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RESEARCH PAPER

Using Display Energy Certificates to quantify public sector office energy consumption

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The influence of internal and external characteristics on energy use in the public sector office stock in England and Wales is explored using a database of 2600 Display Energy Certificates (DECs) combined with other sources of disaggregated office information. The DEC office benchmarks are shown to match the median fossil thermal and electrical consumptions well. Analyses of heating, ventilation and air-conditioning (HVAC), size, occupancy density, building age, location and rateable value are considered. While newer offices are shown to have lower typical fossil-thermal consumption than older offices, this is counterbalanced by higher electrical consumption, resulting in higher typical CO_2 emissions. This has implications for the UK's emissions reduction targets for 2050, indicating that while building regulations that focus on thermal performance have been successful, a focus on electrical consumption (both regulated and unregulated) is key. The results are also compared with existing benchmarks for all UK offices, splitting the sample into four generic types, and compared with a similar smaller study of private offices. This indicates that public offices typically used less energy than the general benchmarks had previously predicted, particularly for prestige offices.

Keywords: benchmarks, building stock, CO_2 emissions, Display Energy Certificates, energy use, non-domestic stock, offices

Introduction

This paper is the second in a series looking at the results of the first year of Display Energy Certificates (DECs) for public buildings in the UK. The first paper covered energy use in schools (Godoy-Shimizu, Armitage, Steemers, & Chenvidyakarn, 2011), while this paper focuses on offices, the second largest category in the 2008/2009 DEC database.

The key driver for this research is to gain a better understanding of the factors that determine energy use in buildings. This is a necessary first step towards effectively improving the building stock, which is likely to be an important part of reaching the UK's legally binding CO_2 emissions reduction targets (UK Parliament, 2008). Unfortunately, despite years of research into non-domestic buildings, there is still claimed to be a 'lack of [. . .] comprehensive understanding of its composition and energy use' (DECC, 2009, p. 4).

In conjunction with the DECs, the analysis presented in this paper uses disaggregated information gathered from other public datasets.

Public office stock

In the UK there are approximately 350 000 offices including both commercial and public properties (ONS, 2008). These buildings consume 18% of the annual energy used by the non-domestic building sector, and account for approximately 2% of national energy consumption (DECC, 2010). Comparison with historical data suggests that the number and total floor space of offices is increasing as a proportion of the non-domestic total (DCLG, 2009). As a significant source of emissions, offices have the potential to form an important part of the UK's emissions reduction strategy.

Although the public sector only makes up a portion of the total office stock, a recent report highlighted the potential for the government to lead by example to encourage wider improvement across the non-domestic sector (APUDG, 2008). This is arguably more important for offices than other non-domestic building types as offices appear in both the public and the private stock (unlike, for example, retail, which is predominantly private), with broadly similar use patterns and occupancy, except for some specific types, such as in the high-end financial sector.

To date, extensive research has been published concerning energy consumption in UK offices. This includes comprehensive surveys of small samples of office buildings (Bordass, Cohen, Standeven, & Leaman, 2001; Knight & Dunn, 2005), less detailed surveys with larger samples (Action Energy, 2003; BBP, 2010; BRE, 1998), and statistical and building physics modelling which typically uses large-scale surveys as input data (Bowles et al., 2011; Bruhns, 2008). Typically, small-scale comprehensive surveys provide detailed analysis of building types, but can be difficult to extrapolate to the entire building stock. The sample selection may not be representative of the overall stock. Large, but less detailed, surveys can provide information for the stock as a whole (*e.g.* for benchmarking purposes), but can be limited by a lack of detailed information quantifying the precise drivers of energy performance. Modelling enables estimates to be made of the potential impact of changes to the existing stock (*e.g.* large-scale refurbishment programmes of changes to climate), but can require very detailed input and calibration data depending on the type of method.

Despite the need for improvements within the stock, there has been surprisingly little analysis of large-scale surveys of actual building performance of offices in recent years (as noted by Pérez-Lombard, Ortiz, González, & Maestre, 2009). In comparison, large-scale detailed surveys of the English housing stock are carried out annually (DCLG, 2012a). As a source of detailed, disaggregated data, DECs represent a unique opportunity to investigate energy use in public sector offices. Additionally, the fact that they are produced annually provides an opportunity for long-term monitoring of performance, and the evaluation of the impact of changes.

Display Energy Certificates (DECs)

DECs, mandatory since 2008 in public buildings over 1000 m^2, present actual metered energy use of buildings as well as a normalized rating, which allows the comparison of building performance against the rest of the stock. While there has been some discussion about extending DECs to cover private buildings (DCLG, 2010; UKGBC, 2011), this is currently not the case. The DECs collected for this paper only cover buildings in England and Wales over 1000 m^2; recent changes have required buildings with a floor area between 500 and 1000 m^2 to be included, though this was introduced after the data presented here were collected (DCLG, 2012b). The analysis presented here is only directly applicable to public sector offices over 1000 m^2 in England and Wales. DECs also include a building's annual CO_2 emissions, as well as information on various building characteristics including total floor area, heating, ventilation and air-conditioning (HVAC) system and details of any renewable energy generated on-site. The DEC Operational Ratings are normalized by adjusting the given benchmarks for weather and occupancy to give a fair 'typical' energy use against which the actual energy use is compared; the present analysis is just considering the unadjusted actual energy use. Full details of the methodology can be found in *Operational Ratings and Display Energy Certificates* (CIBSE, 2009).

Aims

This paper presents an analysis of almost 2600 offices in the DEC database for 2008/09, characterizing the current energy use of the public office stock in England and Wales. It then considers typical office typologies, defined in other literature, and the key factors that influence energy consumption, including HVAC, size, building age and location.

Methods

For this study, a database of around 25 000 DECs from 2008 to 2009 was obtained via a Freedom of Information request to the UK Government in mid-2010. Of this, around 15% are for offices. Significant processing and validation of the raw DEC data was necessary prior to carrying out the analysis. This included removing buildings with questionable data (unfeasibly high floor areas, default energy use figures, zero fossil-thermal use, etc.), multiple building types, and duplicate DECs, totalling almost 40% of the office DECs. The method followed the approach used for the schools analysis and is explained in detail by Godoy-Shimizu et al. (2011). Only buildings identified as 'General Office' in the DEC methodology were included in this analysis.

Following the processing and removal of questionable data entries, additional information was added to the DEC database using two sources: the Valuation Office Agency (VOA) 2010 ratings list, which includes information for UK non-domestic hereditaments for the purposes of taxation;[1] and the UK Government Property and Land Asset database which was released in January 2012.[2] These data sources were matched to DEC entries using office names, addresses and floor areas.

Due to the availability of data, it was not possible to match every validated office DEC to the additional information sources, so some of the analyses within this paper use smaller sample sizes (noted where applicable). Figure 1 summarizes the final office disaggregated database, following the data validation and clean-up procedures outlined above. The final database included: 2581 offices with DECs, 506 with both a DEC and matched VOA data; 249 with a DEC and matched UK Government Asset data; and 133 offices that had data matched from all three sources.

In the analysis that follows, references to 'the DEC database' refer to the offices information that has been validated and combined with other data, not the raw DEC information. Where necessary a single-factor analysis of variance (ANOVA[3]) test with a 95% confidence level was used to determine the significance of different building types and factors. Where not included in the main text, data tables containing key results can be found in the in the Supplemental data online.

It should be noted that top-down statistical analysis of this nature cannot directly determine causal relationships. Additionally, limitations in data availability mean that certain key factors such as hours of occupancy and HVAC plant efficiency have not been considered in this study. However, the analysis reveals the broad trends in the public sector office energy consumption in conjunction with more detailed studies will be useful for understanding the drivers of energy performance.

Offices

Energy use and CO_2 emissions

In order to understand the current energy performance of public offices in England and Wales, profiles were generated illustrating the annual energy consumption and CO_2 emissions of the stock. Figure 2 presents the cumulative frequency distributions for both fossil-thermal and electricity consumption, comparing them with the Chartered Institution of Building Services Engineers (CIBSE) benchmarks (fossil-thermal = 120 kWh/m^2; electricity = 95 kWh/m^2) (CIBSE, 2008). The spread of the curves indicates the range of energy use, while the median value (the 'typical' benchmark) and 'good practice' and 'poor practice' benchmarks can be read off at 50%, 25% and 75% respectively on the *y*-axis.

Despite the fact that the benchmarks are adjusted for each building to account for factors such as location and opening hours, Figure 2 shows that the CIBSE General Office benchmarks are very close to the actual median consumption for both electricity and fossil-thermal consumption. This indicates that when taking the public office stock as a whole, the benchmarks provide a good measure of the typical energy use in office buildings, reflecting the findings of a recent review of DECs (Bruhns, Jones, Cohen, & Bordass, 2011).

Although the graph presents the energy consumption characteristics of the database, in order to understand the relative environmental impact of different energy uses the carbon intensities of each fuel must be considered. Currently, UK grid electricity CO_2 intensity is high compared with most other fuels. Significantly, natural gas (which supplies heat for almost 90% of the offices in the database) has a carbon intensity around one-third that for grid electricity. The carbon intensity of natural gas is 0.18 kg CO_2/kWh; the carbon intensity of grid electricity (in 2008) is 0.54 kg CO_2/kWh (DEFRA, 2012). This means that electricity accounts for 45% of the total energy consumption, but over 70% of CO_2 emissions. Figure 3 presents the profile for total annual CO_2 emissions from the offices, along with the CIBSE illustrative

DATA SOURCE	KEY DATA
DEC (following first stage validation)	Address; floor area; heating fuel; HVAC type; annual energy consumption & emissions.
VOA	Internal floor space breakdown; no. of floors; rateable value.
UK Govt Property & Land Assets	Building age (built & refurb); building occupancy.

Figure 1 Summary of the final office database

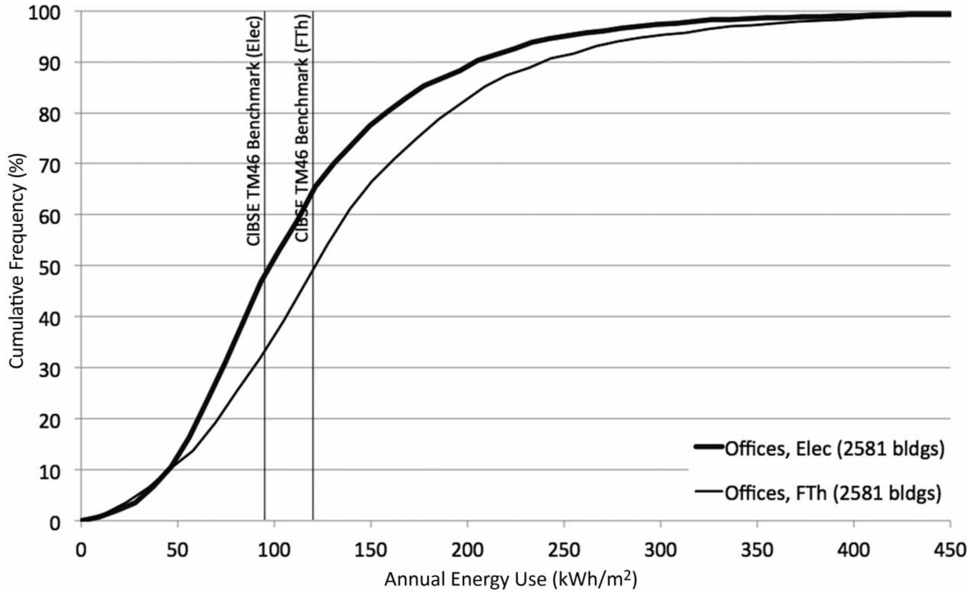

Figure 2 Annual energy use profiles
Notes: ELEC = electrical energy, FTh = fossil-thermal energy (benchmarks: fossil-thermal: 120 kWh/m^2; electricity: 95 kWh/m^2)
Source: CIBSE (2008)

benchmark figure. Key figures from the energy and emissions graphs are presented in Table 1.

Generic office types

Office type survey

Past research has defined four generic office types, each with a different characteristic set of features and corresponding energy benchmarks, as illustrated in Table 2 (Action Energy, 2003). The benchmarks show an increase in typical energy use from Type 1 to Type 4 and, most significantly, a switch from fossil-thermal-dominated to electricity-dominated consumption. This reflects increases in building size, complexity and occupancy intensity. While the surveys originally used to generate the benchmarks were carried out around 20 years ago, the benchmarks are 'still likely to be reasonable guides for assessing energy consumption' (UKGBC, 2007, p. 37), although they may underestimate electricity consumption for

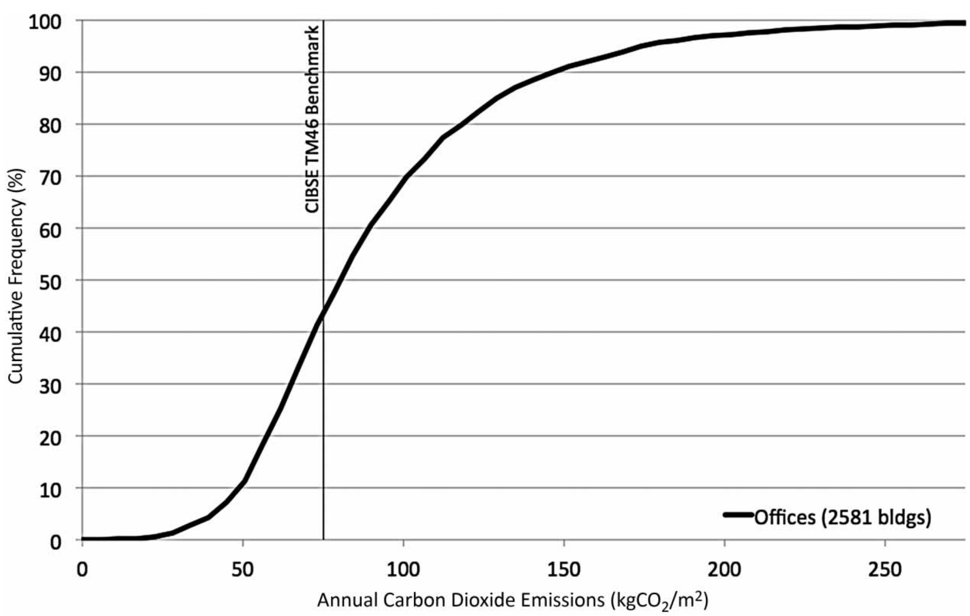

Figure 3 Annual CO_2 emissions profile

Table 1 Energy and emissions statistics

Building type	Parameter	10%	25%	50%	75%	90%	Mean	SD
General Offices	Electrical energy (kWh/m^2)	46	68	98	143	204	115	76
	Fossil-thermal energy (kWh/m^2)	46	80	122	173	238	137	87
	Total energy (kWh/m^2)	141	175	228	299	393	252	117
	CO_2 emissions (kg CO_2/m^2)	49	62	80	109	147	91	46

lighting and information and communication technology (ICT).

Given that these benchmarks were created to be indicative of the overall UK office stock, the DEC database was tested to determine whether similar energy use patterns are found specifically within public offices. A random sample of 900 offices in the database was selected for classification into the four generic office types. Following an external visual survey carried out online using Google Streetview and Bing Multimap, and using information from the DEC database on the HVAC system and size, 332 offices were classified into the four generic types. In order to mitigate the uncertainty in this process, due to the lack of detailed internal surveys, surveys were carried out twice independently and then checked against the size and HVAC criteria set out in Table 2; all cases where

Table 2 Key characteristics of the four basic office types

Type 1: Naturally ventilated cellular

- Small size (100–3000 m^2)
- Simple form (*e.g.* converted residential)

Typical electricity: 54 kWh/m^2/year

Typical fossil-thermal: 151 kWh/m^2/year

Type: 2: Naturally ventilated open

- Small/mid size (500–4000 m^2)
- Often purpose built
- Lights and switches shared, covering larger areas

Typical electricity: 85 kWh/m^2/year

Typical fossil-thermal: 151 kWh/m^2/year

Type 3: Air-conditioned, standard

- Mid size (2000–8000 m^2)
- Purpose built, often speculative

Typical electricity: 226 kWh/m^2/year

Typical fossil-thermal: 178 kWh/m^2/year

Type 4: Air-conditioned, prestige

- Large (4000–20 000 m^2)
- Purpose built, national or regional headquarters
- Major catering facilities/cafeteria
- Major information technology uses

Typical electricity: 358 kWh/m^2/year

Typical fossil-thermal: 210 kWh/m^2/year

Source: Action Energy (2003).

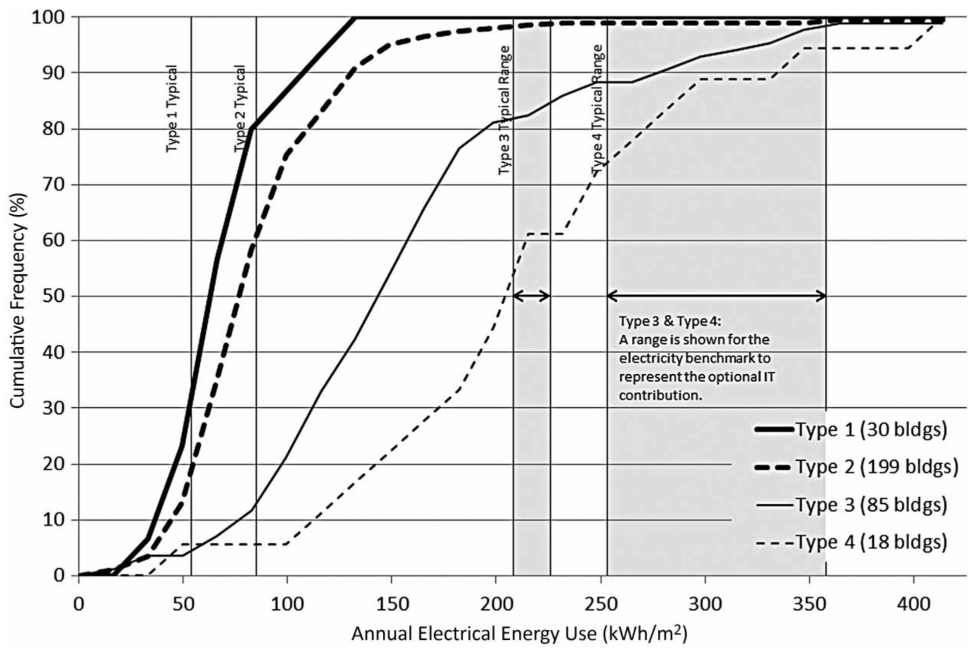

Figure 4 Variation of annual electrical energy use profiles with office type
Note: Typical benchmarks are from Action Energy (2003)

there was a disagreement in category were removed. The analysis presented below is for these 332 offices.

Energy use by office type

The electrical and fossil-thermal energy use profiles for the four office types from the survey are shown in Figures 4 and 5 (a summary of results is shown in Table 3). The electrical use profiles show that while there is no statistically significant difference between Type 1 and Type 2 offices (ANOVA, $p > 0.05$), Types 3 and 4 are significantly higher, with a significant difference between them (ANOVA, $p < 0.05$). However, while the Type 1 and Type 2 median values (62 and 75 kWh/m^2 respectively) are close to the typical benchmark figures, the Type 3 and Type 4

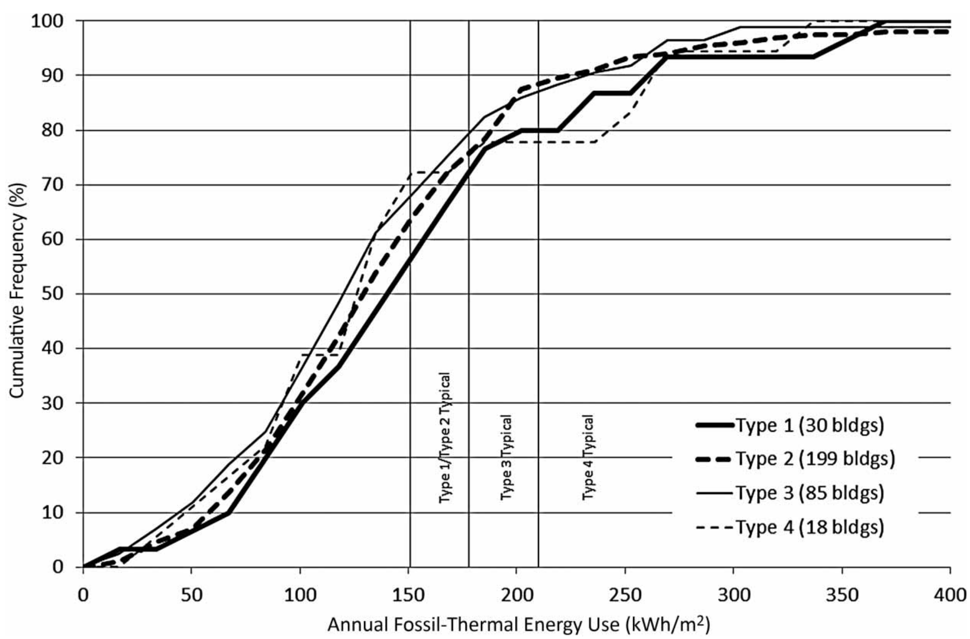

Figure 5 Variation of annual fossil-thermal energy use with office type
Note: Typical benchmarks are from Action Energy (2003)

Table 3 Energy use and emissions, by office type

	ELEC (kWh/m^2)				FTh (kWh/m^2)				CO_2 (kg CO_2/m^2)			
Office type	25%	50%	Mean	SD	25%	50%	Mean	SD	25%	50%	Mean	SD
1	52	62	68	25	94	141	153	80	55	66	68	22
2	60	75	85	50	91	131	142	85	57	68	75	31
3	105	145	155	78	87	120	132	79	79	108	112	50
4	161	205	211	85	91	132	141	81	107	138	144	51

figures are lower (145 and 205 kWh/m^2, respectively), even when compared with the benchmarks that do not include the optional computer room electricity. Also, the standard deviation is higher for Types 3 and 4, indicating a higher variation in electrical use intensity for these offices.

From the definitions in Table 2, it can be seen that going from Type 1 to Type 4 there is an increased use of air-conditioning, more complex equipment and systems, larger floor areas and increased occupancy densities. These factors, and the increasing levels of artificial lighting and electrical equipment for more prestigious (*i.e.* Type 4) offices (Action Energy, 2003), could explain the electrical use trends seen above.

Figure 5 presents the fossil-thermal profiles for the four building types. The median fossil thermal use is lower than the benchmarks for all office types, particularly Types 3 and 4, and much closer to the CIBSE benchmark of 120 kWh/m^2. However, there is no significant difference in fossil-thermal use between each of the samples of office types (ANOVA, $p > 0.05$). This is an unexpected result, considering the difference in internal gains and building fabric associated with office type. Type 1 offices are more likely to be older, converted buildings (*e.g.* residential or industrial), which could lead to a lower quality building fabric with higher losses, while higher equipment use intensity and occupancy levels in prestige offices could further reduce the space heating requirement, despite more complex systems being more prone to wastage and poor performance. The effect of age on office energy use and emissions is investigated below.

Figure 6 presents the resulting CO_2 emissions profiles for the four office types. It shows no significant difference in typical emissions between Types 1 and 2, falling in between their respective benchmarks, while Types 3 and 4 are each significantly higher than this (ANOVA, $p < 0.05$), but still much lower than the benchmark values.

If the benchmarks shown here are still considered representative of the general office stock (UKGBC, 2007), this could indicate that public offices use less energy than the general office stock, particularly for Type 3 and Type 4 offices. This then suggests that the DEC database is not necessarily representative of the whole office stock, and in particular private sector offices. This is corroborated by a report by the Better Building Partnership (BBP), which showed much higher energy use for Type 3 and Type 4 offices, which had median emissions of 190 and 217 kg CO_2/m^2 respectively (BBP, 2010). However, it should be noted that due to a greater prevalence of high-end, larger offices, the BBP stock may not be representative of the entire private office stock.

A summary of the energy use and emissions from the four office types is shown in Table 3.

Key factors influencing energy performance

The previous section considered four generic office types, each with a set of typical office characteristics. In order to understand the relationship between the characteristics themselves and building performance, this section assesses each individually. The following characteristics were investigated to determine their influence on office energy use:

- HVAC system
- size and occupancy density
- building age
- location
- rateable value

HVAC system

A survey of the UK non-domestic building sector performed in 1994 found that approximately 6% of UK offices (24% of total office floor space) incorporated air-conditioning (BRE, 1998), with larger and newer offices more likely to include it. Analysis of the DECs shows that currently 16% of public offices have

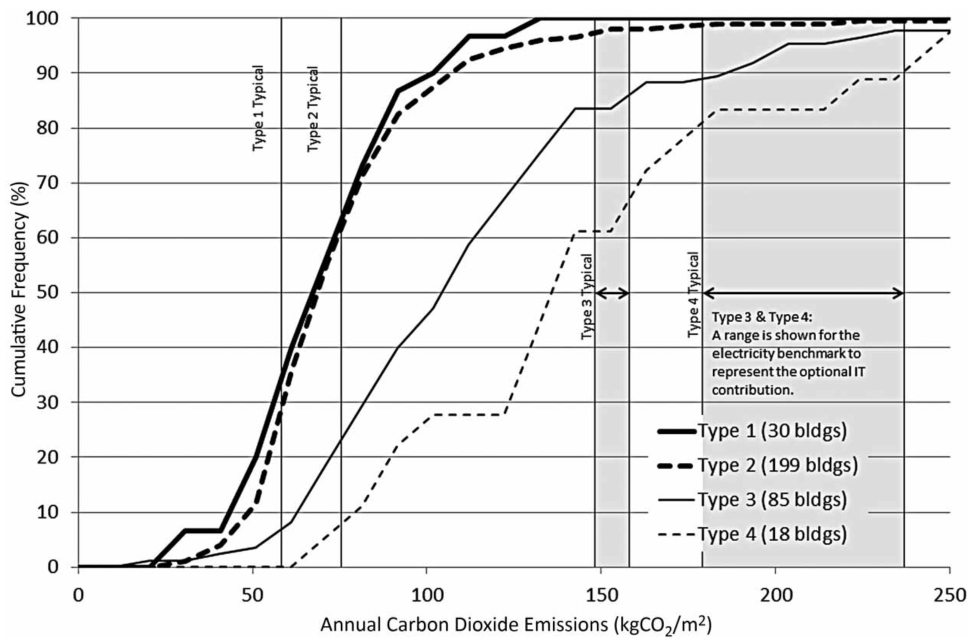

Figure 6 Variation of annual CO_2 emissions with office type
Note: Typical benchmarks are from Action Energy (2003)

air-conditioning, and almost 50% have some form of mechanical ventilation. While the data suggest that there is still a trend towards larger and newer buildings having air-conditioning, the proportion of total public office floor space with air-conditioning is only one-fifth.

Due to the requirement for additional plant, mechanically ventilated and air-conditioned buildings typically have higher electrical energy use than naturally ventilated buildings (Thomas, 1999). Given the carbon intensity of electricity, this can result in increased average CO_2 emissions. Furthermore, as research suggests the market for air-conditioning will continue to grow (AMA Research, 2010), understanding the impact that HVAC has on energy consumption is an important area of research. The analysis presented in this section investigates the extent to which energy consumption in offices is affected by the choice of HVAC system. A table with key figures for different HVAC types is provided in the Supplemental data online.

Evaluation of the fossil-thermal energy performance for the different HVAC types found that while the difference between naturally ventilated and air-conditioned buildings is significant (ANOVA, $p < 0.05$), the difference between the typical values is small (only 15.5 kWh/m^2, representing 12% of the typical use for naturally ventilated offices). Mechanical ventilation and air-conditioning can provide opportunities for heat recovery and greater control over infiltration, compared with natural ventilation. However, the complexity of the plant can also result in greater risk of systems performing or being designed poorly. The similar energy profiles and small energy difference indicates that the variation in fossil-thermal energy use between the four office types is not just due to the different HVAC systems.

While the variation in fossil-thermal consumption profiles with HVAC is small, this is not true for electrical consumption. Figure 7 shows that there is a 72 kWh/m^2 (91%) increase in median use between naturally ventilated and air-conditioned offices, though there is no significant difference between mechanically ventilated and mixed-mode offices (ANOVA, $p > 0.05$), which lie halfway between. Furthermore, the results show that 'poor practice' naturally ventilated offices have similar electricity use to 'good practice' air-conditioned offices. The variation in electrical consumption might be caused directly by the additional ventilation and cooling plant described previously, however it is also likely to be related to a higher prevalence of conditioning in prestigious offices, which have greater internal electrical loads in general. With the similarities in fossil-thermal consumption, the CO_2 emissions profiles are largely defined by the electrical profiles, showing very similar trends.

Size and occupancy density

The relationship between building size and energy use was investigated, and the fossil-thermal and electrical energy use profiles are shown in Figures 8 and 9 respectively; key figures are provided in the Supplemental data online. While median fossil-thermal use does decrease slightly with building size, which

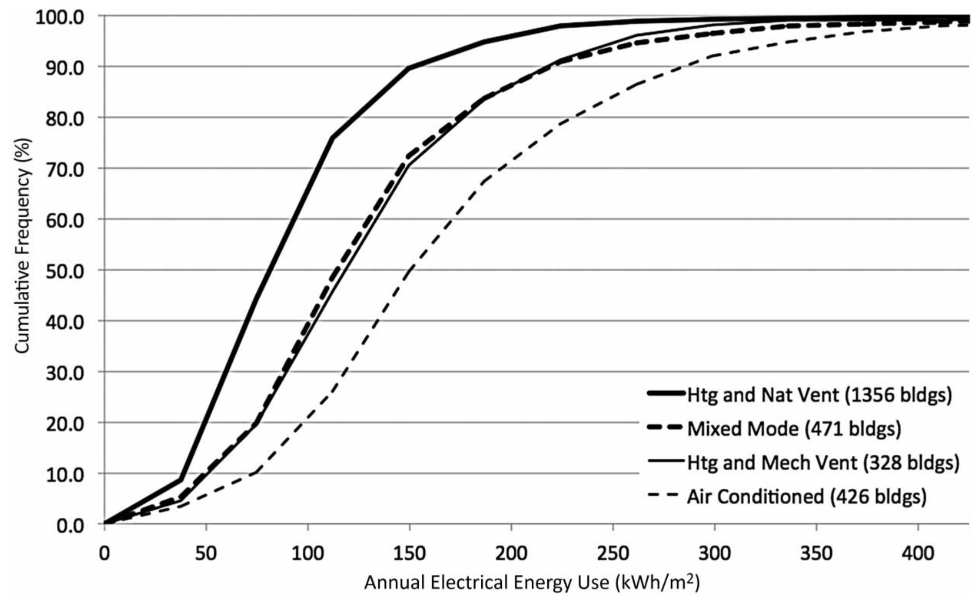

Figure 7 Variation of annual electrical energy use with heating, ventilation and air-conditioning (HVAC) type

may be expected due to envelope area-to-floor area ratios decreasing as floor area increases (*e.g.* Steadman, Bruhns, & Gakovic, 2000), there is no significant difference (ANOVA, $p > 0.05$). Electrical use does vary, however, with a small but significant change as office size increases (ANOVA, $p < 0.05$). This suggests that as buildings get bigger and deeper, aspects of the building design that require electricity become more intense, such as HVAC systems, occupant energy use or the inclusion of energy-intensive uses like information technology (IT) rooms.

Previous research has highlighted occupancy density as a variable that helps drive a building's energy consumption, but noted problems with obtaining reliable, accurate data (BBP, 2010; Bruhns et al., 2011). Furthermore, research by IPD (2007) found that space is used less efficiently in public sector than private sector offices (median densities of 15 and 12 m^2/person respectively), and recommended an aspirational 'floor space standard' of 12 m^2 per person. (It should be noted that due to the way that occupancy density is typically defined, an increase in occupancy density

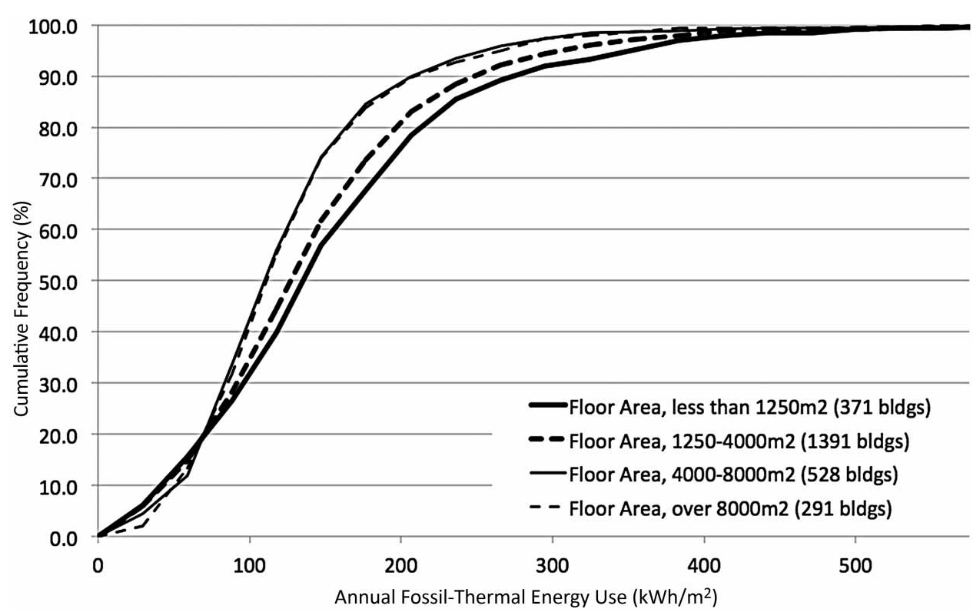

Figure 8 Variation of annual fossil-thermal energy use with office size

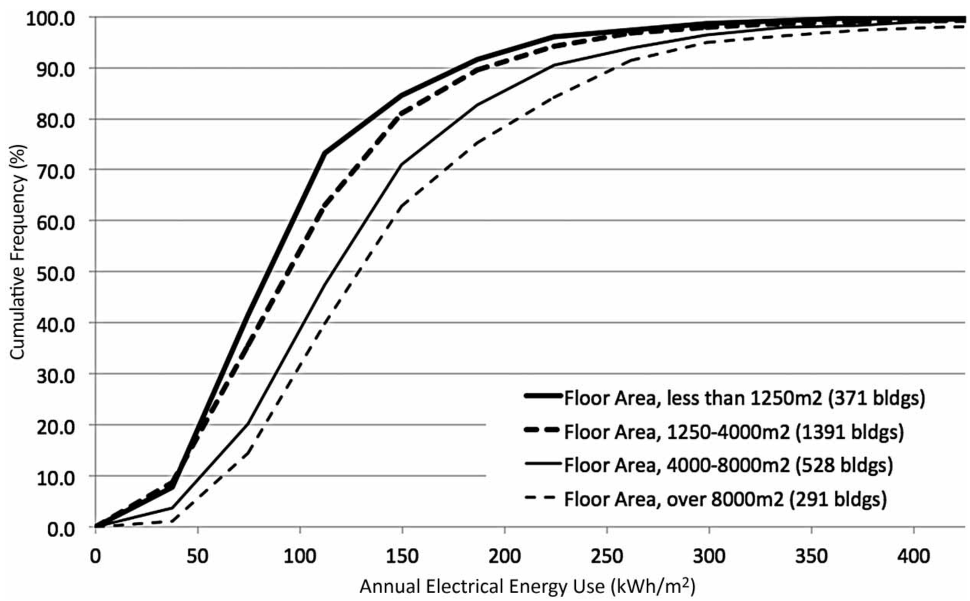

Figure 9 Variation of annual electrical energy use with office size

means a decrease in m^2/person.) Figures from the Government Land and Property Asset database provided the full-time-equivalent (FTE) number of office-based staff and contractors for 213 buildings in the DEC database allowing the variation of energy use with occupancy density to be investigated (Figures 10 and 11). The lack of robust occupancy data for most of the building stock precludes the DEC methodology from using per capita benchmarks rather than per unit area, though the UKGBC considered that once better processes have been established, occupancy and density indicators could be included (UKGBC, 2011). A summary of the relationship between occupancy density and the surveyed buildings is provided in the Supplemental data online.

The results show a slight rise in fossil-thermal energy use occupancy density falls, up from 15 m^2/person. This is likely due to decreased opportunities to share workspaces, and lower internal occupancy and computing heat gains, at lower densities. Conversely, there is a significant increase in typical electrical

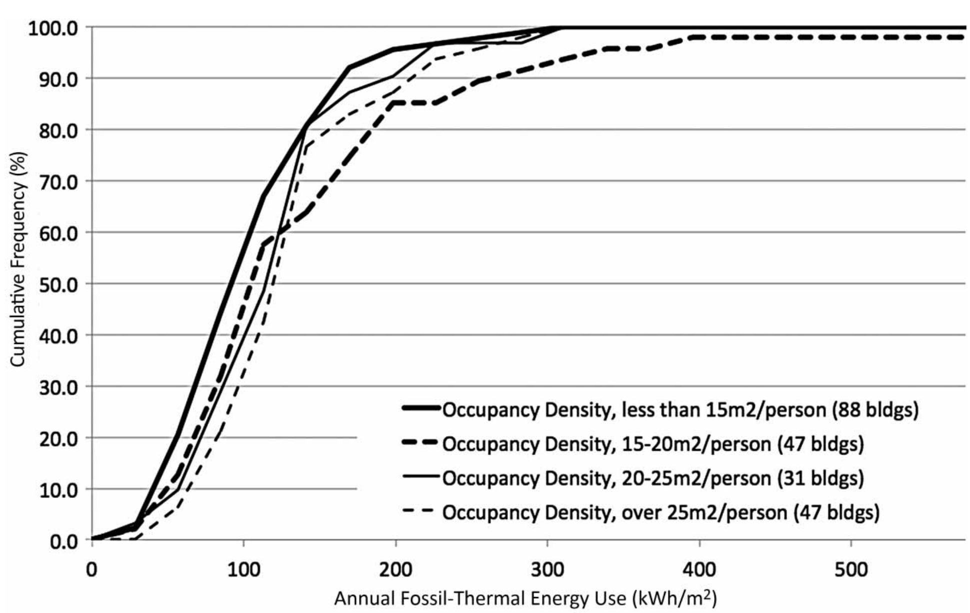

Figure 10 Variation of annual fossil-thermal energy consumption with occupancy density

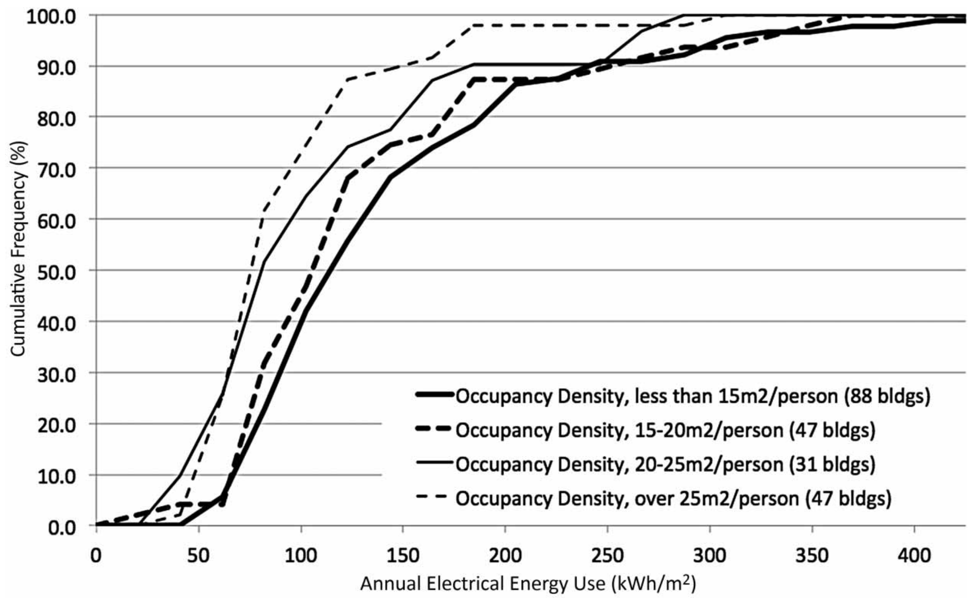

Figure 11 Variation of annual electrical consumption with occupancy density

energy use as the occupancy density increases (ANOVA, $p < 0.05$). This is perhaps partly due to increases in small power use, and shared equipment from denser floor plans, or could be a result of a greater reliance on air-conditioning systems to maintain comfortable temperatures with higher internal gains.

Building age and the impact of refurbishment

Within the offices database building age information is known for approximately 550 offices. Figures 12 and 13 illustrate the variation in annual fossil-thermal and electrical energy consumption with age for original constructions. The offices built pre-1959 have been grouped together for these graphs to give a similar sample size for each category, and to tally with the introduction of building fabric standards in the early 1960s. Further details about the changes to building standards over time are explained below.

Median fossil-thermal energy drops by 10% between offices built before 1959 and those built during the 1980s, and a further 39% for those built since 2000. Despite the lower median figure, the interquartile range remains relatively constant and the results show that modern buildings do not inevitably perform better than old ones. For instance, the 'good practice' fossil-thermal energy use for pre-1959 offices equals the typical figure for 1990s' offices. Within the UK, following on from the initial introduction of fabric standards in 1962 (for condensation), regulations have been in place for the conservation of fuel and power in non-domestic buildings since the late 1970s (King, 2007). Over time, minimum requirements have been introduced for factors such as fabric insulation, infiltration and system efficiencies. Since their inception, building regulations have been getting progressively more stringent; for instance, fabric insulation standard *U*-values for walls have dropped four-fold in the last 45 years (King, 2007). The drop in fossil-thermal energy use in buildings built over the last 30 years likely reflects the introduction of building regulations, and increasing requirements for thermal performance.

The electrical consumption result shows an opposite trend to fossil-thermal consumption, indicating that total electrical consumption in buildings has not been affected by building regulations in the same way. Median consumption rises by almost 75% between the pre-1959 buildings and those built since 2000, with most of the rise occurring in the past three decades. Furthermore, while the interquartile range remains relatively constant for buildings built before 1999, it almost doubles for post-2000 buildings, showing a much greater variation. The graph also shows a greater difference between the median and upper quartile than between the median and lower quartile at most age bands. This highlights the impact of high-consuming buildings in the overall office stock electricity profile. The results reveal that the lower quartile electricity consumption in modern buildings is higher than the median consumption in buildings built pre-1980.

The rise in electrical consumption may be caused by a number of factors. Firstly, the typical equipment,

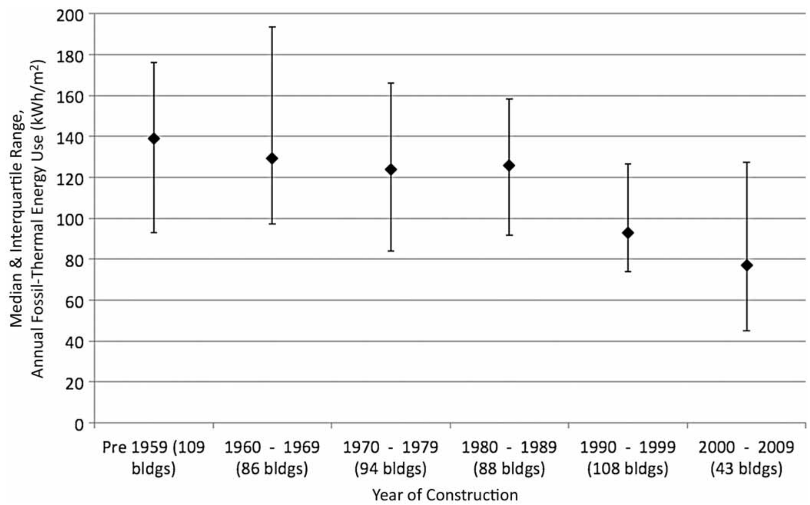

Figure 12 Variation of annual fossil-thermal energy use with the year of construction

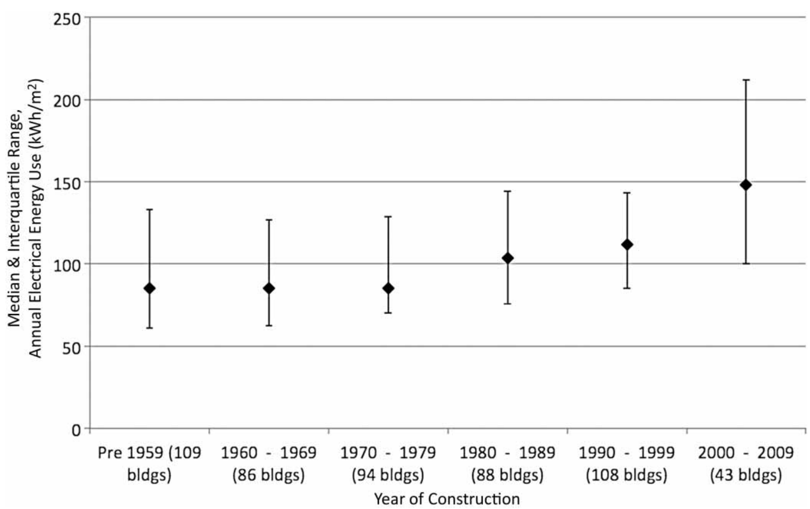

Figure 13 Variation of annual electricity use with the year of construction

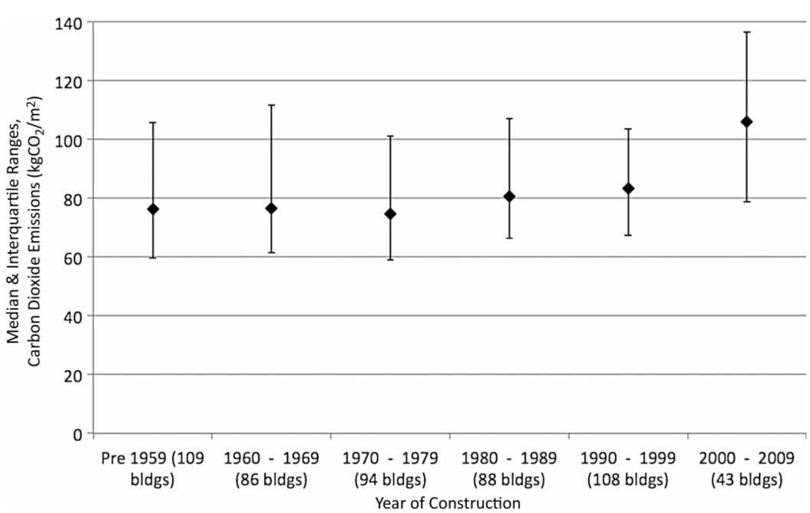

Figure 14 Variation of annual CO_2 emissions with the year of construction

lighting and small power installations for new buildings have increased significantly over the past several decades, negating the improvements in electrical efficiencies, *e.g.* liquid crystal display (LCD) screens and light-emitting diode (LED) lighting (UKGBC, 2007). Although equipment generally has far shorter lifespans than the buildings themselves (*i.e.* it is unlikely that a building built in 1950 uses the original HVAC equipment, lift equipment and electrical appliances), newer buildings may be more suited – and more desirable – to occupiers with high ICT requirements. Secondly, and perhaps more importantly, the data show a greater prevalence for air-conditioning and mechanical ventilation, which have above been shown to relate to increased electrical consumption, in new offices compared with old ones (a difficulty in commissioning and operating more complex recent buildings may also explain some of the wider variation in newer offices). If the main driving factor is HVAC, then an increase in retrofitting of air-conditioning in older buildings would (all else being equal) result in older buildings increasing in CO_2 emissions and reduce this trend over time. Finally, newer buildings may have more prevalent electric hot water provision, leading to lower fossil thermal and higher electrical use.

It is well understood that there is a correlation between electrical and heating consumption as electrical equipment and lighting within buildings generate heat, which will offset some of the need for additional heating. Consequently, the variation in fossil-thermal consumption may partly be attributable to the variation in electrical consumption.

The results show that median electrical consumption increases by approximately 60 kWh/m^2 across the age categories, while median fossil-thermal consumption drops by roughly the same amount. Therefore, due to the higher carbon intensity of electricity, the CO_2 emissions profile closely follows that for electricity consumption. Median emissions increases by approximately 40% between pre-1959 and 2000s constructed buildings, with a particularly large rise in buildings constructed since 1990. The interquartile range of emissions is also highest for the newest buildings (Figure 14).

The analysis above does not consider buildings with major refurbishments since original construction. However, within the database a number of buildings have been identified as being refurbished between 1990 and 2009. In studies that assess the UK's long-term CO_2 reduction targets, this is particularly important due to the slow turnover of the non-domestic stock (UKGBC, 2007) and the potentially high embodied energy and capital costs associated with demolition and new builds. For this reason, the energy performance of offices refurbished in the last 20 years was compared with those buildings newly built during the same period.

Despite the relatively small sample size, the results show similar energy profiles for both electrical and fossil-thermal consumption for the refurbished and new buildings. Consequently, the resulting CO_2 emissions profile shows no significant difference between refurbished and new buildings (Figure 15). Original construction dates are only available for half the refurbished buildings, so comparison with the energy profiles for the original dates was not feasible.

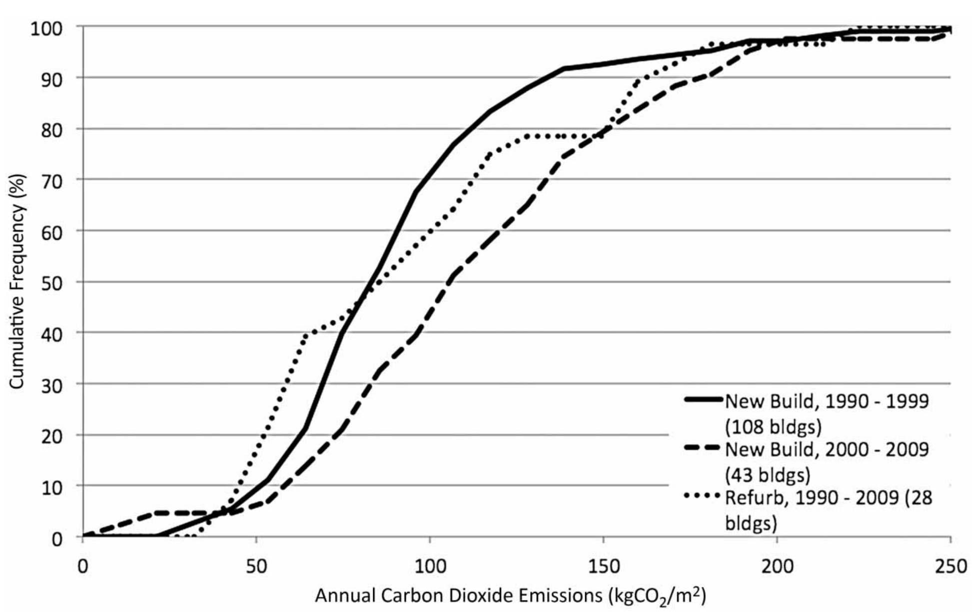

Figure 15 Variation of annual CO_2 emissions for new and refurbished offices

Furthermore, no information is available regarding the reasoning for these buildings to be refurbished, or their performance prior to refurbishment. However, the fact that the performance of the refurbished buildings matches those with the highest CO_2 emissions (*i.e.* the most modern offices) is a worrying result that warrants further research.

Regional variations

The relationship between office location and energy consumption was studied with the hypothesis that fossil-thermal energy consumption correlates with regional external temperature variations. This is reflected in the DEC methodology that assumes that 55% of fossil-thermal consumption varies with external temperature compared with 0% of electrical use, and adjusts the benchmark figures accordingly (CIBSE, 2009). It should be noted that offices were distributed fairly evenly around the 10 regions of England and Wales, with the highest proportion in London (15%) and the lowest in Wales (6%).

Figure 16 shows maps illustrating the mean fossil-thermal and electrical consumption and CO_2 emissions for each region in England and Wales. This does not suggest any clear trends in fossil-thermal consumption across the country, in contrast to a similar analysis of English schools, which showed an increase from south-west to north-east (Godoy-Shimizu et al.,

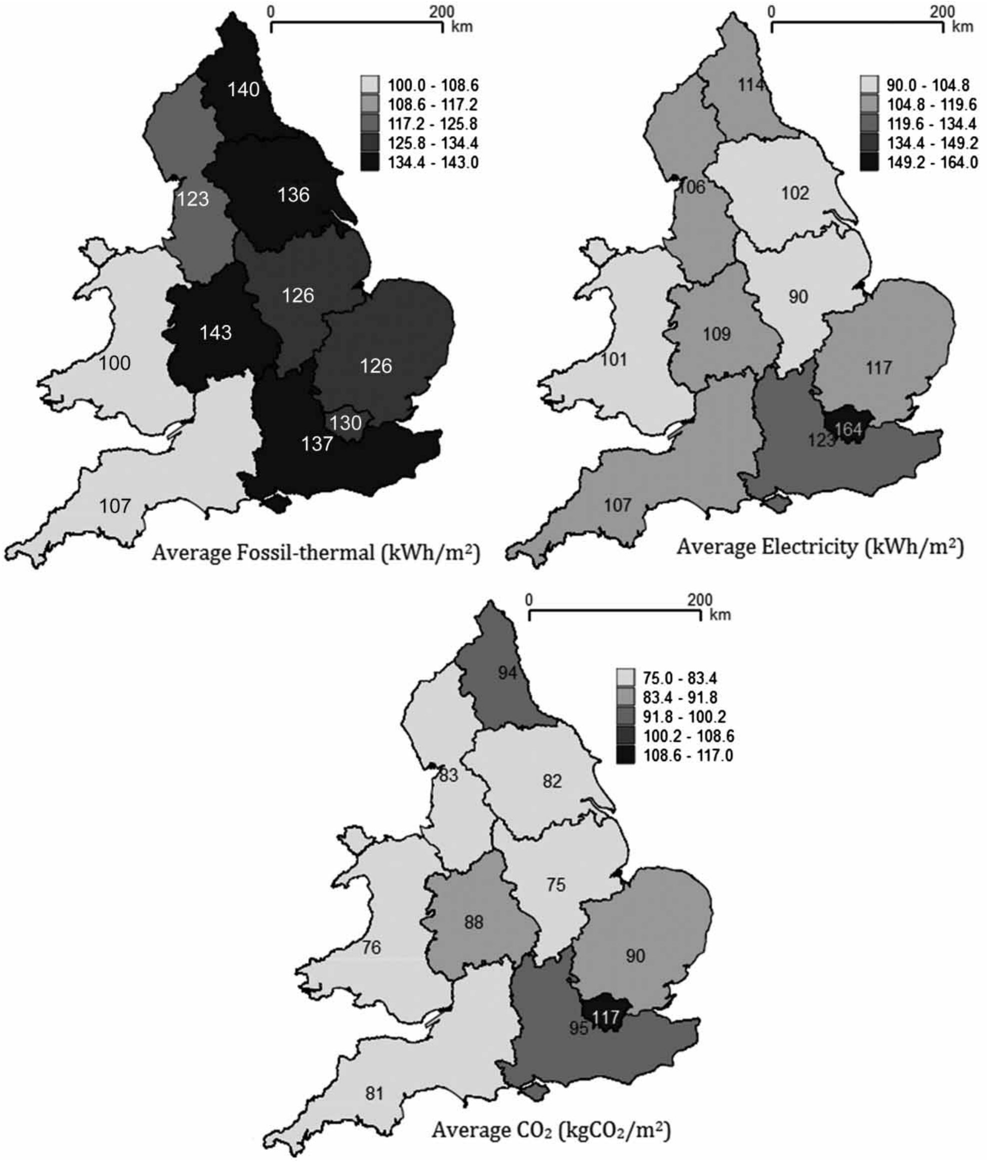

Figure 16 Regional fossil-thermal, electricity energy use and CO_2 emissions

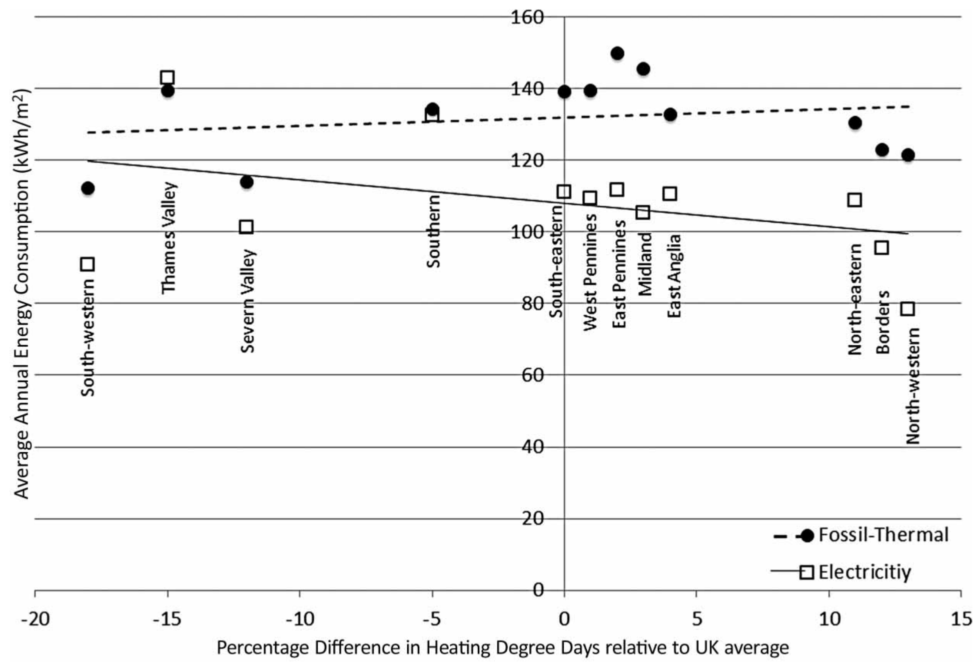

Figure 17 Mean annual fossil-thermal and electricity energy use variation with heating degree-days

2011). The map for electrical use shows that consumption is significantly higher in London than all the other regions, which have similar consumptions figures. Due to the relatively smaller variation in fossil-thermal consumption with location as well as the lower carbon intensity compared with electricity, it is the electrical trends that are reflected in the CO_2 emissions map.

The DEC methodology requires fossil-thermal energy use benchmarks to be adjusted based on regional degree data to calculate the final rating, so that buildings are not penalized for being located in colder climates. The mean fossil-thermal and electrical consumptions are plotted against the heating degree-day data for each region in Figure 17.

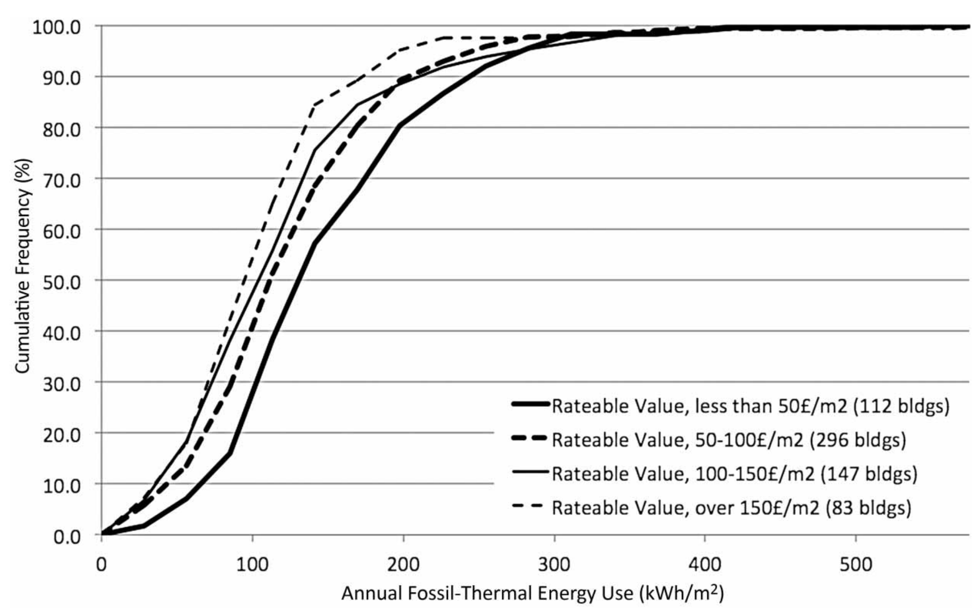

Figure 18 Variation of annual fossil-thermal energy use with rateable value (RV)

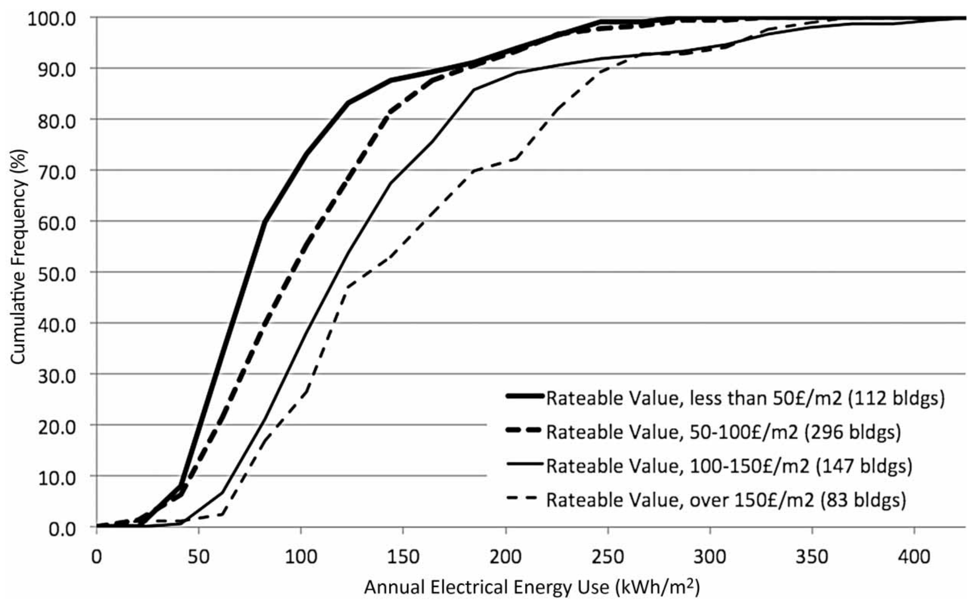

Figure 19 Variation of annual electrical energy use with rateable value (RV)

Figure 17 shows some correlation for both fossil-thermal and electrical energy use with climate ($r = 0.20$ and -0.40 respectively). The trend between fossil-thermal use and climate is broadly as expected, albeit with a surprisingly low correlation, which may suggest that the proportion of energy that is affected by climate is lower than expected in public offices. However, further investigation – for instance looking at DEC data and climate over several years – would be needed to verify this. The correlation between electricity use and climate is higher than expected. This may simply reflect the distribution of office types across the country, which was shown previously to affect electricity consumption. The survey found that while Type 1 and Type 2 offices are spread fairly evenly around the country, the highest proportions of Type 3 and 4 offices are located in the Thames Valley (36% and 52% respectively). If the Thames Valley

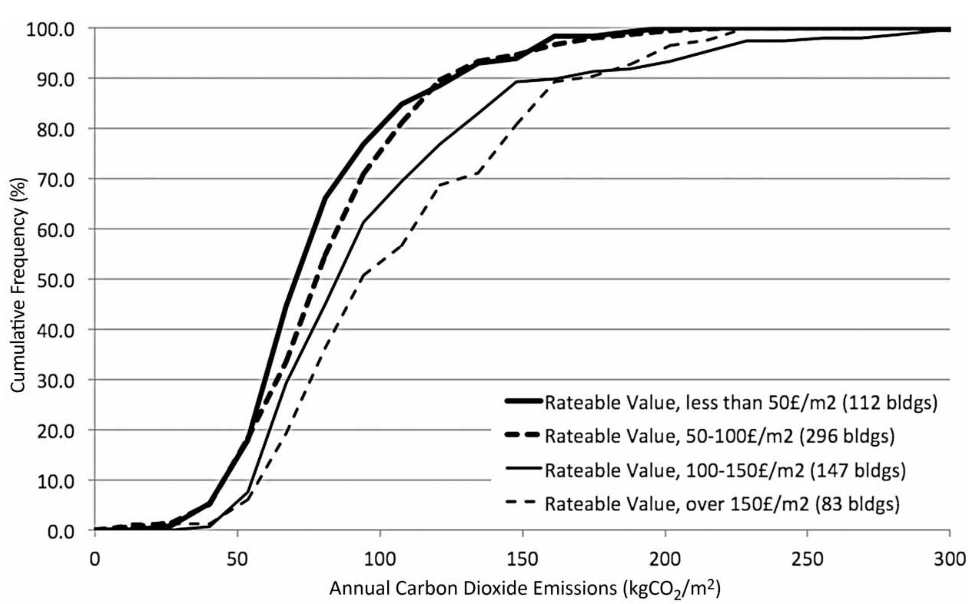

Figure 20 Variation of annual CO_2 emissions with rateable value (RV)

electricity point is removed, the correlation coefficient changes to $r = -0.16$, which is more in line with expectations.

Rateable value (RV)

RV represents the 'open market annual rental value' of a non-domestic property (VOA, 2010). It was expected that this would reflect the design quality, age, HVAC type and location in offices, and would therefore correlate to a variation in energy use.

Figures 18 and 19 illustrate the variation of annual fossil-thermal and electrical energy use with RV. The graphs show that fossil-thermal consumption decreases and electrical use increases as RV rises significantly in both cases (ANOVA, $p < 0.05$). This indicates that properties with a higher rental value typically have lower fossil-thermal consumption and higher electrical consumption. The drop in median fossil-thermal consumption between offices with an RV below £50/m^2 and those above £150/m^2 is less than two-thirds of the corresponding increase in median electrical consumption. The result is that CO_2 emissions rise steadily as RV increases (Figure 20).

The results are also consistent with the variation in RV found between the different office types. A summary of the relationship between RV and the surveyed buildings is provided in the Supplemental data online. The mean RVs were £68, £82, £159 and £260/m^2 for the four types respectively, and similar patterns were found in energy use and emissions (though unfortunately only limited data were only available for Type 4 offices).

Although RV is a result, rather than a driver, of building design, this analysis suggests that it may be a useful indicator for identifying the most energy-consuming buildings and estimating energy use in the general office stock at the large scale.

This result highlights the potential for the VOA data to be used in understanding CO_2 emissions from the non-domestic sector, as well as the building quality and type.

Conclusions and further work

This paper presents the top-down statistical analysis carried out on the public office stock in England and Wales. The analysis was carried out on a database of disaggregated, detailed information covering almost 2600 offices. The paper includes an overview of the current state of energy use in the public office stock and the corresponding CO_2 emissions profiles, a comparison of the DEC data against existing benchmarks, and an evaluation of the impact of different building and occupancy characteristics on energy consumption.

Owing to the top-down nature of the analysis, and the types of data available, this work cannot be used directly to determine fully the causal relationships. Several important factors that will have a significant influence on energy consumption, such as the hours of operation or the specific type and performance of HVAC plant, are not included in the combined database. Nonetheless, the results of this study are useful, both directly and indirectly, for understanding the public sector office stock in England and Wales. Directly, the analysis highlights the broad trends, and can be used for identifying those offices likely to have higher energy performance than the overall stock, and which may benefit most from improvements. Indirectly, the study could be used to determine the drivers of performance of offices, if used in combination with detailed surveys or modelling.

Energy performance of offices

The analysis has evaluated the energy performance profiles for public offices in England and Wales and shown that the 'typical' (50th percentile) and 'good practice' (25th percentile) benchmarks established for the DECs accurately represent the England and Wales office stock. Despite the fact that fossil-thermal accounts for the majority of energy use in offices, the current variation in carbon intensity across fuel types within the UK means that electricity typically accounts for around 70% of the total CO_2 emissions per office. Consequently, electricity use was frequently found to drive the CO_2 emissions profiles in the analysis of different building characteristics and design options. Significantly this means that, assuming occupancy behaviour remains unchanged, decarbonization of the grid will have a major impact on the relative advantages and disadvantages of different building options for low carbon design.

Analysis was also performed for different office types using four broad typologies defined by Action Energy (2003) for the general UK office stock. A sample of the public offices in the DEC database for England and Wales was surveyed and allocated to the four office types, and the energy consumption patterns of the different types were compared with the original Action Energy benchmarks. Type 4 offices ('prestige' buildings) significantly show median electrical consumption between 50% and 200% higher than the other types. The results corresponded well with the benchmark figures for Type 1 and 2 offices but the Type 3 and 4 offices were found to have lower electrical consumption than the benchmarks, even when the optional computer room electrical use in the benchmarks was removed. A further comparison with a small sample of London-based private offices suggested that public sector offices have lower emissions than their private counterparts, particularly for prestige offices, though this effect may be magnified due to the London location. This indicates that while the analysis here may be useful for understanding the general stock for simpler offices, it may not be applicable to high-end prestige private offices.

Additional factors

Additional factors linked to the office types were also considered individually, including HVAC, size and density, age, location and RV.

Analysis of the energy performance of offices with different HVAC installations revealed similar fossil-thermal performance, but significant differences in electrical consumption. This results in overall profiles that suggest that the median CO_2 emissions for air-conditioned offices is around twice that for naturally ventilated ones. It should be noted, however, that this will partly be due to the differences in the level of electrical equipment typically found in air-conditioned offices compared with naturally ventilated ones, and the need to deal with the heat generated.

Evaluation of the relationship between energy performance and building age revealed that newer buildings had significantly lower fossil-thermal consumption, which may reflect improved thermal fabric and systems. However, this was offset by higher electrical consumption, which may be attributable to increased use of electrical equipment and air-conditioning. These factors may also explain some of the reductions in fossil-thermal consumption, which is primarily for heating in office buildings. The age results suggest that, although fabric and energy efficiency requirements in the building regulations may be working well to improve the thermal performance of new building constructions, electricity consumption is the factor that defines the CO_2 emissions characteristics of the office stock. Currently, they do not cover many of the sources of electricity consumption (most significantly small power loads), which may be a major part of this. If buildings constructed with modern methods produce higher emissions than older ones, this calls into question the ability to meet reduction targets, which often assume that soon modern buildings will have very low emissions and the big problem will be the existing stock.

Analysis of the energy consumption of different regions revealed surprisingly little correlation between heating degree-days and fossil-thermal consumption. This may suggest that a smaller proportion of fossil-thermal consumption is dependent on external temperature than currently assumed (55%), or reflect systematic differences in energy use across England and Wales. However, further investigation would be needed to confirm this. The fact that energy data are collected annually means that DECs are well suited to undertaking longitudinal studies, such as looking at the impact of climate on buildings with different characteristics.

Finally, analysis was undertaken to ascertain the relationship between RV (effectively the building rent) and office energy performance. The analysis revealed strong trends for decreasing fossil-thermal and increasing electrical consumption with RV. This suggests that it may be a useful indicator in estimating office energy performance. Furthermore, comparison with the results of the survey suggests that RV may also be useful as disaggregated data for indicating office typology.

Further work and the future role of DECs

This study further highlights the role of DECs in understanding energy use and emissions in the UK non-domestic stock; a detailed discussion of the potential role in evaluating building performance and policy options can be found in Godoy-Shimizu et al. (2011). This study also shows the potential research benefits from combining the many existing large-scale, publicly available datasets (*e.g.* the UK Government property and land asset information). However, the difficulty in matching data across the different sources suggests that greater standardization of data collection may be necessary to take full advantage of the information that is being gathered.

While this paper shows that there are some similarities in energy performance between simpler public offices and the general UK office stock benchmarks, it also highlights significant differences particularly in more complex prestige offices. This suggests that a similar large-scale study focused on private offices may be very beneficial. However, in order to achieve this, it will be necessary to use DECs, or a similar method of collecting and disseminating stock disaggregated data, in the private sector. An initiative to adopt DECs in the private sector is currently supported by many construction industry bodies including the UKGBC, The Royal Institute of British Architects (RIBA) and CIBSE.

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Supplemental data

Supplemental data for this article can be accessed at [http://dx.doi.org/10.1080/09613218.2014.975416]

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Endnotes

[1]See http://www.2010.voa.gov.uk/.

[2]See http://data.gov.uk/dataset/epims/.

[3]ANOVA testing is used to test the hypothesis that groups of data are drawn from different populations by calculating the variance of data within the groups and considering the variability between groups. The *p*-value given in the text refers to the probability of the sample variances observed if the groups are from the same population (Kirkup, 2002).