MEASURED BUILDING AND AIR CONDITIONING ENERGY PERFORMANCE: An empirical evaluation of the energy performance of air conditioned office buildings in the UK.

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Abstract
Building on previous papers presented on this topic at IEECB 2004 and IEECB 2002, this paper presents further findings from an energy monitoring study of the energy and carbon performance on air conditioning systems in 32 UK office buildings over a period of three years with the aim to aid the development of improved guidance on the appropriate use of air conditioning systems, and to help identify strategies to achieve national carbon emissions reduction targets.

This paper focuses on the building energy use and carbon emissions from 27 buildings in which the air conditioning systems have been monitored derived from energy billing data and monitoring and targeting (M&T) data. The results presented include analysis of the overall energy consumption and associated carbon emissions of each building studied, comparisons to the relevant UK national benchmarks, breakdown of energy use by fuel type and identification of the proportion of energy used and carbon emissions attributable to cooling purposes.

The results indicate that current UK national Office energy consumption benchmarks are probably set at the correct level, and also show that the higher overall energy consumption of air conditioned buildings is NOT inherently due to the use of AC systems, but is as much to do with other building end-use. The buildings monitored with low HVAC energy consumption did not necessarily lead to energy savings at the building level.

Keywords
Air Conditioning, Office Buildings, Monitoring, Energy Use, Carbon Emissions, Benchmarks, UK.

Introduction
The European Directive on the Energy Performance of Buildings (EPBD)[1], the promise of Emissions Trading Schemes (ETS), and fears about the security of energy supply. These are all strong drivers that are already changing the way we design our buildings. These drivers all have a common theme: they place a much greater emphasis on designing low carbon emission buildings and services.

One area that is marked out for particular scrutiny by current and forthcoming legislation is the energy consumption, and hence carbon emissions, of air conditioning systems. However there is very little information on actually how much energy AC systems consume when used in the real world, with all the imperfections this brings in design and maintenance, and which factors influence this consumption the most.

Aiming to fill this information gap, research undertaken at the Welsh School of Architecture[2] set out to collect empirical data on the actual performance of air conditioning systems ‘in practice’ in UK office buildings. The information collected would aid the development of improved guidance on the

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appropriate use and selection of air conditioning systems and help identify strategies to achieve the UK's national carbon emissions reduction targets.

This research has measured the energy consumption, and hence associated carbon emissions, of a number of air conditioned office buildings and their services 'in use' between April 2000 and December 2002.

The primary findings for this work focused specifically on the performance of the air conditioning systems have already been presented at a number of conferences[3,4,5] and further publicised in journals[6,7,8] and a project web-page[2], but the headlines include:

- Chilled ceiling and beam systems appear to be the most efficient way of providing comfort cooling in UK Offices where appropriate.
- Direct expansion (DX) cooling-only systems to a lesser also have the potential to be very efficient, but often fail to achieve their potential performance in practice due to poor operation.
- The control of the systems studied showed a response to internal loads, seasonal and daily variation in climate, but time control was typically poor. On average operating almost twice as much as expected indicating that a 50% saving in energy consumption and carbon emissions may be possible from more effective time control alone.
- Analysis of the part-load profiles of the systems studied showed that the majority of the systems generally had twice the capacity required for the actual loads served over the monitoring period and this over-sizing maybe in part due to current design practices which appear to over-estimate the internal cooling loads actually found in practice.
- All the generic types of air conditioning studied appear capable of meeting current UK 'good practice' energy consumption standards for comfort cooling on an individual basis, emphasising the importance of appropriate control, maintenance and operational management.
- A strong correlation was observed between recent computer design modelling of 'good practice' energy consumption and the monitored results suggesting that current modelling techniques appear accurate for comparative design assessment, but are less accurate at predicting actual energy performance of a given site without detailed operational parameters.

Overall the research to date has shown that AC systems as currently used in the UK show the potential for substantial improvements in system Carbon emissions performance, and significantly these improvements can be accomplished through existing technology.

Further analysis of this work is now underway[9] including a detailed analysis of fabric and solar loads in the office buildings studied[10,11] and analysis of other data collected including that discussed by this paper which focuses on the building energy use and carbon emissions from the buildings in which the air conditioning systems have been monitored.

The results presented include analysis of the overall energy consumption and associated carbon emissions of each building studied, comparisons to the relevant UK national benchmarks, breakdown of energy use by fuel type and identification of the proportion of energy used and carbon emissions attributable to cooling purposes.

Building Energy Consumption & Carbon Emissions

This section discusses the whole building energy consumption, and carbon emissions, from the buildings in which the air conditioning systems have been monitored. The whole building energy consumption data has been derived from site energy bills, or monitoring and targeting (M&T) data, collected with the owner's permission at each site. The data was collected with the aim of determining the overall energy consumption of each building relative to national benchmarks and to determine the proportion of energy consumed by air conditioning systems through comparison to the system performance data previously published.

The overall whole building energy consumption, and calculated carbon emissions, for each of the buildings studied is summarised in Table 1. The Table shows the total annual energy consumption for each building by each fuel type, the total delivered energy consumption, and the associated annual carbon emissions. All these values have been normalised to the treated floor area (TFA) of each building.

Table 1: Summary of Annual Whole Building Energy Consumption & Carbon Emissions

Site # / System Type	Electricity	Gas	Total Delivered Energy	Carbon Emissions
	kWh/m²	*kWh/m²*	*kWh/m²*	*KgC/m²*
Cooling Only Systems				
Site 1 - All-Air	215.6	13.0	228.6	31.3
Site 2 - All-Air	284.4	51.5	335.9	43.2
Site 3 - All-Air	n/a	n/a	n/a	n/a
Site 4 - All-Air	389.5	232.4	621.8	68.1
Site 5 - All-Air	294.9	226.9	521.8	54.4
Site 6 - All-Air	290.0	235.7	525.7	54.1
Site 7 - All-Air	204.3	130.0	334.3	36.2
Site 8 - Chilled Ceiling	247.3	99.3	346.5	40.6
Site 9 - Chilled Ceiling	n/a	n/a	n/a	n/a
Site 10 - Chilled Ceiling	76.9	141.0	217.9	18.7
Site 11 - Chilled Ceiling	159.9	0.9	160.9	22.8
Site 12 – Fancoils	286.1	67.2	353.4	44.3
Site 13 – Fancoils	232.6	9.8	232.6	33.6
Site 14 – Fancoils	352.7	165.9	518.6	59.2
Site 15 – Fancoils	n/a	n/a	n/a	n/a
Site 16 – Fancoils	n/a	n/a	366.4	32.4
Site 17 - DX Split	n/a	n/a	n/a	n/a
Site 18 - DX Split	137.6	168.2	305.8	28.8
Site 19 - DX Split	438.2	85.0	523.2	66.9
Site 20 - DX Split	110.5	n/a	110.5	15.7
Site 21 - DX Split	112.1	42.8	154.9	18.3
Site 22 - DX Split	153.1	20.8	173.9	22.9
Site 32 - Unitary HP	147.6	166.3	313.9	30.1
Average	***229.6***	***109.2***	***334.0***	***38.0***
Standard Deviation	***102.0***	***81.1***	***149.1***	***16.3***
Reverse-cycle Heating & Cooling Systems				
Site 23 - Chilled Ceiling	407.7	n/a	407.7	57.9
Site 24 – Fancoils	252.6	n/a	252.6	35.9
Site 25 - DX Split	334.8	42.0	376.8	49.9
Site 26 - DX Split	558.5	n/a	558.5	79.3
Site 27 - DX Split	558.5	n/a	558.5	79.3
Site 28 - VRF HR	252.6	n/a	252.6	35.9
Site 29 - VRF HR	166.5	26.4	193.0	25.1
Site 30 - VRF HR	256.5	91.5	348.0	41.5
Site 31 - VRF HR	334.8	42.0	376.8	49.9
Average	***347.0***	***50.5***	***369.4***	***50.5***
Standard Deviation	***137.9***	***28.3***	***128.4***	***18.9***

The total annual delivered energy consumption of the buildings studied ranged from 110.5kWh/m2 to 621.8kWh/m2, which translates into associated carbon emissions of between 15.7kgC/m2 and 79.3kgC/m2. These measured values compare well to the range of energy consumption we expected, which was between 225kWh/m2 and 568kWh/m2 based on the national benchmark standards[12]. Only Site 4 consumed more energy than expected and a number of sites consumed significantly less than expected indicating better than good practice energy performance.

It is interesting to note that on average the energy consumption of the buildings using reverse-cycle air conditioning systems was 10% higher than those using separate heating and cooling systems. The buildings with reverse cycle systems consumed 369kWh/m2 and the buildings with separate systems consumed 334kwh/m2 on average. Theoretically the reverse cycle air conditioning systems should provide heating more efficiently than gas-fired heating systems in terms of delivered energy, so it is slightly surprising that the buildings that used reverse cycle systems consumed more energy than those that used separate heating and cooling systems. However there are too many variables involved in the whole building data to draw conclusions on the performance of the reverse cycle systems compared to other types of heating system at this point.

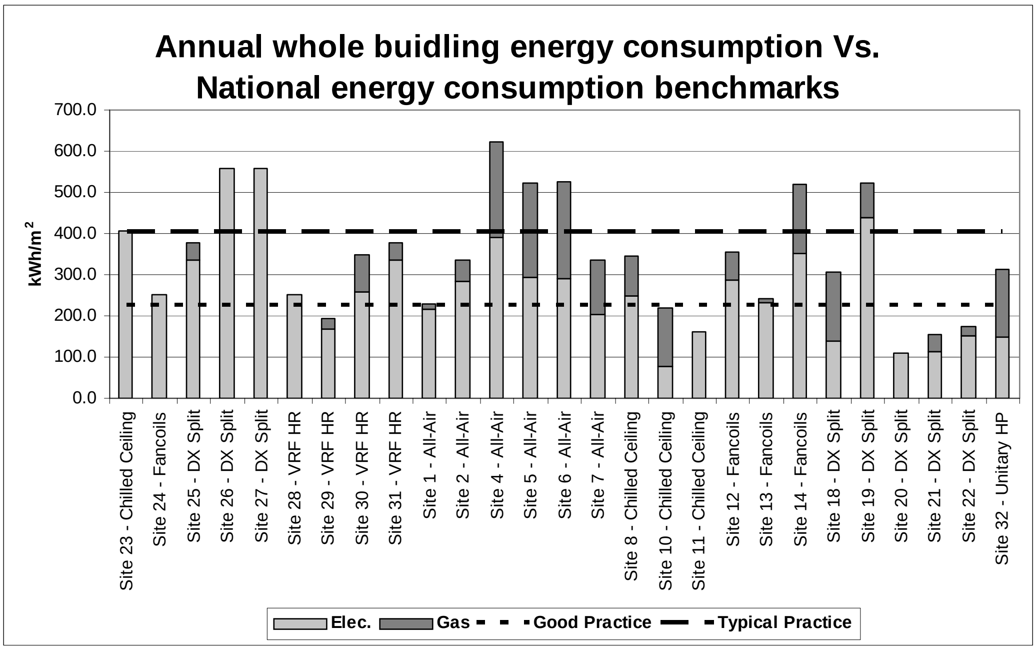
In terms of annual carbon emissions the slightly higher energy consumption of the buildings using reverse-cycle systems is exacerbated by the higher emissions of their electrically driven energy, emitting more carbon emissions per unit of energy consumed, leading to 33% more carbon emissions on average than the buildings using separate gas-fired heating systems.

Comparison to Building Energy Consumption Benchmarks
The total annual delivered whole building energy consumption of the twenty-seven buildings for which data was available is shown in Figure 1 relative to the UK national energy consumption benchmarks for whole building Office energy consumption by fuel type.

When compared to the benchmarks it is evident that the buildings studied represent a broad cross section of the UK stock of office buildings in terms of their energy consumption as the recorded building energy consumption ranged from only 49% of good practice (Site 20), indicating very low energy consumption by national standards, up to 154% of typical practice (Site 4), and indicating high energy consumption by national standards.

The comparison to the benchmarks shows that eight of the twenty-seven sites (30%) were high energy consumers, with consumptions higher than typical practice, and six of the sites (22%) were low energy consumers with energy consumptions lower than good practice. The remaining thirteen sites (48%) of the buildings studied had energy consumptions between good and typical practice standards indicating 'normal' or 'typical' energy performance.

Figure 1: Comparison of annual whole building energy consumption to national energy consumption benchmarks for air conditioned office buildings.



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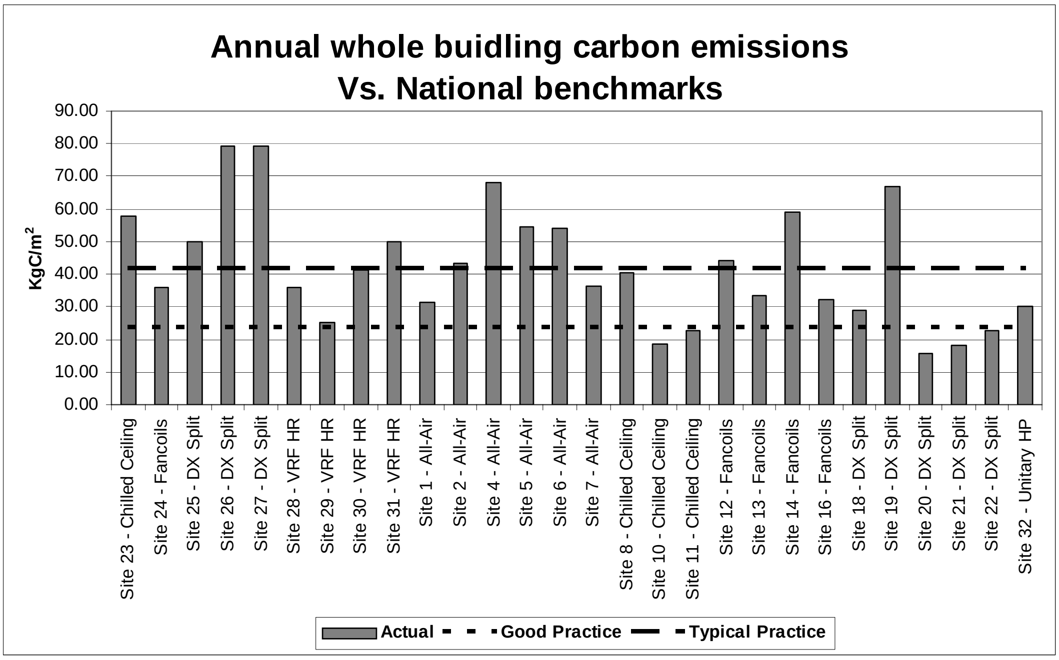
Since the benchmark standards assume upper and lower quartiles for typical and good practice energy performance, i.e. the consumption of the upper and lower 25% of the building stock are considered high and low energy consumers respectively, they compare favourably to the 30% above typical practice and 22% below good practice energy performance of the buildings studied here. Assuming the building sample is broadly representative of the overall UK building stock of air conditioned buildings this also suggests that the current national energy consumption benchmarks for whole building energy consumption are set at the correct level.

Comparison to Building Carbon Emissions Benchmarks

The total annual building energy consumption of the buildings studied in terms of their associated annual carbon emissions are shown relative to the national carbon emissions benchmark standards for air conditioned office buildings in Figure 2 below.

Not surprisingly, the associated whole building carbon emissions data demonstrate similar relationships to one another, and the national benchmarks, as the energy consumption data discussed in the previous section. The exceptions are sites 20, 23, 24, 26, 27 and 28, which only used electricity and due to the higher emissions per unit of energy of electricity compared to natural gas meant that in terms of carbon emissions these building appear to perform less well compared to the other buildings and the national benchmarks.

Figure 2: Comparison of annual whole building carbon emissions to national benchmarks for air conditioned office buildings.)



Proportion of Energy Consumed by Air Conditioning

This section uses the measured whole building and system energy consumption data previously published[2] to assess the proportion of energy consumed by the air conditioning system in each building studied. The proportion of building energy consumption, and carbon emissions, of the buildings studied used by each air conditioning system is shown in Table 2 expressed as a percentage of the whole building consumption and emissions.

Overall the proportion of energy consumed by the cooling only systems ranged from 3% to 43% of the whole building energy consumption and 21% on average. The proportion of energy used by reverse cycle air conditioning systems was 39% on average and ranged from 17% to 67 % of the whole buildings energy consumption.

This compares favourably to the expected proportion of energy consumption which ranged 16% to 23% for the cooling-only and 44% to 62% for the reverse-cycle systems. The only systems that proportionally used less than 16% of the whole building energy consumption for cooling were ones that had better than good practice energy consumption.

The proportion of carbon emissions attributed to the air conditioning systems are slightly higher than the proportion of energy consumption, because they are electrically driven with higher emission per unit of energy than other types of fuel. On average these accounted for 26% and 41% of the emission of the buildings with cooling only and reverse-cycle air conditioning respectively.

Table 2: Measured annual AC system energy consumption and carbon emissions

Site # / System Type	**Annual Energy Consumption**	**Annual carbon Emissions**	**Proportion of Energy**	**Proportion of Emissions**
	(kWh/m^2)	*(KgC/m^2)*	*% kWh*	*% KgC*
Cooling Only Systems				
Site 1 - All-Air	36.0	5.1	16%	16%
Site 2 - All-Air	37.8	5.4	11%	12%
Site 3 - All-Air	41.7	5.9	n/a	n/a
Site 4 - All-Air	164.4	23.3	26%	34%
Site 5 - All-Air	90.3	12.8	17%	24%
Site 6 - All-Air	104.2	14.8	20%	27%
Site 7 - All-Air	99.0	14.1	30%	39%
Site 8 - Chilled Ceiling	22.8	3.2	7%	8%
Site 9 - Chilled Ceiling	17.1	2.4	n/a	n/a
Site 10 - Chilled Ceiling	6.8	1.0	3%	5%
Site 11 - Chilled Ceiling	23.3	3.3	14%	15%
Site 12 – Fancoils	102.2	14.5	29%	33%
Site 13 – Fancoils	55.3	7.8	24%	23%
Site 14 – Fancoils	38.1	5.4	7%	9%
Site 15 – Fancoils	108.1	15.4	n/a	n/a
Site 16 – Fancoils	151.6	21.5	41%	67%
Site 17 - DX Split	57.2	8.1	n/a	n/a
Site 18 - DX Split	23.0	3.3	8%	11%
Site 19 - DX Split	35.9	5.1	7%	8%
Site 20 - DX Split	47.8	6.8	43%	43%
Site 21 - DX Split	44.5	6.3	29%	35%
Site 22 - DX Split	69.4	9.8	40%	43%
Site 32 - Unitary HP	98.2	13.9	31%	46%
Average	***64.1***	***9.1***	***21%***	***26%***
Standard Deviation	***43.0***	***6.1***	***13%***	***17%***
Heating & Cooling Systems				
Site 23 - Chilled Ceiling	70.5	10.0	17%	17%
Site 24 - Fancoils	104.6	14.9	41%	41%
Site 25 - DX Split	160.4	22.8	43%	46%
Site 26 - DX Split	128.3	18.2	23%	23%
Site 27 - DX Split	230.3	32.7	41%	41%
Site 28 - VRF HR	159.1	22.6	63%	63%
Site 29 - VRF HR	131.1	18.6	68%	74%
Site 30 - VRF HR	102.7	14.6	30%	35%
Site 31 - VRF HR	92.6	13.1	25%	26%
Average	***131.1***	***18.6***	***39%***	***41%***
Standard Deviation	***47.6***	***6.8***	***18%***	***19%***

Current energy consumption standards lead us to believe that air conditioned office buildings typically use at least 50% more energy than similar non-air conditioned buildings[12] but, based on these results, the provision of cooling by air conditioning systems on average only accounted for 21% of total building energy consumption. Therefore air conditioning systems on their own do NOT account for all the extra energy typically consumed by air-conditioned buildings compared to non-air conditioned buildings.

The measured data also indicates that the low energy consuming air conditioning systems lead to a reduced proportion of building energy used for cooling, but not necessarily also to reduced whole building energy consumption. For example, Site 19's air conditioning system had a better than good practice energy consumption, and accounted for less than 7% of the total building energy consumption, but the whole building was a high energy consumer with annual energy consumption 30% above typical practice.

This indicates that the underlying reasons for 'air conditioned' buildings consuming more energy, and hence producing more carbon emissions than 'non-air conditioned' buildings is NOT necessarily, or inherently, due to the use of air conditioning to provide cooling. The relatively high energy consumption of 'air conditioned' buildings compared to 'non air conditioned' buildings appears to be as much to do with other energy-use and not just air conditioning. Indeed this other energy end-use could well be the reason for the building have A/C in the first place.

This issue is illustrated in the buildings monitored in this study by that fact that 46% of the air conditioning systems performed at good practice level or better, but only 22% of the buildings also performed at good practice levels. Air conditioning energy efficiency, as a major energy user in buildings, is clearly important to achieving good overall energy and carbon performance, but as the last point emphasises air conditioning systems cannot be considered in isolation from the building and its other energy uses.

Conclusions

The data and results discussed in this paper provided analysis of the overall energy consumption and associated carbon emissions of 27 UK air conditioned office buildings each buildings. The energy consumption of the entire buildings studied showed that the total annual delivered energy consumption of the air conditioned office buildings studied ranged from 110.5kWh/m2 to 621.8kWh/m2, which translates into carbon emissions between 15.7kgC/m2 and 79.3kgC/m2 of treated floor area.

These values are similar to the range of energy consumption expected from the current UK energy consumption benchmarks for air conditioned office buildings and this agreement suggests that the sample of buildings studied by the research is broadly representative of the UK stock of air conditioned office buildings, and also that the current national UK energy consumption benchmarks are probably set at a correct level.

The proportion of energy consumed by the cooling only systems ranged from 3% to 43% of the whole building energy consumption and 21% on average. The proportion of energy used by reverse cycle air conditioning systems was 39% on average and ranged from 17% to 67 % of the whole buildings energy consumption. Significantly the data shows that buildings with lower energy consuming A/C services resulted in a lower proportion of the whole building energy consumption and not reduced whole building energy consumption.

Importantly this indicates that the underlying reasons for 'air-conditioned' buildings consuming more energy, and carbon emissions than 'non air-conditioned' buildings, is NOT inherently due to the use of air conditioning but primarily due other energy end-use within the building, such as lighting and small power office equipment.

Therefore any serious attempt to reduce energy consumption and emissions from UK office buildings needs to target improvements not just at the HVAC systems, although obviously important, but also equally at the other energy end-users. As a result any savings made to lighting or small power equipment loads should also result in energy savings from the air conditioning system as cooling loads will be reduced. But furthermore it is evident from the range of energy consumption at both the system and building level presented that the potential for savings compared to current practice are considerable.

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