Study on Energy Use by Air-Conditioning: Final Report

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Executive summary

This study comprises several different elements, each directed at improving DECC's understanding and characterisation of UK electricity consumption by air conditioning in non-domestic buildings; especially that used to support the cooling function (rather than air handling). These include: analysis of measured consumptions; examination of the contents of air conditioning inspection reports and energy performance certificates; a literature search; and the development of procedures to extend the scope of DECC's product policy model as applied to air conditioning.

The principal results of the study are as follows:

- The analysis of energy performance certificates shows that the median (calculated) cooling energy demand in retail premises is considerably higher than in offices (though more variable)[1]. In particular, heat gains from lighting can be much higher in retail premises. Since the total cooled retail space appears to be comparable with that for offices - exact figures are not available – this sector seems to merit further study.
- Within the sample of Energy Performance Certificates, the calculated annual electricity consumption for cooling in offices is generally comparable with the 'typical' consumption per unit floor area benchmarks developed 20 years ago. A significant proportion (30%) of energy used for cooling is in buildings which exceed these benchmark values. In general higher cooling consumption is associated with high calculated electricity consumption by office equipment, and – to a lesser extent – with that by lighting.
- The seasonal efficiency of cooling generators reported in the Energy Performance Certificates was relatively low (although a large proportion of the reports simply retained the default values that were provided in the software). The current and planned minimum seasonal efficiency requirements under the Energy-related Products Directive are more demanding than the reported values and should

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[1] Most existing UK studies of air conditioning energy use have focussed on office buildings.

therefore have a significant impact over the longer term (cooling products typically have life times of 10 to 20 years, if not longer).

- Calculations of the impact of changes to the Building Regulations, and European cost-optimal calculations, show that calculated consumption levels in new (and major refurbished) buildings, are considerably lower than in the existing stock. However, new-build and major refurbishment rates are low compared to the size of the existing stock and the impact will remain marginal in the short run.
- In a sample of monitored offices, 77% of the energy used for cooling was in systems that exceeded the benchmark “typical” consumption per unit floor area. There was some evidence of systems operating at times when buildings were (claimed to be) unoccupied. The most common recommendations from UK air conditioning inspection reports (as with a similar European study), related to operational and maintenance issues, and in particular to control settings. There is therefore a suspicion that this is at least a partial cause of the extra consumption (calculations assume that systems are off when not required). In addition, a significant component of annual consumption was often from persistent low consumption when no cooling was being provided. This has rarely been included in calculated consumptions (but is now included in current European calculation standards and regulations)
- The impact of location on the average annual electricity consumption for cooling in the monitored systems was estimated. The highest consumptions (in London) were 25% higher than the lowest (Edinburgh, Glasgow and Belfast). Microclimatic effects may extend this range . In particular, higher consumptions can be expected within Urban Heat Islands, while colder locations, such as those at higher altitudes are likely to require less cooling.

The DECC Product Policy Model is used to estimate the future impact of product policy measures such as the effect of EU minimum energy performance standards; which progressively remove the least energy efficient products from the market. The model looks at stocks and sales of the different products; and estimates energy savings, which are then compared to a business–as-usual (BAU) scenario of no legislation. The present study supports the use of the product policy model when applied to air conditioning, in two ways: by expanding its functionality, and by providing empirical values for some of its inputs. The functionality is extended in several ways.

- A new algorithm allows annual consumption produced by the existing model to be apportioned between months based on system and building characteristics; and geographical location. Weather data for 14 UK locations are provided, but the procedure can also be applied to other climatic data sets including those which take account of the effects of urban heat islands or climate change.
- The procedure in the algorithm also generates standardised estimates of peak half-hourly power requirement for different climates, and the corresponding values of “equivalent full-load hours” (EFLH - the ratio of annual consumption to peak power); which is an input to the existing model. The measured values of peak power are lower than industry “rules of thumb” (though somewhat closer to the results of computer simulations). This, combined with the relatively high observed levels of

annual consumption, yields an empirical value of EFLH that is considerably higher than that currently used in the model. In practice, the effect is largely offset by the fact that the model does not take into account that installed cooling capacity is commonly significantly higher than the peak power levels that actually occur. Ideally, the EFLH values should be increased and an explicit allowance made for unused cooling capacity.

The report also provides a summary of policy options for reducing electricity consumption for cooling in air conditioning systems, These are classified into three types – those that:

- are primarily focussed on other energy uses but which impact on air conditioning;
- are specifically directed at air conditioning system components; or
- have a wider scope which includes air conditioning.

There are several areas where knowledge is still weak:

- The geographical and sectoral distribution of air conditioned floor space. Information provided to DECC by the Valuation Office Agency (VOA) has allowed the total floor space for the four main building types (offices, shops, warehouses and factories) to be provided for 2012 for England and Wales. A more detailed stock breakdown identifying the proportion of the building stock with full or partial air conditioning was requested, but was not provided within the timeframe of this study. However, VOA data on the proportion of buildings with air conditioning for 1994 is provided in Annex A, together with rough estimates for 2009.
- Comparing the 1994 and 2012 floor area data shows that there has been a 9% increase in the floor area for the four main building types over the period. However, the changes within each building category are much more significant with warehouse space more than doubling and factory floor area decreasing by around 80% between 1994 and 2012. This information is presented in Annex A.
- The range and distribution of product and system efficiencies in the installed stock. This is outside the scope of the VOA information, but current knowledge could be improved by the analysis of a larger and more structured sample of energy performance certificate data.
- The age distribution of installed systems is important to estimate replacement rates and therefore the future impact of product performance regulations. This could be addressed by expanding existing market models to include more detailed sales data from past market research studies.
- Monitored data has proved to be valuable but are limited in quantity. Additional measurements – especially for the retail sector – are needed. These could be complemented by simulation studies to explore the sensitivity of consumption to building and system parameters and occupation patterns.
- Peak power demands have rarely been studied and therefore there is little understanding of, for example, aggregate peak power demand that takes into account diversity between systems or buildings.

- At a policy level, the expanded product policy model could be used to explore the implications on electricity consumption of physical effects such as urban heat islands and possible climate change and of policy options. Two overlapping generic problems for general energy–efficiency policy affect air conditioning: how to incentivise actions following recommendations, and how to accelerate the take-up of energy efficiency measures in general. A greater emphasis on reporting actual consumption compared to reference benchmarks may have a useful role in this respect.

1. Introduction

This is the Final Report for DECC's Study on Energy Use by Air-Conditioning, providing an overview of the findings. All the questions (listed below) have been addressed, but the responses have sometimes been limited by a shortage of information. The study comprised several different elements, each directed at improving DECC's understanding and characterisation of UK electricity consumption by air conditioning in non-domestic buildings, especially that supporting the cooling function (rather than that for air handling). The main report includes only key references - an extensive list of documents can be found in Annex A. Analysis methods and detailed results are contained in 6 separate Annexes at www.bre.co.uk/ac_energyuse.

1.1. Scope and objectives

1.1.1. In summary, the basic **requirement** of the contract was to undertake a review of the electricity used by air-conditioning in the UK, including the following:

- A literature review of the trends in air conditioning usage patterns in the UK and the possible future impacts of new technology
- Assessment of the most common problems noted in around 500 anonymised air-conditioning inspection reports in the Energy Performance of Buildings Directive Register (EPBD), provided by DECC. This was supplemented by an additional task to analyse a sample of recorded Energy Performance Certificate data for the buildings containing the inspected air conditioning systems.
- Identification of buildings for which existing cooling demand and electricity data from air-conditioning systems can be obtained and analysis of this data

- Making recommendations to update the key inputs to DECC's existing model of electricity demand from air-conditioning
- Development of an algorithm to estimate the peak and monthly electricity demand due to air-conditioning in the UK that can be used by DECC to supplement their model of electricity consumption from air-conditioning.

1.1.2. Key **objectives** and **research questions** to be addressed were:

1.1.2.1. Objective 1: To review existing academic literature on usage and lifetime of air-conditioning equipment in the UK non-domestic sector. Research questions:

- What does the literature tell us about the operating hours in different sections of the economy?
- How does actual operation compare with anticipated operation, for example from estimated cooling demand?
- What is the distribution of air-conditioning by Government Office Region (GOR)?
- What does the literature tell us about the peak demand and monthly demand as a function of outdoor temperature?
- How is lifetime estimated?
- Where are the gaps in our information? (For example by sector of the economy? by technology? by rated capacity of the air-conditioning equipment?)

NOTE: assessing sales data was out of scope.

1.1.2.2. Objective 2: To analyse existing data on the electricity demand of air-conditioning. Research questions:

- How does actual air-conditioning use compare with modelled use?
- What is the peak electricity demand for air-conditioning, as a function of outdoor temperature?
- What is the monthly variation in the electricity demand for air-conditioning?
- How should the current model of electricity demand be revised?

1.1.2.3. Objective 3: To assess to what extent air conditioning is being installed, maintained and operated in an energy efficient manner. Research questions:

- Are air-conditioning systems sized optimally?
- Are systems maintained and operated correctly?

- Is there any information on refrigerant leakage rates?
- What are the most common recommendations made by air-conditioning inspectors for improving efficiency?
- What other studies exist in this area?

1.1.2.4. Objective 4: To estimate the potential for energy efficiency. Research questions:

- How efficiently do different systems work at part load?
- Which new technologies are near deployment?
- How attractive are these to the consumer, compared to standard technologies?
- How much electricity could be saved by new technologies, or improved operation and maintenance of existing technologies?

1.1.2.5. Objective 5: To make recommendations on how to accelerate deployment of efficient appliances and how to improve installation. Research questions:

- Which technology classes could save most electricity?
- Which technology classes use most and can these be replaced?
- Are there implications for Eco-Design?

1.2. Structure of this report

1.2.1. The work was divided into six Work Packages that reflected the structure of questions above. However, several of the objectives are addressed by more than one of the work packages and so this report presents the results by topic, drawing together the different perspectives from each work package.

1.2.2. The six separate detailed Annexes are arranged by work package.

2. Background and Fundamentals

In order to provide a context for the results, the following paragraphs provide an overview of different types of air conditioning systems and the heat balance in a cooled space.

2.1. Types of air conditioning system

2.1.1. Fixed air conditioning systems can be divided into three main categories:

- Split Systems comprise an indoor unit and an outdoor unit connected by refrigeration pipework. The system can usually operate in cooling-only mode or as a heat pump. Multi-split and variable refrigerant flow (VRF) systems are similar in principle but have more than one indoor unit. These systems do not have integral air movement systems but may be used with separate mechanical ventilation systems.
- Central systems usually serve several spaces, and usually provide mechanical ventilation, especially when based on chillers. There are many types of system that distribute cooling using both chilled water and cooled air. These include fan-coil, active chilled beam and induction systems. There are also several types of all-air system: constant volume, variable volume, dual-duct and terminal reheat. As heat transfer by cooled air is less energy-efficient than by chilled water, these systems tend to have high fan energy consumption. Other systems such as chilled ceilings and embedded systems do not provide mechanical ventilation. Heat pump loop systems have a constant temperature water loop circulated around the building with self-contained heat pumps providing either heating or cooling of individual rooms by transferring heat from or to the loop. The loop is kept cool by a central chiller, cooling tower or dry air coolers. Chillers are commonly air-cooled but may be water-cooled.
- Packaged units have the complete refrigeration circuit in a single unit which is located on the outside of the building (often on the roof) together with an air handling unit which supplies conditioned air to the building via ducts.

2.2. Building heat balance and cooling demand

2.2.1. A space in a building requires cooling when the heat gains within it exceed the ability of the available heat loss mechanisms to dissipate the heat while maintaining the indoor temperature at an acceptable level.

2.2.2. Typically, heat gains arise from solar gain through windows, walls and roof, and heat emitted from lighting and equipment and by occupants. Heat gains and losses from air conditioning and other building services systems, and air leakage from ducts, also contribute to heat gains or losses. Most of the energy used by fans in order to move air also reappears as a heat gain to the conditioned space.

2.2.3. Although peak solar gains can be large they are infrequent and other, more persistent, heat gains are usually more important over the year as a whole. In offices, heat gains per m^2 of floor area from people and lighting are each typically around 12 W/m^2 plus about 25 W/m^2 from equipment. Peak solar gains may be of the order of 50 to 100 W/m^2 but average daily values are typically between 5 and 10 W/m^2. Thus solar gains are important for sizing but other factors are more important for annual energy consumption. In retail premises, heat gains from lighting are higher – typically between 20 and 50 W/m^2, but can be over 100 W/m^2 in jewellery shops[B].

2.2.4. Provided that the outdoor temperature is cooler than the indoor temperature, heat losses occur by conduction through the building fabric and by the exchange of outdoor air with room air by mechanical or natural ventilation. (If the outdoor air temperature is above the indoor temperature, there is a heat gain). The sensitivity of cooling demand to outdoor temperature is therefore largely determined by the levels of insulation and ventilation.

2.2.5. For a given level of heat gains, the need for cooling (or heating) depends on the outdoor temperature: at some value, often referred to as the base temperature or self-heating temperature, the space is in thermal equilibrium. At lower temperatures there is a heating need, at higher ones a cooling need. The value of the base temperature depends on the level of heat gains, the ventilation rate and the level of insulation of the building. Increasing the insulation level has two effects: it reduces solar heat gain through the building fabric (solar energy is absorbed at the outer surface either reducing heat loss or causing heat gains); and by reducing heat losses it lowers the base temperature, so cooling is required at lower outdoor temperatures. In new office buildings, the base temperature above which cooling is needed may be 12 ^{o}C or lower. In systems with “tempering” of supply air – as described in Annex E – there may be a cooling load at outdoor temperatures as low as 5 ^{o}C.

[B] Display lighting is often provided by halogen lamps which are less efficient than the lamps such as fluorescent T8 and T5 tubes that tend to be used for general lighting.

2.3. Impact of preheating ("tempering") of supply air

2.3.1. In spaces with high heat gains or high levels of insulation there will therefore be cooling loads at relatively low outdoor temperatures. In principle, the supply of uncooled outdoor air can partially or completely offset these loads – a mechanism known as "free cooling". However, in order to avoid discomfort due to cold draughts, the temperature difference between the supply air and room air must be limited.

2.3.2. Because different types of air supply terminals create different airflow patterns within a room, the maximum acceptable temperature difference between supply and room air varies between different terminals (and therefore types of air conditioning system), varying between 4 and 10^{o}C. For example, the (cold) air supply jet from a ceiling diffuser will initially "attach" itself to the ceiling above the occupied part of the room. Its temperature will rise as it entrains warmer room air and (as long as it is not deflected by light fittings or other irregularities), a relatively high initial temperature difference is acceptable.

2.3.3. In order to maintain the temperature difference at an acceptable level, and thus avoid cold draughts, the supply air may be "preheated" (or "tempered"); this generates an additional demand for heating. As a result, the free cooling effect is reduced (and results in an increased cooling demand compared to the absence of supply air temperature restrictions). As the supply air temperature is now maintained at a constant level, sensitivity of the cooling demand with outside temperature is now determined only by conduction through the building fabric and the base temperature is lower. The importance of these effects on annual consumption is clearly dependent on climate.

2.3.4. All-air systems are designed to recirculate room air such that the temperature of the mixed outdoor air and recirculated room air meets these criteria and does not therefore require preheating. Natural ventilation by window opening is not amenable to preheating and it is assumed that users control the window opening to maintain comfort.

2.3.5. Individual room air conditioner units in naturally ventilated rooms do supply cooled air at lower temperatures – but not generally at ceiling level – and, anecdotally, are more likely to give rise to complaints of cold draughts.

3. Installed Stock

Detailed information on the installed stock of air conditioning systems in the UK is sparse but the majority of systems are in office and retail buildings.

3.1. Information provided to DECC by the Valuation Office Agency (VOA) has provided information on the total floor space for the four main building types (offices, shops, warehouses and factories) for England and Wales in 2012. A more detailed stock breakdown identifying the proportion of the building stock with full or partial air conditioning was requested, but was not provided within the timeframe of this study. However, VOA data on the proportion of buildings with air conditioning for 1994 is provided in Annex A, together with rough estimates for 2009.

3.2. Comparing the 1994 and 2012 floor area data shows that there has been a 9% increase in the floor area for the four main building types over the period. However, the changes within each building category are much more significant with warehouse space more than doubling and factory floor area decreasing by around 80% between 1994 and 2012. This information is presented in Annex A.

3.3. In 1994 there was estimated to be just over 39 million m^2 of air conditioned space in England and Wales. 54% of this was in offices and 38% in retail premises. 58% was in South East England including London.

3.4. Estimates of stock growth based on sales and lifetimes of products[1,2], suggest that the total cooling power of installed systems has a cooling power about 2 ½ times that of 1994, with most sales during the period being for offices and retail premises[C]. Since floor area has increased at a slower rate than this, market penetration must have increased.

3.4.1. Projections based on this stock modelling show that the market penetration of air conditioning is likely to continue to increase, although at a declining rate, for at least two decades. During this period the proportion of sales which are of replacement products will increase, perhaps reaching 50% by 2020.

3.5. The sample of EPC data and inspection reports covered a cooled floor area of just over 1 million m^2 of air conditioned space, with 38% in retail premises, 37% in offices and 13% in hotels. 38% of the floor area was in London and

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[C] Rough estimates for 2009 indicate that buildings with air conditioning installed accounted for around 30% of total retail floor area and around 65% of total office floor area in England and Wales.

the South East. The sample contains information about the types of system installed and includes a small proportion of (often inherently inefficient) system types that are rarely installed today. Central systems using chillers and split and VRF systems were both found in all the major sectors, but the majority of office space was cooled by central systems and most retail premises used split systems or VRF systems.

3.6. Analysis of the EPC data sample appears to show no relation between property size and proportion of cooled area, although there are discernible variations in the proportion of cooled area between building types. Most building types have around 70-80% of their floor area cooled, but in primary health care, hospitals and warehouses, this proportion falls to around 50%.

4. Annual Electricity Consumption

This section brings together information from various elements of the study relating to the annual electricity consumption for cooling and some of the reasons that it differs between systems. Where available, information on electricity use by fans and for heating is also reported. More details can be found in Annexes C, D and E.

4.1. Electricity consumption for cooling in offices

4.1.1. Long-standing benchmarks for the intensity of electricity consumption for cooling in existing offices are for typical consumptions to be in the range 31 to 41 kWh/m^2 pa, with “good practice” consumption levels of 14 to 21 kWh/m^2 pa.[3] The “cost-optimal” level for new offices, calculated for the Energy Performance of Buildings Directive (EPBD), is 9 kWh/m^2.[4]

4.2. The median calculated intensity (weighted by consumption) for the 99 offices in the Energy Performance Certificate sample was 30 kWh/m^2. However, buildings where the average consumption was above the 40 kWh/m^2 pa “typical” benchmark intensity accounted for 30% of the total cooling energy in the sample. Although the efficiency of new systems may be expected to be better than that of older ones, the benchmarks seem to be still appropriate. Since the calculations are based on standardised occupation patterns, indoor temperatures and equipment use, the variations of intensity must result from other factors. These include building design, the range of activities within the spaces in the building (different activities have different assumptions for occupancy and energy use by and heat emission from equipment), heat gains from lighting (lighting system characteristics are entered by the assessor), location and system efficiency.

4.2.1. From the information contained in the EPC report it can be inferred that variations of equipment energy use are associated with nearly 50% of the variance of air conditioning consumption. (In addition to the direct heat emissions from equipment, use may be correlated with occupancy). Although the lighting energy consumption intensity – kWh/m^2 pa - is of similar magnitude to that of equipment, it shows a much greater variation and accounts for a much smaller proportion of the variation in air conditioning energy consumption than for equipment. In part this may be because in day-lit spaces, lighting will often not be used at times when cooling demand is high (during the day and when the weather is warmer). A further 10% of the variance is related to system effects (system efficiency and the presence of different types of system within the same building), The remaining variation is presumably due to variations of building design or location. Reported cooling consumption figures from simulation studies are typically in the range 5 to 15 kWh/m^2 pa for buildings and systems designed during the last 10 years, and up to 45 kWh/m^2 pa for older types of system such as dual-duct or induction systems which are rarely now installed (but are present in small numbers in the EPC sample).

4.2.2.

4.2.3. In contrast to the EPC calculations, 77% of the electricity used for cooling in the monitored buildings (adjusted to London weather) was in buildings with consumption intensities of over 40 kWh/m^2 pa. (64% above 45 kWh/m^2 pa). This could be caused by several factors, of which the most obvious is that calculated consumptions assume that systems only operate at times when they are required to do so while actual operation may not be as well controlled. However, differences in system efficiency, building design, occupation pattern and location are all possible contributors. The measured consumptions showed no systematic variation with the floor area serviced or the type of system, beyond a tendency for chilled ceilings (which are unlikely to be used in spaces with high cooling loads) to have slightly lower consumptions.

4.2.3.1. The impact of location was examined by adjusting the consumptions to reflect the distribution of outdoor temperatures at each of 14 UK sites. Consumptions based on London weather were the highest at 17% above the (unweighted) average: figures for Belfast, Edinburgh and Glasgow were the lowest at 8% to 10% below the average.

4.2.4. Based on the monitored data, there is considerable variability from system to system of the annual use of electricity for cooling per unit of conditioned space. This is not a consistent function of floor area or of system type, and is greater than variations between different locations in the UK. Comparisons with calculated consumptions in EPCs suggest that, while building design probably accounts for a significant proportion of the variation, system use and building occupation patterns are also significant. The “equivalent full load hours” consumption metric discussed in section 5 below has less variation but exhibits similar patterns.

4.3. Electricity consumption for cooling in other types of building

4.3.1. Retail buildings are the second most important market sector for air-conditioning in terms of floor area, but there is very little information on electricity consumption, and there are no public benchmark values. It has been reported that in a typical hypermarket, 29% of electricity consumption is for refrigeration (excluding air conditioning), 23% for lighting (and contribution to cooling loads) and 9% for air conditioning [5] The calculated EPC electricity consumptions have a much larger range of intensities than for offices, with a median intensity (weighted by energy) of between 110 and 115 kWh/m^2 pa - more than 3 ½ times the equivalent value for offices. These may mean that total electricity consumption for air conditioning in the retail sector is higher than in offices, despite its smaller total floor area. About 50% of the variance is accounted for by variations of system efficiency. Smaller retail units typically have split systems, while large stores may have central systems. Variation of energy use by equipment is associated with approximately another 1/3 of the variation of air conditioning electricity use. The remainder of the variation of air conditioning consumption is associated with variations in lighting energy consumption. Although the average calculated energy consumption by lighting is higher than that for equipment, its variability is similar. Lighting energy intensity (including display lighting) is known to be very variable in retail premises, and can be extremely high. When calculating an energy performance rating, equipment energy consumption is determined by the type of retail activity, while the descriptions of lamps and lighting systems are input by the EPC assessors.

4.3.2. The median intensity for restaurants is 50 kWh/m^2 pa, with a narrower range than for offices. Air conditioning is mostly by split and VRF systems and variations in system efficiency account for about 50% of the variance.

4.3.3. The median intensity for hotels is 35 to 40 kWh/m^2 pa, with a narrower range than offices. The calculated cost optimal level for new buildings is 7 kWh/m^2 pa, but comparisons are difficult because of the wide range of activities that may be found in hotels, and differences in the provision of air conditioning between different types of space. Air conditioning is mostly by split and VRF systems and variations in system efficiency account for about 60% of the variance.

4.4. Policy implications for efficiency of lighting and equipment.

4.4.1. The (calculated) air conditioning electricity consumptions in EPCs depend on the magnitude of each driving factor (as determined by the assessor’s data inputs including activity choices) and the (calculated) sensitivity of air conditioning consumption to the factor in question. From the analysis above, it appears that in the two principal market sectors of interest – offices and retail - the sensitivity of electricity consumption for cooling to consumption by equipment is higher than to that for lighting (though both contribute to cooling load). Per kWh of reduced consumption, reductions to equipment consumption are the more important. This remains the case in retail premises even though electricity consumption for lighting is typically twice that for equipment.

4.5. "Rest of system" consumption in offices.

4.5.1. Simulation studies show that in centralised systems, fans (especially) and other system components consume comparable amounts of electricity to that used for cooling.[6] (Most of which is converted into heat and adds to the cooling demand). All-air systems are calculated to have particularly high consumptions. This is reflected in the calculated EPC data as a major component of "auxiliary energy", and is calculated as the product of specific fan power[D] (SFP - entered by the assessor), air flow rate (set as the higher of two requirements set respectively by occupancy levels and system type) and hours of operation (set by the activity assigned to spaces). Benchmark figures are "typical" 60 to 67 kWh/m^2 pa; "good practice" 30 to 41 kWh/m^2 pa.

4.5.2. Unfortunately, SFP values are not retained in the EPC database. Although air conditioning inspectors are asked to estimate SFP, it was rarely reported in the inspection reports.

4.5.3. "Rest of system" consumption was only recorded for some of the monitored systems, and it was often not clear which components were included. The information that was available did not contradict expectations from simulations but was too fragmentary to confirm it.

[D] It is a measure of the electric power that is needed to drive a fan (or collection of fans), relative to the amount of air that is circulated through the fan(s). It is not constant for a given fan, but changes with both air flow rate and fan pressure rise.

5. Peak power and Annual Load Factor

The monitored data were analysed to produce standardised peak half-hourly power demands for each system and location and are detailed in Annex D. These were lower than would be expected from industry guidelines for design cooling power or from the installed cooling capacity but broadly comparable with other measurements and simulation results. Values of “equivalent full-load hours” (EFLH) were derived as the ratio of annual electricity consumption to peak power. The higher than expected consumptions and lower than expected peak power levels resulted in high values for this parameter.

5.1. The values of peak electrical power are in the range 20 to 30 W/m^2 which is slightly higher than the median value found in a European project[7] and, depending on the efficiency of the cooling plant, is equivalent to a peak cooling power of perhaps 50 to 75 W/m^2. This is slightly lower than peak loads from simulations, which are typically between 60 and 100 W/m^2.[8] Design rules of thumb[9] for general office areas are somewhat higher at 65 to 125 W/m^2 or 120 to 180 W/m^2 for areas close to windows. (The equivalent figure for retail premises is 140 W/m^2 though simulated values appear to range between 35 and 95 W/m^2).[10] To provide resilience, the rules of thumb have to take account of the possibility of heat gains that are above the norm, so are likely to be set at relatively high “safe” levels.

5.2. There is a general trend for systems with higher consumption to have higher peak power levels. The ratio between annual consumption in kWh pa and peak power in kW, is the EFLH value. For the monitored sample and London weather the mean EFLH value is 2145 hours, with a standard deviation of 1248 hours, illustrating the wide variation between systems. (However, the variation is less than that found for annual consumption; where the respective coefficients of variation are 0.58 and 1.09.) There is no consistent variation with floor area or system type, although there is more variation for systems serving small areas; these systems are mostly split or VRF systems. The EFLH value is less variable than the consumption intensities and so is a better basis for estimated aggregate electricity use provided that peak power levels are known or can be estimated accurately. As already noted, spaces with higher consumptions seem likely to be subject to more variable levels of heat gain and these system types permit more control by individual users.

5.3. Average EFLH values for different locations were also calculated. While peak power is a function of external temperature range, consumption depends on the distribution of temperatures throughout the year. The highest values (at Leeds) were 19% higher than for the lowest (Belfast) – again showing less variability than for annual consumption figures.

6. Monthly weightings

The distributions of cooling electricity consumption between months were calculated for each system and for each location and these are also detailed in Annexe D. There were significant differences between different systems and between the average distributions for different locations. Overall, 30% of the cooling consumption was in the six months between November and April.

6.1. With London temperatures, the peak month for electricity consumption for cooling was July, which accounted for 19.2% of consumption on average and between 9% and 54% for particular systems. The proportion of consumption in each of the months November to April inclusive did not vary significantly for any system. (It was zero for one system).

6.2. At most locations, the highest monthly average consumption was in July; averaging 17.6% of annual consumption, although in Glasgow, Edinburgh and Norwich the highest consumption was in August. The location with the highest value was Newcastle at 20% and the lowest was at Southampton at just over 15%. Differences between locations were most marked in June, July and August. Nearly 31% of annual consumption took place in the six months between November and April. In these months, variations of consumption between locations and months were small, reflecting the fact that most of the consumption was associated with “baseload” consumption rather than related to outdoor temperatures.

7. Product and System Lifetimes, Efficiency and developments

There is little empirical information about the distribution of products of different efficiencies in the stock, or of current sales. The EPC data provides a degree of insight but many of the entries are default values.

7.1. Industry estimates of product lifetimes were obtained from the literature search. 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 Air Handing Units (AHUs). Metal ductwork has an expected life of 40 years as long as it is maintained. Separate estimates from analysis of market research data and curve-fitting generally agree with these values, except that the best-fit lifetime for chillers in the UK was significantly longer at 31 years. (The same technique applied in other European countries yields values close to the industry estimates.) This might reflect the relatively low operating hours in the UK. (The curve-fitting also shows that about 40% of the 2009 chiller stock was 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.) In the inspection reports, 28% of systems contained the refrigerant R22 which indicates that this equipment is at least fifteen years old.[E]

7.2. Europe-wide information on the efficiencies of products placed on the market is accessible from the voluntary but widely-used Eurovent-Certification scheme, but this contains no information about the sales of each product. This information shows that the full-load efficiency (EER) of the best cooling products on the market has improved over the last 10 years, and the average value (by product) has slightly improved.

7.3. The most significant change has been the adoption of a seasonal efficiency metric (SEER)[F], initially by Eurovent-Certification and more recently by the Energy-related Products Directive. Since air conditioning cooling generators

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[E] From 1st January 2004: HCFCs, including R22 refrigerant, was banned for use in new air conditioning systems throughout the EU. From 1st January 2010: virgin R22 refrigerant was banned for use in maintenance and repairs. From 1st January 2015: all R22, including recycled and reclaimed refrigerant, was banned for use in maintenance and repairs

[F] The SEER rating of a unit is the cooling output during a typical cooling-season divided by the total electric energy input during the same period.

operate predominantly at part load, part-load efficiency is of more practical importance than full-load efficiency. Since the introduction of energy labelling for smaller products, the number of highly-rated products has markedly increased and the number of high-efficiency chillers on the market has also grown.

7.4. EPC assessors are encouraged to overwrite the default values for SEER when they can justify higher values, but this had been done for only 40% of EPCs. (Use of the default value triggers a recommendation to consider replacement). In Table 1 the default values are in the “2 to 3” column. The actual efficiencies are unknown but could be better or worse than the defaults. Current and imminent minimum performance requirements for the Energy-related Products Directive are in the range 3.5 to 4.5 depending on the product. If the default values are taken at face value, this will represent a substantial improvement. However, with product life varying between 10 and 20 years (or more) depending on the product, the penetration of compliant products into the stock will require several decades.

7.5. The overall efficiency of central systems using chilled water or air is less than that of the cooling generator because of additional energy losses by air leakage from ductwork and air handling units and heat gain into chilled water pipes and air ducts. There were 24 recommendations to improve duct leakage from the 164 systems with ducts, but assessing the quality of airtightness on site is often difficult. Seasonal system efficiencies are calculated by the EPC software using assessors’ estimates (or default values) of SFP and air leakage but these values are not accessible from the database. Calculated overall system efficiencies range from 0.6 to 3.1.

System type	**Number of reported SEERs in range**				
	< 2	**2 to 3**	**3 to 4**	**4 to 5**	**>5**
Active chilled beams		1			
Chilled ceilings or passive chilled beams		2		2	
Constant volume system (fixed fresh air rate)	1	26	3	1	
Constant volume system (variable fresh air rate)		12	1		
Dual duct CAV (constant air volume)		1	1		
Dual-duct (VAV) (variable air volume)		4	3		1
Fan coil systems		39	13	5	1
Indoor packaged cabinet VAV (variable air volume)[G]		4	2		
Induction system		3			
Single room cooling system		15	3	1	
Single-duct VAV (variable air volume)	1	7		1	
Terminal reheat (constant volume)		1			
Water loop heat pump		1			
Split or multi-split system	3	401	146	23	12

Table 1: Distribution of SEER values from EPCs

7.6. Recent innovation in air conditioning systems for buildings has been - and seems likely to remain - largely in the form of incremental engineering improvements to existing products and systems rather than through radical change. Apart from redesign to reflect restrictions on the choice of refrigerants, the main developments in recent decades have been: improvements to part-load cooling efficiency; an increase in the range of reversible systems that also provide heating; and continuing technical development (and growing market share) of variable refrigerant flow (VRF) systems that use refrigerant as the distribution medium. Many VRF systems have the ability to recover heat extracted from spaces that require cooling and re-use it in spaces that (simultaneously) have a heating need. The planned phase-out of refrigerants with high global warming potential has already resulted in the development of new refrigerants such as HydroFluoroOlefins (HFO) and HFO/HydroFluoroCarbons (HFC) blends. More generally, product efficiency still falls short of the theoretical Carnot[10] levels so there remains potential for improvement, though the engineering challenges are significant.

7.6.1. Several types of system – not all of recent development – currently occupy niche markets in the UK.

[G] Unlike constant air volume (CAV) systems, which supply a constant airflow at a variable temperature, Variable air volume (VAV) systems vary the airflow at a constant temperature.

- Systems not using vapour compression technology: adsorption, absorption and liquid and solid desiccant systems can make use of waste or renewable heat[H].
- Engine-driven systems replace the electric motor of the cooling generator by a fossil- or biomass- fuelled engine, sometimes as part of a combined heat and power system.
- Large, reversible ground-source heat pump systems in which the ground provides seasonal thermal storage. These are now an established technology for large commercial developments. An added advantage is a reduced need for conventional heat rejection equipment on rooftops.
- Short-term thermal storage to reduce peak electricity demand can be provided by ice or other latent heat storage, but reduces overall efficiency in the UK climate.
- Decentralised systems using local air handling units have lower fan energy consumption and can provide local time and temperature control, but require additional wall penetrations.
- Embedded emitters (typically within ceilings and floors) are used in some European countries (and occasionally in the UK). They enable the use of higher chilled water temperatures which should, in turn, improve cooling efficiency (as do conventional chilled ceilings) and lower peak cooling demands (because of the effect of the thermal capacity of the building structure) but are best suited to applications where 24-hour cooling is required.

7.7. Magnetic cooling is perhaps the only significant emerging technology, based on the magnetocaloric effect[12]. This technique can be used to attain low temperatures and is claimed to be potentially safer, quieter, more compact, and have a higher cooling efficiency than vapour compression methods. Current commercialisation effort is directed to room temperature applications with the announcement of a “proof of concept” prototype wine cooler in 2015.

[H] In 2008 these systems constituted less than 1% of air-conditioning chillers (by cooling power). Absorption chilling is mostly used in industry where there is a ready supply of heat.

8. Algorithm for modelling monthly electricity demand from air-con

An algorithm has been developed which allows the estimates of annual electricity consumption for air conditioning produced by DECC’s Product Policy model to be apportioned between months. The algorithm also produces standardised peak power values and corresponding EFLH figures. In addition, it can be used to adjust annual and monthly consumptions for outdoor climate data relating to different locations and for projections of possible future climate change. The impact of changes to internal heat gains and insulation levels of buildings can also be explored with the algorithm. The monitored data provide empirical values for key inputs to the model, albeit from a limited sample size. The literature search and other parts of the study also provide insights into the choice of input data – these are summarised separately under the appropriate headings in this report.

8.1. The basis of the algorithm is a generalisation of the existing concept of energy signatures – used, for example, in degree-day calculations - to include features of air conditioning systems that are not present in heating-only systems. The energy signatures are combined with daily temperature data for a particular location to produce standardised monthly consumptions and apportionment factors. The definition of an energy signature requires some knowledge of characteristics of the systems and buildings being analysed and example signatures have been produced for the monitored systems in offices. An alternative source (of idealised signatures) would be by simulation of buildings and systems - ideally these would also take into account factors (such as weekend operation and base-load consumption) that were observed in the monitored systems. Temperature data for 14 “Test Reference Years” (TRY) and summer design years for UK sites are available from CIBSE; the TRY years have been used in this study. Additional temperature data sets are available for climate change projections and for the London urban heat island.

8.2. Peak power estimates are also derived from energy signatures, in conjunction with an additional term to take account of within-day variations; such as time-of-day effects, and day-to-day effects that are not related to outdoor temperature (including solar gains). Peak power and EFLH values are discussed in section 5 of this report.

8.3. The explicit study requirement for input data for the product policy model was for EFLH figures. The values extracted from the monitored data were significantly higher than the current default values in the model (which are themselves higher than simulations of ideally-controlled systems). In practice, the effects of this difference are largely offset by the fact that the model does not account for the installation of surplus cooling capacity; in the monitored sample this was considerable.

9. Operation and Maintenance

There is evidence that imperfect operating practices result in a significant wastage of energy and that the quality of system maintenance is patchy. Air conditioning inspections identify some poor practice and recommend actions to correct them, but it is not known how frequently these are acted on.

9.1. Published European studies[13] have identified that better operating practices applied to air conditioning systems offers potential energy savings of similar magnitude to those from load reduction or use of equipment of higher efficiency. In addition, many of the recommendations from system inspections relate to control settings (but do not identify other operational weaknesses such as unnecessary operation, which would require consumption data to identify).

9.2. The data from monitored buildings supports this contention to the extent that observed average electricity consumption was significantly higher than calculated values and there was evidence of unnecessary operation at weekends and probably overnight.

9.3. The analysis of air conditioning inspection reports confirmed that the most frequent recommendations related to operation and maintenance issues.

9.3.1. While 82% of systems were reported to be “well maintained by competent staff”, 65% of these had specific recommendations that related to maintenance issues, suggesting that the overall assessment may have related to the existence of a maintenance contract rather than to the quality of its implementation.

9.3.2. The majority of inspections were of split systems, most of which were in retail premises, but just over 50% of the cooling capacity was in large systems in offices. 44% were assessed as being “correctly sized” (relative to rules of thumb), with equal proportions being over- and under-sized. F-gas reports were only available for about 20% of the systems.

9.4. Cooling related recommendations may also be included in EPCs and analysis of these for a sample of buildings is presented in Annex C. As the EPC assessment process only considers the expected performance based on the installed equipment, the scope of the cooling recommendations provided will be much more limited than for Air Conditioning Inspection Reports.

9.4.1. In the EPC sample[I] of 490 buildings, a total of 229 cooling related recommendations were identified. The vast majority (98%) of cooling related recommendations in the sample EPCs were automatically generated; of these, 84% are a recommendation to investigate the efficiency of the chiller identified, regardless of whether there is any potential for improvement. This recommendation is the most frequent because it is automatically generated whenever a default value is entered into the EPC calculation.

9.4.2. If the automatic "default chiller" recommendation is excluded from the analysis, 48% of the remaining recommendations relate to reducing ductwork leakage[J]; 34% for replacing chillers and other system components; 8% metering and monitoring; 6% were related to controls; and 4% various other recommendations.

9.4.3. Table 2 compared the relative frequency of recommendations from the ACIR and EPC analysis.

[I] The EPC and ACIR samples are both drawn from the initial sample of 500 buildings, but have a small number of different individual buildings missing, so the samples are very similar but not entirely identical.

[J] Duct leakage is primarily a maintenance issue

Description	% Air-Conditioning Inspection Report Recommendations	% EPC Recommendations
Controls	27%	6%
Maintenance	16%	48%[K]
Documentation	10%	
Staff training	10%	
Metering & Monitoring	8%	8%
Refrigerants	7%	
Equipment	7%	34%
Internal heat gains	4%	
System sizing	4%	
External heat gains	3%	
Renewable energy	2%	
Others	2%	4%

Table 2 Key Recommendations from Inspection Reports and EPCs

10. Options for the reduction of electricity consumption

Previous analyses have shown that the potential for reducing electricity consumption for air conditioning can be divided into three areas of comparable importance, each presenting different policy challenges: load reduction, system efficiency and operational and maintenance practice. It is difficult to place policy options in a robust order of priority – this section summarises options together with their strengths and weaknesses. The options are classified into three types, those that: are primarily focussed on other energy uses but which have an impact on air conditioning; are specifically directed at air conditioning system components; or have a wider scope which includes air conditioning.

10.1 Since the installed stock of air conditioning systems is projected to increase for at least the next decade, in a "business as usual" scenario, electricity consumption by air conditioning systems will also increase.

10.2 Annex F presents the UK results from the modelling study; "Study to assess barriers and opportunities to improving energy efficiency in cooling appliances/systems"[14], which was carried out in 2012 by BRE and was funded by CLASP[L]. This study identified and quantified the potential impact of a range of potential energy performance improvement measures and policy instruments which comprised packages of these energy efficiency measures to reduce energy consumption over a ten-year period, relative to a business as usual case.

10.3 The study takes account of practical constraints and identifies the "realisable savings" that would accrue, taking into account the replacement rate of air

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[L] Collaborative Labelling and Appliance Standards Program conditioning systems and components, refurbishment rates of buildings and rates of market growth.

10.4 This study uses a purpose-built model, which takes into account inter alia climate; system type; system and product efficiency; product and system replacement rates; building type; and difference of cooling demand between existing and new buildings.

10.5 Potential energy savings were modelled for a range of different energy performance improvement cases which modelled the potential impact of energy labelling; minimum energy performance standards for chillers and other system components; reducing air leakage rates; reducing the cooling load; and reducing ventilation air flow rates. The energy savings attributable to each energy performance improvement case was calculated for both the existing (2010) stock of air conditioning systems and for new installations between 2010 and 2019.

10.6 The study was carried out before the introduction of eco-design requirements for air conditioning and so these are not included in the base case. However, the minimum energy performance standards (MEPS) for room air conditioners (RAC) <12kW, which were introduced in March 2012, approximate to the energy efficiency improvement case “RAC proposed MEPS”, which correspond to light MEPS. The moderate and demanding MEPs for chillers approximate to the minimum performance levels in the 2015 draft eco-design requirements proposed for 2018 and 2021, respectively. However, it is not possible to make a direct comparison between the as the performance levels set with the eco-design requirements vary depending on the product type, its cooling capacity and the global warming potential (GWP) of the refrigerant used.

10.7 These energy performance improvement cases were used as a basis for estimating the savings that could potentially be achieved by applying a range of policy instruments. These are identified as follows:

- Moderate product Minimum Energy Performance Standards (MEPS) for moveable units, Room Air Conditioners (RACs), Chillers, AHUs and Ductwork. These would apply to all new installations and are set at a level that would probably be cost-effective from an end-user perspective.
- Demanding product Minimum Energy Performance Standards (MEPS) for moveable units, RACs, Chillers, AHUs and Ductwork (Demanding products MEPS); These would apply to all new installations and are set at a level that is expected to be cost-effective from the societal perspective.
- Reduced fresh air rates (Reduced fresh air) applied to all new and existing installations of centralised systems. The policy component would be expected to be cost-effective from the societal perspective and, also in many cases from the end-user perspective

- Moderate system Minimum Energy Performance Standards (MEPS) applied to all new installations of centralised systems and are set at a level that would be cost-effective, in most instances, from an end-user perspective.
- Load Reduction: This relates to improvements to the building envelope and applies to all new and existing installations. It is set at a level that could realistically be achieved cost-effectively at the UK level from a societal perspective.
- Inspection: This relates to improvements to the way in which central cooling systems are operated in response to an inspection. These savings relate to controls and behavioural improvements that could realistically be achieved cost-effectively at the UK level from a societal perspective.
- Detailed Audit: This relates to improved operation (as outlined in inspection above), plus the implementation of recommendations for component upgrade identified during a more thorough inspection process, and possibly linked to operational benchmarking. The level of component upgrade relates to the moderate system MEPS outlined above. The savings identified equate to a level that is potentially cost-effective at the UK level from a societal perspective.
- Moderate MEPS Building and system: This relates to MEPS being applied at the building level, where the level of savings is defined by the combined effect of moderate system level MEPS in addition to load reduction measures applied to the building envelope. The savings identified therefore equate to a level that could realistically be achieved cost- effectively at the UK level from a societal perspective.

10.8 However, there are some inherent difficulties in estimating the scale of potential savings for some of these instruments; in many cases they interact. For example, improving the efficiency of cooling generators reduces the energy-saving potential (and cost-effectiveness) of measures to reduce heat gains or to improve day to day operation. They may also have side effects – reducing heat gains from office equipment increases the need for heating. Thus the choice of an initial action can affect the viability of subsequent – there is an element of “path dependency” (which is not explored here).

10.9 The estimated realisable savings arising from these energy savings measures for the period 2010 – 2019 is provided in Table 3 and presented graphically in Figure 1.

Energy Savings Measure	Installations	Realisable Savings (Cooling)	Additional Savings (Ventilation)
Moderate RAC MEPS	New	2.8	-
Demanding RAC MEPS	New	4.6	-
Moderate Chiller MEPS	New	1.0	-
Demanding Chiller MEPS	New	3.0	-
Demanding AHU MEPS	New	0.6	-
Ductwork MEPS	All	10.5	-
Reduced Fresh Air	All	1.8	5.2
Moderate System MEPS	New	0.1	0.4
Load Reduction	All	1.1	8.5
Inspection	All	3.7	3.7
Detailed Audit	All	7.8	2.4
Moderate Building MEPS	All	1.3	4.2

Table 3: Estimated Cumulative Realisable Energy Savings for the UK from Selected Energy Savings Measures over 10 years (2010-2019) in TWh

10.10 Inspection assumes savings will be made through improvements to controls and behaviour change; whilst detailed audit encompasses controls, behaviour change and component replacement, including system switching. Moderate building Minimum Energy Performance Standards (MEPS) is a combination of load reduction and system level MEPS.

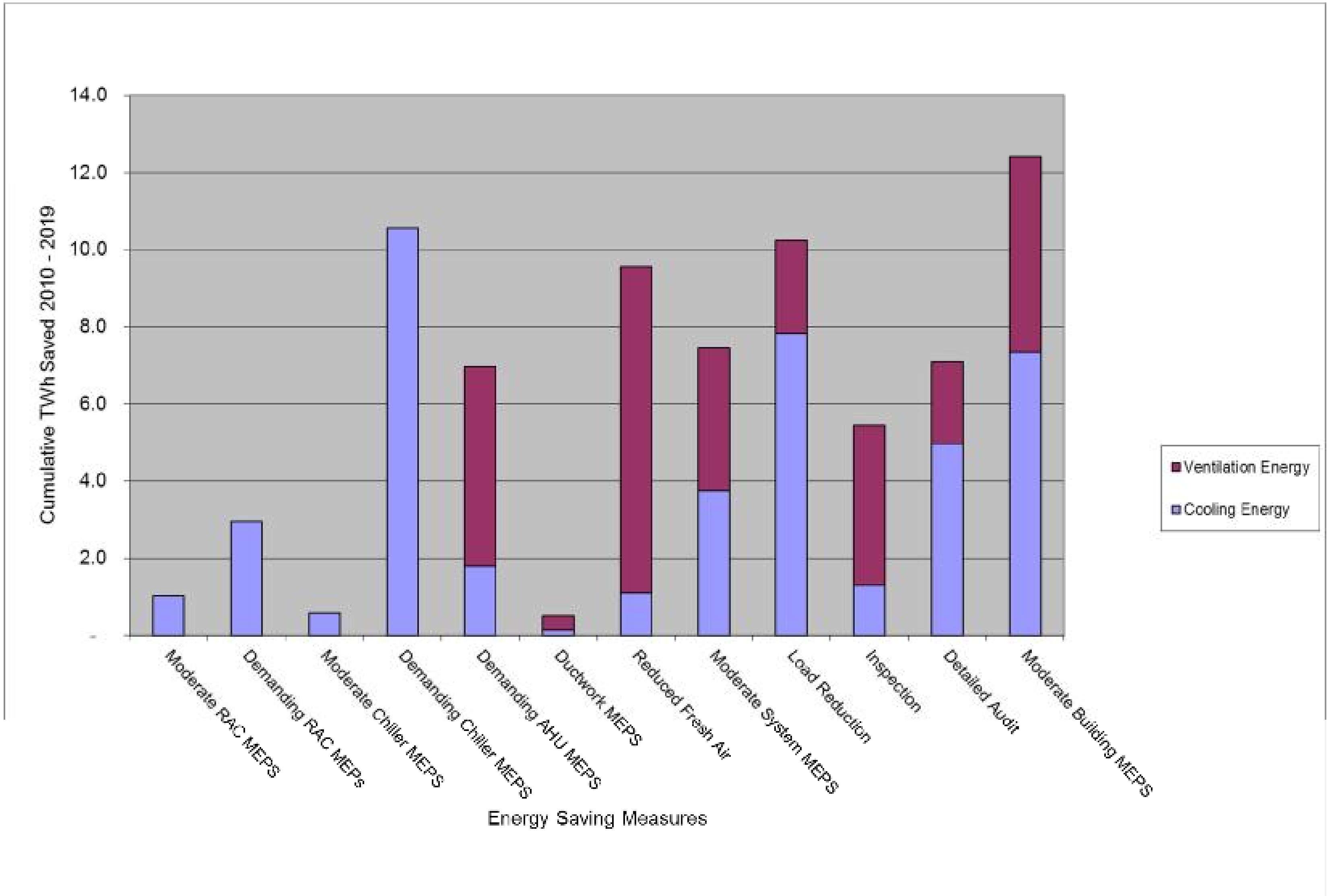

Figure 1: Estimated Cumulative Realisable Energy Savings from Selected Energy Saving Measures over 10 years (2010-2019) in TWh

11. References

[1] E.R. Hitchin. Future environmental impacts of room air-conditioners in Europe, Building Research & Information 37 (4) (2009)358–368.

[2] R. Hitchin, C. Pout, P. Riviere. Assessing the market for air conditioning systems in European buildings, Energy and Buildings 58 (March) (2013)355–362.

[3] Energy Consumption Guide 19: Energy Use in Offices, 1998,http://www.cibse.org/pdfs/ECG019.pdf (accessed December 2013).

[4] DCLG Energy Performance of Buildings Directive (recast) Cost optimal calculations: UK report to European Commission May 2013 https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (accessed November 2015)

[5] Tassou SA, Ge YT, Hadawey A and Marriott D (2011) Energy consumption and conservation in food retailing. Applied Thermal Engineering 31: 147–156.

[6] EDSL Comparative energy consumption of air conditioning systems: simulation study BRECSU 07/0 2001.

[7] Ian Knight, Power demands of heating, ventilation and air conditioning components in EU Buildings, REHVA Journal May 2014

[8] Jenkins D, Banfill B, Pellegrini-Masini G Non-domestic conclusions of the Tarbase project – Reducing CO_2 emissions of existing buildings, Energy Research Group, Heriot-Watt University, undated.

[9] Rules of Thumb - Guidelines for building services (5th Edition) (BG 9/2011)

[10] BSRIA Blue Book 2013, BSRIA 2012

[11] John Murrell (2009). "A Very Brief History of Thermodynamics". https://web.archive.org/web/20091122191251/http://www.sussex.ac.uk/chemistry/documents/a_thermodynamics_history.pdf

[12] Gschneidner, K. A.; Pecharsky, V. K. (2008). "Thirty years of near room temperature magnetic cooling: Where we are today and future prospects”. International Journal of Refrigeration 31 (6): 945

[13] I. Knight, et al., HARMONAC – Harmonizing Air Conditioning Inspection and Audit Procedures in the Tertiary Building Sector Energy Final Report, 2012 http://www.harmonac.info/fileadmin/downloads/docs/home/HARMONAC%20FINAL%20Report%20-%20Public%20Version.pdf (accessed December 2013)

[14] Pout C, Hitchin R and Butler D “Study to assess barriers to and opportunities for improving energy efficiency in cooling appliances/systems, Prepared for CLASP, March 2012,

https://www.bre.co.uk/filelibrary/pdf/rpts/Realisable_enegry_savings_in_European_air-conditioning.pdf