show estimated market penetration for 2009 for these figures assuming that the percentage growth in both floor area and air conditioning stock figures had been the same over all regions and all sectors. Comparison of air conditioning sales from analysis for the ErP Directive [84, 150] and changes in total floor areas from VOA data suggest that the country-wide proportion of floor which is air conditioned is currently about 65% in the office sector and about 30% in the retail sector. This is, however, a very crude estimate and is not directly taken from the literature.

Region (E&W)	Percentage of floor area with full or partial air conditioning in 1994			
	Office	Retail	Factories	Warehouse
East Anglia	22% (46%)	15% (31%)	7%	1% (2%)
East Midlands	14% (29%)	11% (23%)	6%	4% (8%)
Northern	11% (23%)	14% (29%)	7%	1% (2%)
North West	19% (39%)	16% (33%)	7%	2% (4%)
South East	40% (83%)	19% (39%)	16%	4% (8%)
South West	24% (50%)	15% (31%)	10%	3% (6%)
Wales	15% (31%)	11% (23%)	6%	1% (2%)
West Midlands	22% (46%)	14% (29%)	5%	3% (6%)
Yorkshire and Humberside	15% (31%)	13% (27%)	6%	1% (2%)

Table A10: Estimated percentage of Floor Area with Air Conditioning in 1994 from [212] (Rough estimates for 2009 in brackets)

Later information is held by the Valuation Office Agency and total floor area figures for 2012 (but not the corresponding values for buildings with air-conditioning) were provided to DECC. Data on the proportion of buildings that are air conditioned is recorded and could be obtained in the future to provide an updated understanding of the proportion of buildings that are air conditioned.

8.4. The 1994 data only provided information for factories, offices, shops and warehouses, which account for the majority of the non-domestic stock, but the 2012 data also includes information on other building types, shown in Table A11. However, floor area data[7] is only comprehensive for the main building types.

[7] The floor area data refers to rateable floor area which may excludes common circulation areas and plant rooms. The measurement conventions for rateable floor also vary depending on the building type and whether the hereditament comprises a whole or part building.

Property Type	Number of Premises	Number of Premises with Floor Area data	% with Floor Area Data
Factories	11,020	10,880	99%
Offices	391,780	390,130	100%
Shops	524,840	524,530	100%
Warehouses	470,860	470,860	100%
Other properties	467,670	223,300	48%
All Property Types	**1,866,170**	**1,619,700**	**87%**

Table A11: Summary of Valuation Office Agency Data on Number of Premises and Floor Area broken down by Main Property Type 2012

8.5. Table A12 and Table A13 compare the number of premises and total floor area, respectively, for the main VOA property types.

Number of Premises	1994	2012	% change
Factories	305,989	11,020	-96%
Offices	277,394	391,780	41%
Shops	588,604	524,840	-11%
Warehouses	186,815	470,860	152%
Main Building Types	**1,358,802**	**1,398,500**	**3%**

Table A12: Comparison of Number of Premises England and Wales in 1994 and 2012 broken down by Main Property Type

Floor Area (1,000m^2)	1994	2012	% change
Factories	213,548	41,621	-81%
Offices	70,737	102,211	44%
Shops	94,217	92,345	-2%
Warehouses	119,373	304,180	155%
Main Building Types	**497,875**	**540,357**	**9%**

Table A13: Comparison of the Total Floor Area of Premises in England and Wales in 1994 and 2012 broken down by Main Property Type

8.6. The overall change in building numbers and floor area for the main building types between 1994 and 2012 is relatively modest at 3% and 9% respectively. However, the changes within each of the main building types are much more striking with factories showing a massive decrease in both numbers and total floor area. Whilst this reduction will be in part due to a decrease in the UK manufacturing base and the adoption of more efficient production methods e.g., assembly to order etc., these factors are not likely to be sufficient to account for the scale of reduction. Another factor which may be contributing to the decline is the way that premises are classified for rating purposes based on the main activity carried out within them and it may be that manufacturing activities that were being carried out in premises which fall under other building classifications e.g., warehouses.

The data show that the number and floor area of warehouse premise have both increased by over 150% between 1994 and 2012 whilst the number and floor area of offices have both increased by over 40% with shops showing a small decrease in both number (11%) and floor area (2%) over the same period.

8.7. Because offices have a higher proportion of air conditioned premises than the other main building types it is likely that this is one of the drivers behind the observed increase in demand for air conditioning.

9. The geographical variation of air-conditioning installations and operation within the UK

9.1. The literature search only revealed 4 references of which only 2 contained directly relevant information – which is, however, somewhat dated. Two of the remaining two references relate to trends in and a small-scale survey of the retail sector, and to historical statistics of the regional distribution of offices, shops etc. – see Table A14.

Region (E&W)	Air conditioned floor area in 1994 1000 m^2		
	Office	Retail	Warehouse
East Anglia	496 (1240)	523 (1308)	84 (210)
East Midlands	510 (1275)	696 (1740)	465 (1163)
Northern	276 (690)	969 (2423)	40 (100)
North West	1341 (3353)	1800 (4500)	386 (965)
South East	15110 (37775)	6351 (15878)	1360 (3400)
South West	1257 (3143)	1369 (3423)	199 (498)
Wales	338 (845)	523 (1308)	78 (195)
West Midlands	1116 (2790)	1206 (3015)	444 (1110)
Yorkshire and Humberside	759 (1923)	1341 (3353)	215 (538)

Table A14: Estimated Distribution of Floor Area of Building with Air Conditioning in England and Wales in 1994 from [182] (Rough estimate for 2009 in brackets)

9.2. Whilst more recent information on the buildings with air conditioning has not been obtained (See 8.4 in this Annex) it is possible to compare regional changes in the total floor area for the main building types over the last 19 years. When this is combined with data on the proportion of each building type that is air conditioned it provides an indication of how the distribution of air conditioned buildings across the Government Office Regions may have changed. Table A15 and Table A16 compare the regional distribution of property numbers and floor area, respectively, for the four main VOA property types.

Floor Area (1,000m^2)	1994	2012	% change
East Midlands	3,631	5,195	43%
East of England	6,276	8,083	29%
London	22,465	26,771	19%
North East	2,182	3,726	71%
North West	7,606	11,140	46%
South East	11,136	21,700	95%
South West	5,192	6,978	34%
Wales	2,251	3,647	62%
West Midlands	5,036	7,494	49%
Yorkshire and the Humber	4,962	7,356	48%
Grand Total	**70,737**	**102,090**	**44%**

Table A15: Changes in the Total Floor Area of Office Buildings in England and Wales 1994-2012

Floor Area (1,000m^2)	1994	2012	% change
East Midlands	6,095	6,296	3%
East of England	8,835	7,873	-11%
London	14,529	13,139	-10%
North East	5,806	4,164	-28%
North West	12,748	11,930	-6%
South East	12,748	19,900	56%
South West	9,044	8,139	-10%
Wales	4,939	4,634	-6%
West Midlands	8,850	8,257	-7%
Yorkshire and the Humber	10,623	7,938	-25%
Grand Total	**94,217**	**92,270**	**-2%**

Table A16: Changes in the Total Floor Area of Shops in England and Wales 1994-2012

9.3. For offices there were larger than average increases in floor area for the South East, North East and Wales. The increase in office floor area in London is less than half of the national average, but still accounts for over 25% of the total floor area in England and Wales.

9.4. Although there is very little change in the overall floor area of shops in England and Wales there has been a notable 56% increase in the floor area of shops in the South East. Apart from the East Midlands, which shows a modest increase of 3%, the total floor area has declined in all other Government Office Regions.

9.5. The total floor area of Warehouses has increased in all Government Regions, although the increase in London (19%) is much smaller than the average for England and Wales. In contrast there has been a massive four-fold increase in the floor area of warehouses in the South East.

Floor Area (1,000m²)	**1994**	**2012**	**% change**
East Midlands	12,422	32,242	160%
East of England	14,368	29,319	104%
London	16,119	19,206	19%
North East	5,532	12,988	135%
North West	18,552	42,131	127%
South East	11,063	56,548	411%
South West	6,994	23,845	241%
Wales	5,881	15,186	158%
West Midlands	13,960	38,861	178%
Yorkshire and the Humber	13,960	33,788	142%
Grand Total	**118,851**	**304,114**	**156%**

Table A17: Changes in the Total Floor Area of Warehouses in England and Wales 1994-2012

9.6. The decline in Factory floor space is relatively evenly spread across all Government Office Regions.

Floor Area (1,000m²)	**1994**	**2012**	**% change**
East Midlands	23,147	4,476	-81%
East of England	17,630	3,957	-78%
London	12,942	1,963	-85%
North East	10,877	2,586	-76%
North West	34,752	6,908	-80%
South East	25,321	5,389	-79%
South West	17,507	2,357	-87%
Wales	13,563	3,122	-77%
West Midlands	31,330	4,584	-85%
Yorkshire and the Humber	26,479	5,958	-77%
Grand Total	**213,548**	**41,300**	**-81%**

Table A18: Changes in the Total Floor Area of Factories in England and Wales 1994-2012

10. Trends in cooling loads imposed on systems.

10.1. This issue was not explicitly required by the project specification but it was agreed to note whether references relating to it were found. 21 references were identified that had a bearing on trends in cooling loads, of which 9 had direct relevance.

10.2. References covered the potential impact of changes in internal heat gains from equipment and building design and renovation measures to reduce solar heat gains [62]; urban heat island effects [109,110] and climate change [28, 132, 152, 153]; and user behaviour and tolerance of warm temperatures [87, 127] – see Table A19.

Potential reduction in annual cooling demands in offices in a UK-like climate	
Option	Potential reduction (Excludes extra energy use by fans or controls)
Shading systems	
External blinds-manual	21%
External blinds-automatic	54%
Improved external blinds -manual	28%
Improved external blinds - automatic	62%
Windows and fabric	
Efficient windows	23%
Reflective walls and roof	10%
Insulated roof	-5%
Equipment and lighting	
Efficient office equipment	23%
Efficient lighting	2%
Additional ventilation	
Automatic openings - night	51%
Automatic openings - night and day	77%
Mechanical extract - night	36%
Mechanical extract - night and day	51%

Table A19 Potential reductions in annual cooling demand from simulations, from [62] Similar results were found for the UK in [208]

11. Operational improvements.

11.1. This issue was not explicitly required by the project specification but it was agreed to note whether references relating to it were found. 17 references were identified that had a bearing on trends in cooling loads, but only 2 had a direct relevance, one of which applied to Japan.

11.2. The Harmonac study [106] carried out detailed assessments of energy saving opportunities in 42 buildings. About 50% of these opportunities related to operation and maintenance; and were typically low cost operational interventions. The same six savings opportunities were identified in more than 30% of the buildings. It found that there is considerable scope for savings from more effective operation and control of air conditioning systems but also showed that EPBD air conditioning system inspections only identify a proportion of the potential operational savings.

11.3. The most frequently identified opportunities in the Harmonic assessment reports were: “clean or replace filters regularly”; “generate instructions (“user guide”) targeted to the occupants”; and “shut off A/C equipment when not required”. The two opportunities assessed as having the highest aggregate savings potential (taking account of frequency of occurrence and potential savings per measure) were: “hire or appoint an energy manager”; and “shut off A/C equipment when not needed”.

11.4. The Harmonac study also carried out 400 air conditioning inspections and found differences when compared to the more detailed examination (of the 42 buildings). The inspections identified that only 23% of savings were operational opportunities; 9% of these were associated with load reduction and 6% were opportunities associated with system efficiency.

11.5. The question of user adaptation and tolerance of temperature variations has been discussed in the literature and overlaps with the more general question of trends in cooling loads noted above.

12. Assumptions on peak temperature

12.1. Surprisingly, the literature search only identified 5 references relating to peak temperatures (other than reports of specific heat waves), two of which contained frequency distributions [189, 197]. The average peak hourly temperature for London is 31.1 ^{o}C with a value of 32.5 ^{o}C occurring every 5 years on average and 36.3 ^{o}C every 50 years (based on historical data)

13. Duration of high temperatures

13.1. Only 5 references were located relating directly to statistics on the duration of high temperatures but four have directly relevant information (There are several other studies of overheating risk that do not state the weather assumptions. The most directly relevant reference for this study is CIBSE TM49 Design Summer Years [53], which provides an example hot summer year for design evaluation but does not report long- (or even medium-) term statistics.

13.2. A Meteorological Office report [211] showed that between 1961 and 2003, the duration of summer heat waves (measured as "heat wave days"[8] per year) has increased substantially in all regions of the UK. The study showed that Northern Ireland has the smallest number of heat wave days (3 in 1961 rising to 8 in 2003) and East Anglia the highest (6 days in 1961 rising to 19 in 2013). The increase in the number of heat wave days over the period was greatest in East Anglia, the Midlands and Central and South East England (increasing by 15.8, 15.3 and 14.3 days, respectively) and lowest in West Scotland, Northern Ireland and North & East Scotland (increasing by 4.3, 6.3 and 6.0 days, respectively). Until about 1979 the increase was similar across all regions (around 6 days), thereafter the regions diverge, with virtually no further change in Scotland and Northern Ireland. The same report showed that daily maximum temperatures increased by about 1.5 ^{o}C over the period in all regions, having previously been declining since the late 1930s. Also, during this period, winter sunshine increased in most regions, probably as a result of the introduction of the Clean Air Act. (The exception is in western Scotland, where precipitation increased). Changes in summer sunshine –more important for air conditioning loads - appear to have been smaller (but are not explicitly reported for the same dates).

[8] The definition of a heat wave day used in the study was that the daily maximum temperature is at least 3oC above the mean daily maximum temperature for the month over the period 1961 to 1990, for at least 6 consecutive days. The actual methodology is unclear, but is presumably a rolling mean. Thus the average number of days per year is not to be taken literally but as a convenient way to express a trend.

14. Impact of energy prices on consumption

14.1. 21 references were found with a bearing on the effect of electricity price on air conditioning energy use, but none of them are directly usable (by, for example, reporting the price elasticity of air conditioning energy use).

14.2. Many references related to the expected impact of electricity supply prices on purchaser behaviour (judged by the evaluation of life cycle costs), or attempted to draw conclusions about causality between product efficiency and historical changes of electricity (or product) price. Another group of references addressed pricing measures intended to reduce peak demand. These references generally reported experimental tariffs for residential customers in climates with summer-peaking aggregate electricity demand, sometimes associated with utility interventions to temporarily reduce cooling output.

14.3. One scoping study (carried out by AEA Technology for DECC) [224] investigated the scope for time of use pricing to influence peak electricity demand in UK public and private sector buildings. It did not specifically focus on air conditioning. 43% of survey respondents had time of use tariffs (and 14% didn’t know whether they had) but only 2 (total sample 66) took measures to reduce peak demands. In general respondents thought that it would be difficult to change working practices. Published electricity load profiles suggest that the UK generating system is unlikely to become summer-peaking in the short-run (especially with the increasing contribution of photovoltaic generation). Local city-centre distribution systems may become stressed however.

15. Lifetime of air conditioning systems and components.

15.1. 9 references to product operational life were found, of which 7 contain directly relevant data.

15.2. Of particular relevance are studies that extract product life as a parameter of empirical curve-fitting [84] and those that summarise industry-standard assumptions [12, 52] (which are probably based on surveys, though this is not entirely clear). These sources give lifetimes of 20 to 25 years for air conditioning chillers (provided that they are not retired prematurely as the result of refrigerant bans) and AHUs. Metal ductwork has an expected life of 40 years. The empirical figures agree well with the standard assumptions – except for the UK, where the best-fit average life of a chiller appears to be significantly longer at 31 years. This estimate could be refined by the acquisition of further market data and reanalysis, but this is outside the scope of this project. One reference offers a “survival curve” [121]. None of the references appear to take account of replacement due to building demolition or major refurbishment. The curve-fitting shows that about 40% of the 2009 chiller stock is more than 10 years old. The proportion of the market which is accounted for by replacement sales is projected to increase as the proportion of older chillers increases.

16. Breakdown by at least one of: Economic sector, System type, System size, Age

16.1. 6 references contained a breakdown or comparison between one of these sectors: generally as estimates of the numbers of different types of air conditioning system.

Appendix A: Publication List

Ref no.	Author	Title	Source: Abstract (A), Full paper (P) Internet Download (ID)
1	Abdel-Salam, Ahmed H., and Carey J. Simonson.	Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV. Applied Energy 116 (2014): 134-148.	A
2	Adam C et al	From model validation to production of reference simulations: how to increase reliability and applicability of building and HVAC simulation models. Les Editions de L'Université de Liège, décembre 2006	A
3	Adnot, J et al.,	Energy Efficiency and Certification of Central Air Conditioners (EECCAC) Final Report – April 2003. Study for the D.G. Transportation-Energy(DGTREN) of the Commission of the E.U., 2010	P
4	Adnot,J et al.,	Ecodesign Preparatory Study ENTR Lot 6 Air Conditioning Systems: Chillers, 2012, July http://www.ecohvac.eu/	P
5	Aherne, V. (Ed.) (2009)	DA19 HVAC&R Maintenance, Melbourne: Australia Institute of Refrigeration, Air conditioning and Heating.	A
6	Alliant Energy	Alliant Energy to initiate Appliance Cycling in all of Iowa today All participating customers included in event CEDAR, Iowa – July 6, 2012 – Interstate Power and Light Co. (IPL), an Alliant Energy company, announced today it will cycle air conditioners for all participating Iowa customers. Weather conditions are such that from 1 p.m. to 7 p.m. today customers enrolled in the Appliance Cycling program will have their air conditioner cycled in 15-minute intervals to reduce overall energy usage.	P
7	Ampofo, F. ; Maidment, G. G. ;Missenden, J. F.	Review of groundwater cooling systems in London, Ampofo, F., Maidment, G. G., Missenden, J. F. Applied thermal engineering. VOL 26; NUMBER 17-18, 2006, 2055-2062	A
8	Andre, P et al	A contribution to the audit of an air-conditioning system: modelling, simulation and benchmarking. Building Services Engineering Research & Technology 29, no. 1 (2008): 85-98.	A
9	Andre, P et al	Simulation of HVAC systems: development and validation of simulation models and examples of practical applications. Octobre 2006	A
10	Andre, P et al	Development of an Evidence-Based Calibration Methodology Dedicated to Energy Audit of Office Buildings. Part 2: Application to a typical office building in Belgium. In Proceedings of the 10th REHVA World Congress - Clima 2010. 2010.	A
11	Angel S	Customer Incentives for Energy Efficiency Through Electric and Natural Gas Rate Design, U.S. Environmental Protection Agency	P
12	ASHRAE	Service Life and Maintenance Cost Database	A
13	Ascione, Fabrizio, et al.	Rehabilitation of the building envelope of hospitals: Achievable energy savings and microclimatic control on varying the HVAC systems in Mediterranean climates. Energy and Buildings 60 (2013): 125-138.	A
14	Attali, S et al.	Factors Influencing the Penetration of Energy Efficient Electrical Appliances into National Markets in Europe, Defra, 2009 http://www.topten.eu/uploads/File/Factors%20influencing%20the%20penetration%20of%20energy%20efficient%20electrical%20appliances%20into%20national%20markets%20in%20Europe-1.pdf	P
15	Aguilar F J, Quiles P V, Aledo S	Operation and Energy Efficiency of a Hybrid Air Conditioner Simultaneously Connected to the Grid and to Photovoltaic Panels. Energy Procedia, Volume 48, 2014, Pages 768–777	A

Ref no.	Author	Title	Source: Abstract (A), Full paper (P) Internet Download (ID)
16	Ahmadzadehtalatapeh M	An air-conditioning system performance enhancement by using heat pipe based heat recovery technology, Scientia Iranica, Volume 20, Issue 2, April 2013, Pages 329-336 (free access)	A
17	Ahmed A	Earth-air heat exchangers and their potential for low-energy cooling of buildings in the UK. , University of Brighton.	A
18	Al-Rabghi, O M., and. Akyurt M M	A survey of energy efficient strategies for effective air conditioning. Energy Conversion and Management 45.11 (2004): 1643-1654	A
19	Altan, H., J. Douglas, and Y. Kim	Energy performance analysis of university buildings: Case studies at Sheffield University, UK."J Architectural Engineering Technology 3.129 (2014): 2.	A
20	Atamturk N et al	Electricity Use and Income: A Review CALIFORNIA PUBLIC UTILITIES COMMISSION June 21, 2012	P
21	Anon,	Efficient air distribution and ventilation techniques that are making a difference, CCN Climate Control News, July 2013, 26	A
22	Anon,	Energy Consumption Guide 19: Energy Use in Offices, 1998,http://www.cibse.org/pdfs/ECG019.pdf	P
23	Auffhammer M, Mansur E T	Measuring climatic impacts on energy consumption: A review of the empirical literature, Energy Economics, Volume 46, November 2014, Pages 522–530	A
24	Auffhammer M	The Relationship Between Air Conditioning Adoption and Temperature U.S. Environmental Protection Agency October 12, 2011	P
25	BEIZAEE, A., LOMAS, K.J. and FIRTH, S.K.,	National survey of summertime temperatures and overheating risk in English homes. Building and Environment, 65, pp.1-17. 2013.	
26	Bengea, S C., et al.	Model predictive control for mid-size commercial building hvac: Implementation, results and energy savings. The Second International Conference on Building Energy and Environment. 2012.	A
27	Bennett, D. H., et al.	"Ventilation, temperature, and HVAC characteristics in small and medium commercial buildings in California." Indoor air 22.4 (2012): 309-320.	A
28	Berger T , Amann C, Formayer H et al	Impacts of climate change upon cooling and heating energy demand of office buildings in Vienna, Austria, Energy and Buildings, Volume 80, September 2014, Pages 517-530	A
29	Bertagnolio S and Andre P.	Development of an Evidence-Based Calibration Methodology Dedicated to Energy Audit of Office Buildings. Part 1: Methodology and Modeling. In Proceedings of the 10th REHVA World Congress - Clima 2010. 2010.	A
30	Bertagnolio S, Lebrun J, and Andre P.	Development and use of equation based simulation tools to support audit of commercial buildings. In Proceedings of the eleventh International IBPSA Conference, Glasgow, UK. 2009.	
31	Bessec M, Fouquau J	The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach, Energy Economics, Volume 30, Issue 5, September 2008, Pages 2705-2721	A
32	Betts D,	Delivering efficiency through air intake screens, HVR Heating & Ventilating Review, July 2014, Vol.53(9), 28-29.	A
33	Boermans T et al	Klimaschutz durch Reduzierung des Energiebedarfs für Gebäudekühlung Von Kjell Bettgenhäuser, Ecofys Germany GmbH, Köln Juni 2011	P
34	Boyano A , Hernandez P ,Wolf O	Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations Energy and Buildings, Volume 65, October 2013, Pages 19-28	A
35	Braun M R, et al	Using regression analysis to predict the future energy consumption of a supermarket in the UK, Applied Energy, Volume 130, 1 October 2014, Pages 305-313	A
37	Brown, N., et al	Air conditioning Surveys in the UK Retail Sector, or 'Keeping the Cold in'. Fourth International Conference Improving Energy Efficiency in Commercial Building (IEECB'06), Frankfurt, Germany. (2006).	P
38	BSI. BS EN 15240:2007	Ventilation for buildings. Energy performance of buildings. Guidelines for inspection of air-conditioning systems.	P
39	BSRIA	UK air conditioning market reports (various)	A

Ref no.	Author	Title	Source: Abstract (A), Full paper (P) Internet Download (ID)
40	Butler D	Improvements in the efficiency of packaged air conditioning, Consulting Engineer for HVAC & R Industry, February 2009, 14-15,	P
41	Caeiro, J et al.	Using street surveys to establishing air conditioning incidence in UK's commercial offices stock. International Conference on Improving Energy Efficiency in Commercial Buildings IEECB. Vol. 8.	P
42	Carlo J, Lamberts R	Development of envelope efficiency labels for commercial buildings: Effect of different variables on electricity consumption, Energy and Buildings, Volume 40, Issue 11, 2008, Pages 2002-2008	A
43	Casas W, Schmitz G	Experiences with a gas driven, desiccant assisted air conditioning system with geothermal energy for an office building, Energy & Buildings, May 2005, Vol.37(5), 493-501,	A
44	Centre for Retail Research	Retail in 2018 - Shop numbers, Online and the High Street A GUIDE TO RETAILING IN 2018	A
45	Chen S, Zhang K, and Setunge S.	Comparison of three HVAC systems in an office building from a life cycle perspective. (2013).	A
46	Chowdhury A A, Rasul M G, et al	Modelling and analysis of air-cooled reciprocating chiller and demand energy savings using passive cooling. Applied Thermal Engineering 29.8 (2009): 1825-1830.	A
47	Chanana, S. ; Kumar, A.	Demand response by dynamic demand control using frequency linked real-time prices, International journal of energy sector management. VOL 4; NUMBER 1, ; 2010, 44-58	A
48	. Chiu J N W, Pauline Gravoille P, Martin V	Active free cooling optimization with thermal energy storage in Stockholm, Applied Energy, Volume 109, September 2013, Pages 523-529	A
49	Chua K J , Chou S K, W.M. Yan Y J	Achieving better energy-efficient air conditioning – A review of technologies and strategies, Applied Energy, Volume 104, April 2013, Pages 87-104	A
50	Cianfrini C, Corcione M, Habib E, Quintino A	Energy performance of air-conditioning systems using an indirect evaporative cooling combined with a cooling/reheating treatment, Energy and Buildings, Volume 69, February 2014, Pages 490-497	A
51	CIBSE	CIBSE Guide F: Energy Efficiency in Buildings 2012	P
52	CIBSE	CIBSE Guide M: Maintenance Engineering and Management Paperback – 30 Apr 2008	P
53	CIBSE	TM49 Design Summer Years for London 2014 ISBN 978 1 906846 27 5	P
54	Cole, W. J. ; Powell, K. M. ; Hale, E. T. ; Edgar, T. F.	Reduced-order residential home modeling for model predictive control, Energy and buildings. VOL 74, ; 2014, 69-77	A
55	Cox R A, Drews M, Rode C, Nielsen S B	Simple future weather files for estimating heating and cooling demand, Building and Environment, Volume 83, January 2015, Pages 104-114	A
56	Day A R.	An improved use of cooling degree-days for analysing chiller energy consumption in buildings, BSERT Building Services Engineering Research & Technology, 2005, Vol.26(2), 115-127,	A
57	Dejvises J,	Modelling of flexible heat demand and assessing its value in low carbon electricity systems. Imperial College London (University of London), 2012.	A
58	Department for Communities and Local Government	ncm_db_activity_11Jun 2-14 http://www.ncm.bre.co.uk/download.jsp	ID
59	Department for Communities and Local Government	Energy Performance of Buildings Directive (recast) Cost optimal calculations: UK report to European Commission May 2013	P
60	De Rosa M, Bianco V, Scarpa F, Tagliafico L A	Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach, Applied Energy, Volume 128, 1 September 2014, Pages 217-229	A
61	Ding Y, Qiang F, et al,	Influence of indoor design air parameters on energy consumption of heating and air conditioning, Energy & Buildings, January 2013, Vol.56, 78-84,	A
62	Dröschel B, et al.,	KeepCool: From Cooling to Sustainable Summer Comfort,2010 www.keep-cool.eu	P

Ref no.	Author	Title	Source: Abstract (A), Full paper (P) Internet Download (ID)
63	Dunn G N, Knight I P.	Energy consumption of air conditioning systems in UK office environments, Indoor Air 2002: Proceedings of the 9th International Conference on Indoor Air Quality and Climate, H Levin, ed., Santa Cruz, California, Vol.2, 349-354,	P
64	Dunn G N., Knight I P., et al.	Measuring system efficiencies of liquid chiller and direct expansion, ASHRAE Journal, February 2005, Vol.47(2), 26-28,30-33,	P
65	Dussault J-M, Gosselin L, Galstian T	Integration of smart windows into building design for reduction of yearly overall energy consumption and peak loads Solar Energy, Volume 86, Issue 11, November 2012, Pages 3405-3416	P
66	EDSL	Comparative energy consumption of air conditioning systems: simulation study BRECSU 07/0 2001 (unpublished)	P
67	EDSL	A Comparative Study of Active Chilled Beam and Fan Coil Unit Energy Consumption HEVAC Fan Coil Unit Group 2014	P
68	Eicker U, Pietruschka D, Haag M, Schmitt A	Energy and Economic Performance of Solar Cooling Systems World Wide, Energy Procedia, Volume 57, 2014, Pages 2581-2589	A
69	Elliott, B, Bull R , and Mallaburn P.	A new lease of life? Investigating UK property investor attitudes to low carbon investment decisions in commercial buildings. Energy Efficiency (2014): 1-14.	A
70	Essam, E.	Energy Efficient Hospitals Air Conditioning Systems Open Journal of Energy Efficiency 2012 (2012)	A
71	European Commission,	COMMISSION REGULATION (EU) No 206/2012of 6 March 2012. Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Air Conditioners and Comfort Fans, 2013 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:072:0007:0027:EN:PDF	P
72	Eurovent Certification	Product Performance Databases at www.eurovent-certification.com	P
73	Fan, Y et al.	Field-based study on the energy-saving effects of CO_2 demand controlled ventilation in an office with application of Energy recovery ventilators. Energy and Buildings 68 (2014): 412-422.	A
74	Faruqui A and George S	Quantifying Customer Response to Dynamic Pricing: The Electricity Journal May 2005, Vol. 18, Issue 4	P
75	Faruqui A and Sergici S	Household response to dynamic pricing of electricity: a survey of 15 experiments, Journal of regulatory economics. VOL 38; NUMBER 2, ; 2010, 193-225	P
76	MARGARET F. FELS,	PRISM: An Introduction, Energy and Buildings, 9 (1986) 5 -18 5	A
77	Futcher J a and Mills G.	The role of urban form as an energy management parameter. Energy Policy 53 (2013): 218-228.	A
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216	Slurry Ice	Slurry Ice Thermal Energy Storage Design Guide undated http://www.epsltd.co.uk/files/slurryice_manual.pdf	F
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218	Struck C, Roelofs J, et al	A comparison of measured and estimated electric energy use and the impact of assumed occupancy pattern, 1st Swiss Building and Urban Simulation Conference, November 2009. - Horw (CH) : International Building Performance Simulation Association - Switzerland - IBPSA-CH, 2009	F
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220	Tomkins J	Calling the deal CIBSE Journal 2November 2013	F
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222	Virk G, et al	Urban Heat Island analysis of Birmingham and Manchester for the creation of new Design Summer Years CIBSE Technical Symposium, London, UK 16-17 April 2015	F
223	Xiaojie L et al	A review of recent development in variable refrigerant flow systems Science and Technology for the Built Environment June 2015	A
224	AEA Technology	SCOPING STUDY FOR MEASURING PEAK ELECTRICITY DEMAND IN NON-DOMESTIC BUILDINGS ED47637 Final Report 28th May 2010	F

Appendix B: Research Areas Covered by each Publication

The Research Areas are described in Table A and the areas covered by each publication are shown in Table B.

Area	Description
Usage	Estimates of usage e.g., annual full load equivalent hours, benchmark comparisons
Measured vs calculated	Comparisons between measured and calculated consumption for a range of non-domestic premises. (For either individual buildings or markets)
Temperature vs operation	Variation of air-conditioning usage with external temperature. (Usage meaning periods of use)
Operation pattern	Usage patterns.(All types of non-domestic buildings)
Technologies	Technology (especially efficiency)
% stock cooled	The proportion of UK office space and other non-domestic buildings which is air conditioned.
Location vs installation/operation	The geographical variation within the UK of air-conditioning installations and operation.
Trends in cooling loads	Trends in cooling loads imposed on systems. (If possible)
Operational improvements	Operational improvements. (If possible)
Peak temperature	Assumptions on peak temperature
High temperature	Duration of high temperature
Energy price vs consumption	Impact of energy prices on consumption
Lifetimes	Lifetime of air conditioning systems and components.
UK like climate?	Relates to a UK-like climate?
Disaggregated?	Includes breakdown by at least one of Includes breakdown by at least one of: • Economic sector • System type • System size • Age
Past 10 years?	Relates to the last 10years?
Policy refs?	Refers to regulatory or other policy instruments
Data collection methods?	If applicable; data collection methodology, sample size, primary or secondary data, age

Table A: Description of Research areas

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
1	✔				✔													
2		✔																
3	✔				✔									✔			✔	
4	✔				✔	✔						✔		✔	✔			
5													✔	✔				
6												✔		X				
7						✔								✔				
8	✔													✔				
9		✔												✔				
10		✔												✔				
11												✔		✔				
12													✔	✔				
13					✔									X				
14						✔												
15					✔													
16					✔									X				
17					✔									✔				
18					✔													
19	✔													✔				
20												✔		✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
21					✔													
22	✔													✔				
23				✔														
24												✔		✔				
25											✔			✔				
26					✔									?				
27					✔									?				
28			✔					✔						✔				
29		✔												✔				
30																		
31			✔											✔				
32									✔					✔				
33	✔				✔									✔				
34	✔													✔				
35			✔											✔				
36				✔		✔								✔				**Smalls retail sample**
37				✔		✔	✔							✔				
38									✔									
39				✔										✔				
40																		
41						✔								✔				**Small sample**

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
42	✔													X				
43					✔													
44						✔	✔							✔				
45					✔									X				
46		✔												X				
47												✔						
48					✔									✔				
49					✔									?				
50					✔													
51	✔													✔				
52													✔					
53											✔							
54					✔													
55	✔													✔				
56	✔													✔				
57					✔													
58				✔										✔				
59		✔			✔		✔							✔				
60	✔													✔				
61									✔					X				
62	✔		✔					✔						✔				
63	✔													✔				
64					✔									✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
65	✔				✔									✔				
66	✔													✔				
67	✔													✔				
68					✔													
69						✔								✔				
70					✔													
71					✔									✔			✔	
72					✔									✔				
73					✔									?				
74												✔		✔				
75												✔		✔				
76	✔													✔				
77			✔			✔								✔				
78						✔								✔				
79			✔											✔				
80					✔									✔				
81					✔									?				
82			✔											X				
83			✔											✔				
84													✔	✔	✔		✔	
85	✔					✔		✔	✔				✔	✔	✔	✔	✔	
86	✔					✔		✔	✔				✔	✔	✔	✔	✔	
87						✔								✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
88					✔									?				
89					✔									?				
90			✔											X				
91			✔					✔						X				
92			✔											✔				
93	✔		✔			✔		✔			?			✔				
94						✔												
95								✔						✔				
96	✔				✔			✔	✔					✔				
97								✔			✔			✔				
98								✔						X				
99					✔									?				
100					✔									X				
101		✔												✔				
102								✔						X				
103									✔					✔				
104	✔													✔				
105	✔													✔				
106									✔					✔			✔	
107	✔		✔	✔					✔					✔				
108	✔													✔				
109			✔					✔						✔				
110			✔											✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
111	✔													✔				
112	✔				✔									✔				
113	✔				✔									✔				
114						✔								✔				
115					✔													
116			✔											✔				
117			✔											✔				
118					✔									◀				
119					✔									✔			✔	
120	✔													✔				
121													✔	✔				
122								✔						✔				
123												✔						
124												✔		✔				
125					✔													
126					✔													
127									✔					✔				
128								✔						✔				
129														✔				
130								✔						X				
131				✔				✔						✔				
132					✔									✔				
133								✔						✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
134			✓											X				
135									✓									
136					✓													
137					✓													
138												✓		X				
139												✓		X				
140												✓		X				
141																		
142	✓													X				
143												✓		X				
144					✓							✓		✓				
145														✓			✓	
146	✓												✓	✓			✓	
147			✓											✓				
148												✓		✓				
149					✓													
150	✓				✓	✓						✓	✓	✓	✓		✓	
151					✓									✓				
152								✓						✓				
153			✓			✓								✓				
154					✓									✓				
155	✓				✓									✓	✓			
156					✓									✓				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
157					✔									✔				
158								✔										
159												✔		✔				
160					✔													
161	✔													✔				
162												✔		X				
163														✔				
164					✔													
165								✔										
166									✔									
167												✔		✔				
168					✔													
169			✔											X				
170								✔						✔				
171					✔	✔		✔						✔				
172					✔									?				
173					✔									?				
174									✔					X				
175					✔									?				
176					✔									?				
177	✔													?				
178					✔													
179						✔								✔				

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
180					✔									?				
181												✔						
182						✔	✔							✔	✔			
183										✔								
184			✔															
185			✔															
186	✔				✔									✔				
187					✔			✔	✔					✔				
188							✔											
189							✔											
190	✔			✔		✔		✔							✔			✔
Supplementary Sources																		
191					✔									✔		✔		
192	✔				✔									✔		✔		
193	✔													✔		✔		
194										✔	✔			✔		✔		
195					✔													
196					✔							✔				✔		
197						✔	✔							✔		✔		
198	✔		✔	✔										✔		✔		

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
199	✓	✓		✓										✓		✓		✓
200	✓				✓									✓		✓		
201	✓				✓									✓		✓		
202	✓			✓	✓				✓					✓		✓		
203	✓			✓					✓					✓		✓		
204					✓									✓		✓		
205				✓														
206					✓									✓		✓		
207								✓	✓					✓		✓		
208	✓			✓					✓					✓		✓		
209					✓									✓		✓		
210					✓									✓		✓	✓	
211																		
212					✓									✓		✓		
213	✓		✓											✓		✓		
214					✓									✓		✓		

Ref no.	Usage	Measured vs calculated	Temperature vs operation	Operation pattern	Technologies	% stock cooled	Location vs installation/operation	Trends in cooling loads	Operational improvements	Peak temperature	High temperature	Energy price vs consumption	Lifetimes	UK like climate?	Disaggregated?	Past 10 years?	Policy refs?	Data collection methods?
215					✔									✔		✔		
216					✔													
217					✓			✓						✔		✔		
218		✓		✓										✓		✔		
219					✓									✓		✓		
220	✔				✔									✔		✔		
221	✔				✓									✔	✔	✔		
222			✓								✓			✔		✔		

✔ = relevant ✓ = some information X= not UK-like climate = key reference ?=uncertain

Table B: Research Areas covered by each Publication