Assessing building performance in use 3: energy performance of the Probe buildings

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By early 1999, the Probe series of post-occupancy studies had reported individually on 16 buildings. This paper compares their energy performance and carbon emissions (for technical performance and occupant satisfaction, see papers 2 and 4 in this issue). All but one building (which paradoxically used the least energy of Probe's air-conditioned offices) claimed to be energy efficient, but achieved performance ranged from excellent to below average. Across the sample, there was a factor of six in carbon dioxide emissions per unit floor area, and even more per occupant. The air-conditioned buildings tended to use the most energy: they usually contained more equipment, were more intensively occupied, but also usually ran more liberally and wastefully – as did more complex systems generally. Often complication seemed to have been added before the fundamentals had been made efficient. Design objectives were also frustrated by poor airtightness, control problems, unintended consequences, a dearth of energy management, and a tendency for systems to default to 'on' – also a pathological trend for information technology and its associated cooling demands. Solutions include load reduction, 'gentle engineering', better matches between demand and supply, and predictions based on a better understanding of in-use performance.

Keywords: benchmarks, carbon dioxide emissions, energy consumption, metering, post-occupancy surveys, sustainability, unintended consequences, United Kingdom

Dès le début 1999, les responsables du projet Probe d'évaluation de la fonctionnalité de bâtiments après emménagement avaient fait rapport sur 16 bâtiments. Le présent article compare le rendement énergétique et les émissions de carbone de ces bâtiments (pour ce qui est du rendement technique et de la satisfaction des occupants, cf. les articles 2 et 4 du présent dossier. A l'exception d'un bâtiment (qui, paradoxalement, était le plus petit consommateur d'énergie des bureaux climatisés de type Probe) tous les autres prétendaient être rentables sur le plan de l'énergie; en réalité, leur note d'évaluation était comprise dans une fourchette entre «Excellente» et «Inférieure à la moyenne». Dans cet échantillon, on a relevé un facteur de six pour les émissions de dioxyde de carbone par unité de surface de plancher et même plus per occupant. Les bâtiments climatisés ont tendance à être les plus gros consommateurs d'énergie: ils contiennent généralement davantage d'équipements, sont occupés de manière plus intensive mais sont aussi exploités de manière plus libérale et affichent des consommations excessives, comme d'ailleurs la plupart de systèmes complexes. Il apparaît fréquemment que l'on ait ajouté des complications avant même d'essayer de rendre plus efficaces les systèmes de base. Les objectifs de conception ont été contrecarrés par une mauvaise étanchéité, des problèmes de contrôle, des conséquences involontaires, une mauvaise gestion de l'énergie et une tendance pour les systèmes à se mettre par défaut sur la position «marche», ce qui est également une inclination pathologique que l'on constate dans les technologies de l'information et dans la demande en refroidissement associée. Les solutions passent par une réduction des charges, une «ingénierie douce», de meilleurs équilibres entre la demande et la fourniture et des prévisions basées sur une meilleure compréhension des performances en service.

Mots clés: Tests de performances, dioxyde de carbone, émissions, consommation d'énergie, mesure, études de fonctionnalité après emménagement, conséquences involontaires, Royaume-Uni

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Introduction

The Probe studies provide feedback from buildings in use, so helping the building industry, its clients, and government to find ways of improving technical performance and occupant satisfaction whilst reducing impact on the environment. Energy performance and carbon dioxide emissions are key concerns at present, with the Kyoto commitments the first small step towards the sustainability transition.

Operational energy use in buildings accounts for 46% of the UK's carbon dioxide emissions. Emissions from the service sector have been growing, both absolutely and proportionally; and are now overtaking those from manufacturing industry. Due to its carbon intensity, electricity use tends to dominate emissions from many UK commercial buildings. However, good thermal performance and minimizing the need for heating will also be important to buildings of the 21st century.

This paper reviews the energy performance of the 16 buildings studied in Probes 1 and 2. Their characteristics are summarized in Table 1 and discussed in more detail in part 2 (Bordass *et al.*, 2001a). The methods used are detailed in part 1 (Cohen *et al.*, 2001). The buildings themselves were also reviewed in *Building Services Journal* at the time of their completion.

It is often said that new buildings are but a drop in the ocean, with annual output representing no more than 1% of the total stock. However, rapid improvements in energy performance are essential. It will be a massive lost opportunity if new buildings add to the problem rather than the solution, particularly as many improvements can be made with relative ease. Furthermore, many of the energy issues exposed are equally applicable to the alteration, refurbishment and management of existing buildings; and to the equipment used in them.

There is a massive range in the energy use indices and CO_2 emissions per square metre of treated floor area of the buildings studied. If expressed per occupant, the variation is yet wider: the two highest building services energy consumers (HFS and ALD) were relatively lightly-occupied; while the low-energy educational buildings had very high peak occupation densities. However, we do not quote per capita consumption, because:

- Area is more reliably measured than occupancy.
- Many aspects of building energy consumption are more area than occupancy-related.
- Others which should be occupancy-related are only weakly so, owing to plant inefficiencies and a tendency to default to ON.
- Hours of use by nominal occupants can differ widely.

Ideally, energy benchmarks would be separated into area- and occupancy-related parts, and FMs would keep records

Table 1 The buildings studied

Name	Abbreviation	Function	(TFA = treated floor area) HVAC strategy	TFA m^2	Date
Probe 1					
Tanfield House	TAN	Very deep plan administrative centre	AC	19800	Sep 95
1 Aldermanbury Square	ALD	Narrow plan speculative office	AC	7000	Dec 95
Cheltenham & Gloucester Bldg Society	C&G	Deep plan headquarters	AC	17400	Feb 96
de Montfort University, Queens Building	DMQ	University engineering department	ANV	8400	Apr 96
Cable & Wireless Training College	C&W	Residential training centre	ANV (part)	11400	Jun 96
Woodhouse Medical Centre	WMC	Doctors' and Dentists' surgeries	NV	640	Aug 96
HFS Gardner House	HFS	Headquarters office	AC	3800	Oct 96
Anglia Polytechnic University	APU	Learning Resource Centre	ANV	5650	Dec 96
Probe 2					
John Cabot City Technology College	CAB	Secondary School	NV/ANV	8800	Oct 97
Rotherham Magistrates Courts	RMC	Courtrooms and offices	MM	4350	Dec 97
Charities Aid Foundation	CAF	Principal office (pre-let)	MM	3700	Feb 98
Elizabeth Fry Building	FRY	University teaching	MM	3130	Apr 98
Marston Books Office	MBO	Principal office (pre-let)	NV/(ANV)	960	Aug 98
Marston Books Warehouse	MBW	Warehouse (pre-let)	NV	5030	Aug 98
Co-operative Retail Services	CRS	Large head office	AC/(MM)	17300	Oct 98
The Portland Building	POR	University teaching	ANV/MM	6000	Jan 99

HVAC Type: AC = Air Conditioned; NV = Naturally Ventilated; ANV = Advanced Natural Ventilation; MM = Mixed Mode (The HVAC type is bracketed if it is a minor part of the building or has a minor influence) DATE refers to date of publication in *Building Services Journal*.

of say person-hours occupancy to some agreed industry standard. However, we are quite a long way off that yet, so prefer to consider energy breakdowns by area and end-use first and to consider other factors like occupancy, intensity of use and weather dependence second.

Gas consumption

Heating systems

All Probe buildings to date have been heated by natural gas, the most widely used heating fuel in recent UK buildings, owing to its availability, convenience and relatively low cost. Most of them had perimeter LPHW (hot water calorifiers served by their gas-fired heating boilers) radiators or convectors, except for:

- The highly-insulated FRY, which was kept at a stable temperature by its embedded ventilation system plus a total of five 200 Watt (sic) electric perimeter radiators in corner rooms.
- The warehouse MBW (with suspended gas-fired warm air heater units).

Heating plant and its installed capacity is summarized in Table 2.

Domestic hot water

Domestic hot water services (HWS) for WCs and tea points in the office and 'other' buildings were usually local electric, with LPHW calorifiers at C&W, HFS and CRS. Where offices had catering kitchens, however, these had LPHW calorifiers, except at the speculative ALD. All the educational buildings had LPHW calorifiers, plus electric water heaters in remote locations at CAB and FRY. POR used solar collectors (Figure 1) and APU condenser heat from the bar cellar cooler to preheat their HWS.

Overview of gas consumption

Figure 2 shows the annual gas consumption of all the Probe buildings, sorted in order of increasing use in kWh/m^2 of treated floor area (gross internal area less plant rooms, unheated stores, ducts etc.) and split into:

- Heating and hot water. With the time and information available, it was not possible to apportion gas use to HWS with any precision. Instead differently-patterned bars are used to identify the various systems installed.
- Catering, for the six buildings with catering kitchens including gas equipment.

Table 2 Heating and hot water plant data

Name	Abbreviation	Heating plant W/m^2	Type	Hot water for kitchens and WCs	
Probe 1					
Tanfield House	TAN	221	Steel boilers	From boiler	Electric
1 Aldermanbury Square	ALD	117	Light modular boilers	Electric	Electric
Cheltenham & Gloucester Bldg Society	C&G	207	Cast iron pressure jet boilers	From boiler (1)	Electric
de Montfort University, Queens Building	DMQ	144	1 condensing, 2 high efficiency boilers (2)	NA	From boilers
Cable & Wireless Training College	C&W	120	High efficiency boilers	From boiler	Varies
C&W leisure building (with swimming pool)		230	High efficiency boilers		
Woodhouse Medical Centre	WMC	47	Wall hung condensing boilers	NA	Electric
HFS Gardner House	HFS	158	Light modular boilers	From boiler	From boiler
Anglia Polytechnic University	APU	132	Low NOx condensing boilers	From boiler plus heat recovery	From boiler
Probe 2					
John Cabot City Technology College	CAB	119	1 condensing, 2 high efficiency boilers	Separate boilers	Electric
Rotherham Magistrates Courts	RMC	184	Cast iron atmospheric boilers	Electric (small)	Electric
Charities Aid Foundation	CAF	108	Cast iron modular boilers	Electric (small)	Electric
Elizabeth Fry Building	FRY	23	Wall hung condensing boilers	Gas heater	Varies
Marston Books Office	MBO	104	Cast iron modular boilers	NA	Electric
Marston Books Warehouse	MBW	99	Warm air unit heaters	Electric (small)	Electric
Co-operative Retail Services	CRS	129	Cast iron pressure jet boilers	Local boilers	Electric
The Portland Building	POR	120	Cast iron modular boilers	From boilers	From boilers

(m^2 is of TFA (treated floor area) = gross internal area less plant rooms, ducts and unheated stores, voids etc.).
Notes: (1) with summer condensing boiler for kitchen; (2) with 38 kW baseload combined heat and power unit.

- Gas-fired steam humidification: this was used in TAN and C&G only.

For clearer comparison, heating consumption has been normalized to a standardized year of 2462 degree-days to a 15.5°C base temperature, as commonly used in the UK.[1]

Figure 1 Turrets at the Portland Building. *Photo:* Bill Bordass
Note: Five glazed turrets help to express POR's environmental control systems architecturally. They contain motorized windows which (with mechanical assistance where necessary) allow air to be exhausted, via the stair towers, from ceiling bulkheads running down the middle of the occupied floors below. Some turrets – like this one – also contain small solar panels for preheating. However, the gas-fired boilers in the plant rooms immediately below are not condensing.

For many of the buildings the normalization could only be crude, since monthly gas bill data was inadequate, with many estimated readings. MBW and C&W did not have enough monthly information to justify any normalization.

> 'On a building average, 71% of CO_2 emissions from the Probe buildings arose from normal building services . . .'

Benchmark comparisons

Figure 2 also shows (marked >>) some relevant benchmarks for offices from Energy Consumption Guide 19, ECON 19 (DETR, 2000); plus a reference good practice AC office building, One Bridewell Street (DETR, 1991), a case study in the Energy Efficiency Best Practice programme. The data reveal a wide range in gas consumption, from under 40 kWh/m^2 at FRY to 400 at C&W, which however had special features including 24-hour residential use and a sports centre with swimming pool. The majority of the Probe buildings used between 100 and 150 kWh/m^2 – mostly for heating – and also tended to fall between ECON 19 'typical' and 'good practice' levels. Since nearly all the buildings claimed to be low-energy, this performance was disappointing. However, commercial and public buildings in the UK which consume much less than 100 kWh/m^2 of heating fuel are rare, even

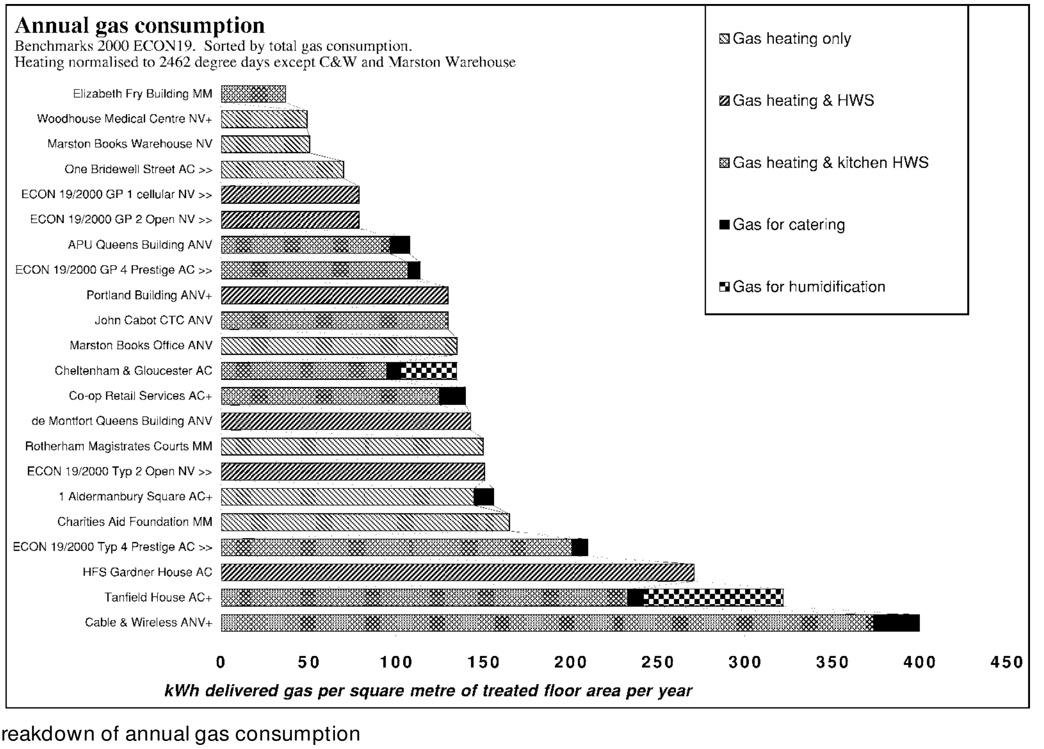

Figure 2 Breakdown of annual gas consumption

Table 3 Chiller and air handling data (AC and MM buildings only)

Name	Abbreviation	Chiller plant		Ventilation	SFP typ/ave W/(litre/sec)	Rate ac/h	Typical hrs/year
		W/m²	Type				
Tanfield House	TAN	172	Reciprocating	Floor VAV	5.0/1.7	12.0/5	4500
1 Aldermanbury Square	ALD	97	Reciprocating, plus ice store	Fan assisted VAV	4.6/3.0	pri 9 max	3500
C&G Bldg Society	C&G	139	Reciprocating	Ceiling VAV	5.0/2.5	8.0/5	3500
HFS Gardner House	HFS	211	Reciprocating	Displacement	4.0/4.0	3.0/3.0	4200
Rotherham Magistrates Courts	RMC	70	Reciprocating	Displacement	3.8/3.8	3.9/3.9	2850
Charities Aid Foundation	CAF	NA	3 rooms only	Displacement	3.1/3.1	3.1/3.1	3000
Elizabeth Fry Building	FRY	NA	Night vent	Vented ceiling slabs	2.2/2.2	2.2/2.2	2500
Co-operative Retail Services	CRS	34	Reciprocating, plus ice store	Displacement	4.0/4.0	4.0/4.0	3000

(m^2 is of TFA (treated floor area) = gross internal area less plant rooms, ducts and unheated stores, voids etc.) SFP = Specific Fan Power in W/(litre/sec) of air moved. Two figures are given – first the ratio of the installed fan power (supply, extract and terminal systems combined) to the design air volumes in the main areas; and second (after the slash) the mean annual average SFP in practice.

though design estimates frequently produce figures of in the region of 50 kWh/m^2 or less.[2]

The higher gas consumers

Apart from the anomalous C&W, the high gas consumers TAN and HFS had two things in common, they were air-conditioned head offices with full fresh-air ventilation and no heat recovery. Both also had long running hours, at TAN owing to its extended occupancy and the difficulty of zoning an office with very large open floorplates. HFS's extended running hours were required to maintain comfort in a building with modest mechanical air change rates (3 ac/h) and a significant air leakage problem. If full fresh air is used (and it is increasingly advocated for health reasons) then heat recovery needs to form an integral part of the package – provided, of course, that the cost and carbon emissions of any electricity used to recover the heat are significantly less than the value of the heat recovered. This is particularly important with displacement ventilation (as in these two buildings): although this reduces the cooling loads falling on the plant, it also means that the air tempering benefits of mixing incoming air with warmer room air before entering the occupied zone cannot be obtained. TAN also had high gas consumption for its central steam humidification; again partly a consequence of its full fresh-air ventilation.

The other buildings which had displacement ventilation (CRS, RMC and CAF) all had heat recovery with cross-flow heat exchangers; and lower – though only average – levels of gas consumption. In all these buildings, further savings could have resulted from better airtightness and better system control; together with better zoning or demand-responsiveness at RMC, where the ventilation often had to run (at constant volumes and at generous levels), even when most of the courtrooms and waiting areas served were empty.

The lower gas consumers

Of the AC buildings in Probe, only C&G consumes less gas than the Type 4 GP benchmark,[3] and this even after a normalization uplift of 34%. FRY, the lowest gas consumer, stands out as an example of what can be done in a massive, well-insulated, airtight building (Figure 3) with managed fabric thermal storage (see paper 2) . . . provided sufficient attention is devoted to detail in briefing, selection of team, design, construction, handover, monitoring and management. However, FRY's gas consumption was initially much higher (although still better than 'good practice' benchmarks) until monitoring revealed control problems. The university took these seriously, and decided to extend the campus electronic Building Management System (BMS) into the building to improve monitoring and control of this slow-responding building, whose behaviour was otherwise difficult to understand. FRY's office ventilation plant also had highly-efficient regenerative heat recovery and the three small domestic condensing boilers with an installed power level of 22.5 W/m^2 as against typically 100 to 200 W/m^2 in the other buildings.[4] Condensing boilers were disappointingly rare in Probe: there were none in the office buildings, just the lead boilers at DMQ and CAB with a full set only at APU and FRY.

The highly-insulated WMC (Figure 4) – again with domestic wall-hung balanced-flue condensing boilers – also had very low heating energy consumption. However, this building had been designed primarily with winter in mind and tended to overheat in summer – partly as the intended ventilation strategy could not be operated by users, e.g. with openable roof windows which were only accessible from ladders (remote controls could quite easily have been added in the design or by the users, but they weren't). Nevertheless, in the quasi-domestic environment of WMC, many of the occupants forgave such deficiencies, as discussed in paper 4 (Leaman and Bordass, 2001). However

Figure 3 The Elizabeth Fry Building (left). *Photo:* Bill Bordass
Note: FRY had the lowest heating energy consumption in Probe. It has lecture rooms on the ground floor, seminar rooms on the first floor, and largely staff offices above. Highly-insulated fabric and triple-glazed windows with mid-pane blinds minimize unwanted heat losses and gains and made perimeter heating unnecessary except in five corner rooms. Heating, ventilation and cooling is provided by blowing air through the hollow cores of the structural floor slabs. The ventilation plant operates during occupied periods, with heat recovery until embedded sensors in the floor slab reach 22°C. If is slab falls below 21.5°C the air is also heated. Overnight, the fans operate to pre-cool the building if slab temperatures are above 23°C and it is at least 2°C cooler outside. Windows are openable if occupants wish. After monitoring and fine-tuning, this building achieved exceptionally high levels of occupant satisfaction for its office staff, together with low energy consumption.

Figure 4 The Woodhouse Medical Centre (left foreground and background). *Photo:* Adrian Leaman
Note: WMC is a relatively simple building with high levels of insulation, giving low heating energy consumption and the lowest carbon dioxide emissions in Probe. Mechanical ventilation with heat recovery was also included, but rapidly abandoned as the occupants did not understand it or perceive any benefits: this is often a problem with unfamiliar techniques and technologies. The design took less account of summer performance, leading to some overheating. However, questionnaires revealed that occupants were more forgiving of problems in this domestic-style environment in Probe's more complex and management-dependent buildings.

not all, in two rooms local split system cooling units had been added.

MBW's gas consumption was also low, but it had background heating only, to a setpoint of 10°C at floor level, seemingly more like 12°C in practice (and achieving rather higher minimum temperatures – typically 15°C – on the mezzanine). The five small offices dotted-about inside it were heated to normal temperatures by internal gains, plus local electric panel heaters, used on-demand. The metering undertaken for Probe allowed MBO's degree-day behaviour to be well established, but warehouse use could only be calculated by annual difference as there was not enough of a cold spell during the monitored period. With degree-day correction, MBW's normalized gas consumption might have been in the region of 75 kWh/m^2.

Electricity consumption

Overview of electricity consumption

Figure 5 shows annual electricity consumption per m^2 of treated floor area for the same buildings and benchmarks as Figure 2. This time the data are sorted in order of increasing energy consumption for normal building services (shown to the left of and including the bar for lighting). To the right of this are items (office equipment, kitchen equipment, computer rooms and their air-conditioning, and so on), which are normally regarded as occupier's equipment and often not included in design estimates of annual energy consumption, or at best rather sketchily. Such omissions – often together with liberal and wasteful operation – contribute to the big differences that often occur between design claims for energy-efficiency and metered consumption in use.

The influence of air conditioning

As with gas, there is nearly an order of magnitude between the highest and lowest electricity consumers. What is going on?

- Clearly, the air-conditioned buildings are at the high end of the scale, the naturally-ventilated and ANV at the low end, and mixed-mode generally in the middle.
- Some of this is the direct result of the extra HVAC equipment: refrigeration and heat rejection, and in particular the fans but also pumps.
- For the most part, the hours of use of the buildings and the energy used by the occupier's equipment also rises; so air conditioning is not the sole influence, but one of a cluster of characteristics which tend to be associated with intensively-used, high-energy buildings.
- Equipment in more complex buildings is more likely to run liberally and wastefully, and with more significant implications for energy consumption.

Though not a Probe building, in the histograms (Figures 1, 5 and 6) we have included reference data from One Bridewell Street. This very efficient AC office, completed in 1987, is the exception that proves the rule. The subject of an energy efficiency case study (DETR, 1991); when revisited by Eley (1996) it was still performing well. The key to its good performance (a ‘pre-let’, built by a developer for a specific customer) was – as at FRY – not so much the technologies used as care: in briefing, design, procurement and management. Its occupier:

- Commissioned a pre-design study to help identify their requirements.
- Insisted on having, influencing (and sometimes paying extra for) some things (such as a BMS and high frequency lighting with infra-red controls) which the developer said were not necessary or affordable.
- Took care to appoint an excellent facilities and engineering manager (who has recently left – it will be interesting to see whether his successors can maintain such high performance).

The result was an AC office which was not only highly efficient in operation (with electricity consumption similar to a typical NV one, and an even lower gas consumption), but which also achieved good occupant satisfaction and unusually high rental levels for the area, demonstrating the ‘triple bottom line’ benefits of good all-round quality. However, unlike the other air-conditioned offices, energy consumption by tenant’s equipment was similar to those in Probe’s NV buildings: partly a result of the tenant’s operations (e.g. now understood to use mostly laptops); and partly the FM’s attention to energy management and waste avoidance in these aspects too. Sadly, the example of One Bridewell Street has seldom been replicated.

The low electricity consumers

The six lowest electricity consumers (i.e. lower than the ECON 19 Typical benchmark for an open-plan office) included al four ANV educational buildings, plus the quasi-domestic WMC and the warehouse MBW. In the educational buildings, part of the reason is relatively low hours of use, more rigid occupancy schedules than in the office buildings; and with teaching rooms – although densely occupied at times – also empty for many hours a day and in vacations. In the year of the survey, occupancy at APU – the lowest electricity consumer – was also well below design levels.

Building services electricity use in these buildings tended to be dominated by lighting, which was usually itself relatively low, owing to lower illuminance standards than in the offices and shorter hours of use, owing to better daylight and more effective controls. The exceptions were:

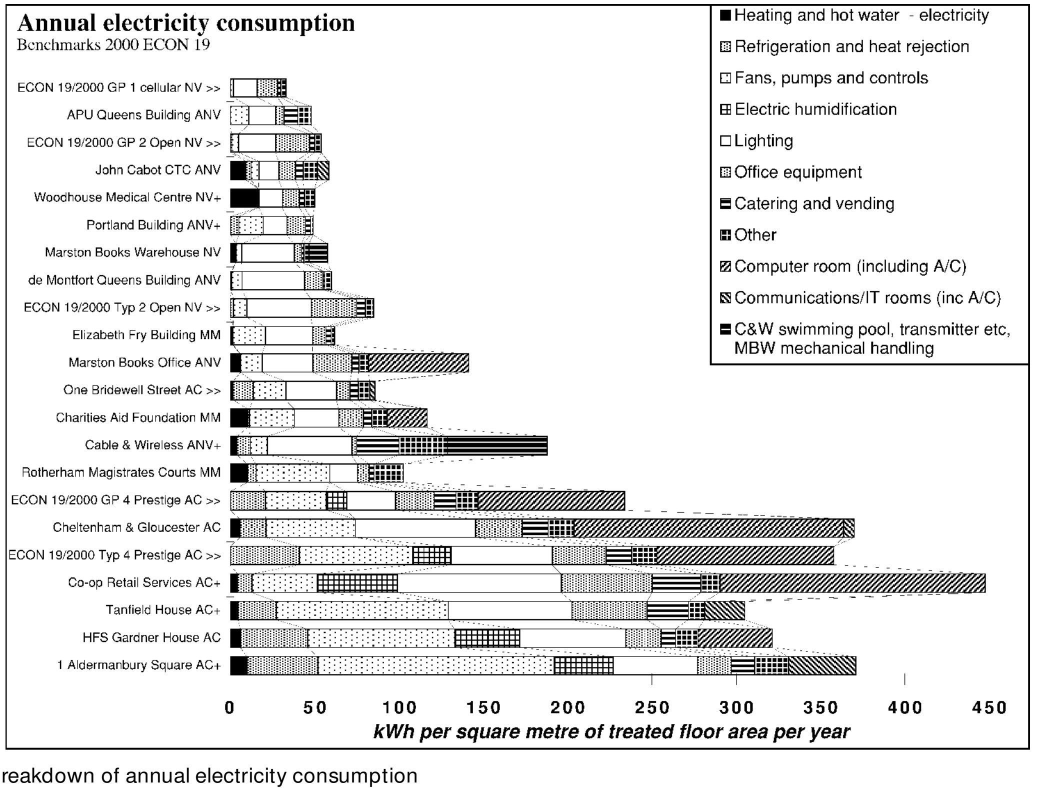

Figure 5 Breakdown of annual electricity consumption
Note: The buildings are sorted in order of increasing consumption for normal building services, i.e. to the right-hand end of the white portion of each bar (lighting).

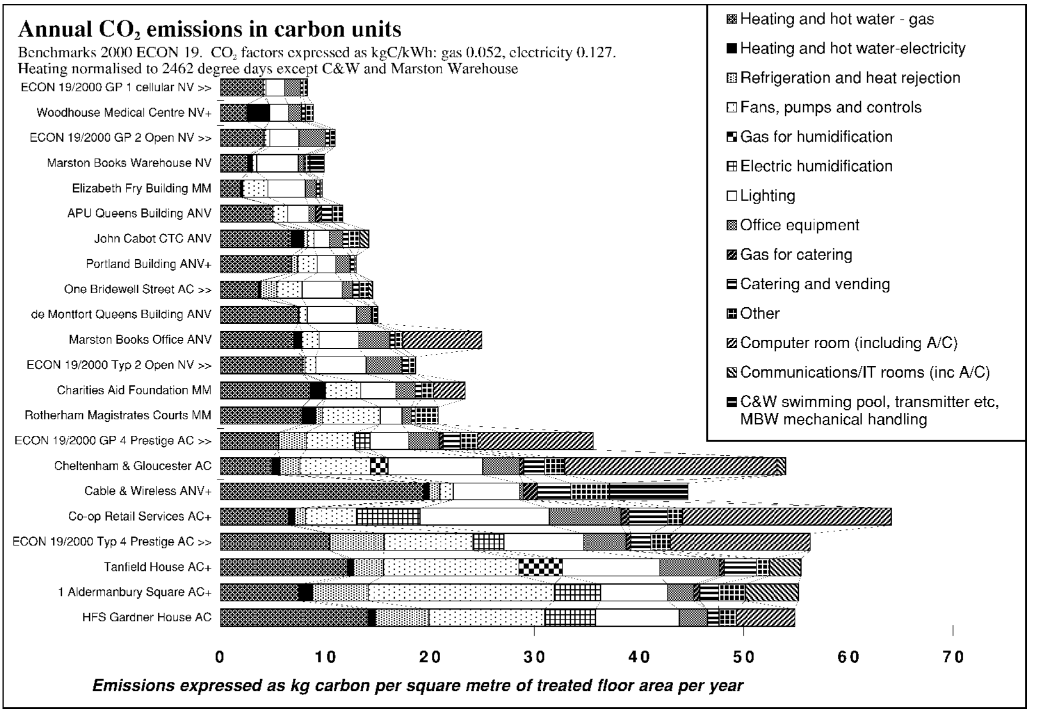

Figure 6 Breakdown of annual carbon dioxide emissions (expressed in kg of carbon content per m² of treated floor area) from gas and electricity consumption
Note: The buildings are sorted in order of increasing emissions for normal building services, i.e. to the right-hand end of the white portion of each bar (lighting).

- CAB, with electric water heating for the toilets and cleaners in the classroom wings (HWS in the kitchens and changing rooms is gas-fired); a constantly-running air-conditioner in the conference room, and a relatively large number of zone heating pumps – which also continued running when they should have been off, owing to shortcomings in BMS control and management.

- WMC, with high consumption (17 kWh/m²) by large numbers of electric water heaters, particularly in the doctors' and dentists' surgeries, with high standing losses and on 24 hours. Using the domestic gas boilers for HWS here would have been more economical in both energy costs and carbon emissions.

- POR, in which the comfort cooling systems in six lecture and seminar rooms ran continuously. The main lecture room is also air-conditioned, but better controlled.

These examples indicate that while these buildings were relatively successful in achieving their low-energy aspirations, the spotlight then fell onto relatively small things which seemed of little relevance in the design strategy, but had disproportionate effects on energy consumption, particularly if they defaulted to ON. It is important for energy predictions to take account of everything, and to continue reviewing estimates and priorities as design and construction progresses.

Although good in relation to an office benchmark, even after allowing for its mezzanine and its two-shift operation, MBW's lighting energy consumption was similar to the 'Typical' standard in the energy consumption guide for industrial buildings, ECON 18 (DETR, 1993). This was a consequence of two countervailing effects:

- A relatively low installed power level – too low in some (underlit) areas.

- The lights being on too much in relation to both daylight and occupancy, owing to shortcomings in the controls – a widespread problem.

The high electricity consumers

The high electricity users – for building services and overall – were distinctively the five air-conditioned head offices. Of these, all used well above ECON 19's Type 4 'good practice' level; and only at C&G and CRS was energy consumption by the building services below the Typical benchmark. Revealingly, C&G (Figure 7) – the lowest building services energy consumer amongst the air-conditioned offices – was the most conventionally-designed and serviced of the group; and had made the fewest claims to energy efficiency. The occupier had also undertaken more energy management, so the hours of boiler, chiller and pump operation were much lower than in the other AC offices; with somewhat less fan operation too.

Figure 7 The Cheltenham and Gloucester Building Society's head office near Gloucester. *Photo:* Bill Bordass
Note: C&G was procured very rapidly: two years from the management's decision that they needed a new building for its design, construction and initial occupation. Hence 'keep it simple and standard' was an important impetus in the design. Its building services, however, had the lowest energy consumption of the air-conditioned head offices in Probes 1 and 2, and relatively high levels of occupant satisfaction; though with some shortcomings, for example in glare control (the client did not want external devices). It was also one of the few Probe buildings in which energy management was being undertaken; albeit with some restrictions owing to the high emphasis senior management gave to service and security in a head office environment.

These buildings were more intensively-used than the others in Probe, often having major IT installations, catering kitchens, and extended hours of use (while usually only for a small proportion of their staff; this tended to bring on energy-consuming systems throughout the buildings). The consequent high levels of electricity consumption are not unusual in prestige air-conditioned offices, even recently-completed ones. Data gathering for ECON 19 and in EnREI projects in the early 1990s (e.g. Arup, 1992) showed similar or higher levels of consumption (and often of wastage) in such offices: particularly rented and multi-tenanted ones.

Not only AC offices are affected in this way: for example an environmental award-winning mixed-mode (MM) principal office surveyed a year after completion used much more electricity than the designers had predicted (Curwell *et al.*, 1999). About half of the extra came from longer running hours and lower operating efficiencies than anticipated, some of which could have been tackled by better facilities and engineering management. The other half came from items (such as catering kitchens, computer and server rooms) which were not considered in the design estimates.

The most common characteristics in all these buildings is that systems default to ON, and run for longer hours and at higher intensities than anyone had anticipated, particularly when making energy consumption estimates. The causes include:

1. A dependency on energy-consuming systems with little choice to use anything else.
2. Deep-plan open spaces in which all systems tend to run even when only a few people are in.
3. Problems with building and systems performance which are most easily overcome by extending operating hours; for example air conditioning to counter the effects of high air infiltration at HFS; or leaving boilers on to avoid pressurization unit lockouts at TAN.
4. Tail-wags-the-dog-effects, where large systems are left running to support small loads. This particularly applies when the same plant serves comfort cooling cooling systems and 24-hour equipment rooms.[5] At TAN the management was in the process of detaching these rooms from the main chilled water system. C&G had also taken two server rooms off a VAV plant which also served one-quarter of the offices and had previously had to run all night.
5. Default states which are non-optimal, but cause the least trouble for occupants and management. The most common of these is blinds closed – lights on, which has undermined many a daylight and lighting control strategy.
6. Poor interfaces to control systems, which make it difficult or impossible for occupants and management to tune the systems as they would like. For example, in several buildings, the lighting control system brought on all the stair and corridor lights whenever anyone was in. At TAN this included all the lights in the WCs (all individual cubicles) and meeting rooms!
7. Unintended consequences of control systems, for example the occupancy-sensing at HFS which often turned lights on in cellular offices unnecessarily; and had to be over-ridden in open-plan areas owing to the irritation it caused. Photocells used for perimeter dimming at HFS were also confused by light reflected upwards onto them from the venetian blind slats, requiring control setpoints to be raised, so reducing the benefits of daylight-linked dimming.
8. Increasing pressures on facilities and engineering managers to deliver service, with little regard for economy.
9. Contracts for outsourced facilities management and maintenance services which say little or nothing about operational management and energy efficiency.

10 A widespread lack of interest in or application to energy management generally, in an environment in which energy prices have been falling and contract deals can save much more money, much more easily than attending to technical and operational details.

While such problems afflict many buildings, their implications for energy wastage tend to be most extreme in the more highly-serviced ones.

The educational buildings often had much higher peak occupation densities, but these had little effect on their energy consumption, which tended to be more related to standards, occupancy times and particularly floor area than to population numbers. The move towards deeper and more open planning and greater intensities of use in educational buildings; and also from local to central control of lighting and other systems, is however changing this, with a trend to greater electricity use.

Electricity consumption by occupiers' equipment

Energy consumption by general office equipment (not including equipment in dedicated rooms, which is separately recorded) was significant, but usually less than the lighting, partly because even in an office building up to half the floor area is usually devoted to other things: circulation, restaurant, toilets, meeting rooms and so on. Typical heat gains from office equipment in the office areas of most buildings were compatible with the British Council for Offices' suggested levels of 15 W/m^2 with local hot spots of 25 W/m^2, but with many lower-density buildings and areas, and occasional pockets of high density. A worrying trend, however, was for equipment to be left on permanently, even overnight: CRS – the last AC office to be surveyed – suffered particularly from this. Some IT departments even advise staff never to turn their computer equipment off.[6]

Computer and communications rooms can use an important part of a building's annual electricity consumption owing to their 24-hour operation. However, they and their air-conditioning are seldom properly accounted for in design estimates or statistical comparisons. In addition, the equipment and the AC plant is hardly ever submetered; though UPS displays can provide valuable information on VA output, if not on true power (and power factors of IT equipment can be low). As a rule of thumb, the annual energy consumption of AC systems in machine rooms is some 80% of that used by the IT equipment, though this proportion typically varies from 50% to 150% or more (and BT has reported 300% for some of its installations). Metering and management of these areas should be encouraged; and any proposed statutory restrictions on in-use building energy consumption will be difficult to implement without such information.

> 'Governments should encourage . . . equipment which are ef cient when on and use the absolute minimum of electricity when off or on standby'

In relation to the ECON 19 benchmarks, four buildings were particularly anomalous:

- MBO's computer room consumption in relation to the Type 2 benchmark. This related to the computers, file servers and printers used to run the business and to manage the operating systems in the warehouse MBW. Although the installation was quite modest (averaging some 6.5 kW, split 3 kW to equipment and 3.5 kW to air conditioning), its round-the-clock use made this mount up to a major part of the consumption of the 962 m^2 office building. Such installations are becoming more common, and can easily increase the annual electricity consumption of an NV building by 50% or more.

- CAF's larger computer room had less impact on this larger building, but was still significant. Air-conditioned (or at least comfort-cooled) computer, file server and communications rooms are becoming common today, even in naturally-ventilated buildings, and need to be accounted for in future benchmarks. Sub-metering would be a useful management aid.

- C&G had a particularly high consumption for its large computer suite. This is hardly surprising for the head office of a large national financial services company, but an estimated 45% of this was used by the air conditioning, in spite of low-energy design features such as glycol 'free' cooling.

- CRS had a similarly high computer suite consumption to support its retailing operation, but here the air conditioning was estimated to use over 60% of the total, partly because the installation was generously sized for the loads that had actually materialized.

Efficient and responsive machine room cooling is an important agenda item for the future. However, in the long run IT loads themselves must come under the spotlight: they are already reducible – sometimes by a factor of ten – using available technology and their energy use and other implications are multiplied tremendously in the design of buildings and the installation and use of air-conditioning systems.

Catering and vending

Apart from condenser heat recovery from a bar cellar chiller for preheating kitchen hot water at APU, no catering installations had paid any particular attention to energy efficiency. Few kitchens were submetered (TAN, CAB and CRS were exceptions); but even here the meters were not usually read. In all the buildings, the catering contractors received all their energy 'free' from their employer, so had no incentive to make either investment or management savings. For energy efficiency to be more seriously considered, contract conditions need to be reviewed.

Other

The biggest item here was usually external lighting, at least on the non-urban sites. Provision and hours of use of outside lighting have been rising over recent years, owing to security concerns; so care is required in design, control and management to avoid waste. In these low-rise buildings, lifts are a minor item; but here architects increasingly prefer hydraulic designs, which are more attractive and flexible but much less energy efficient than traction ones.

Carbon dioxide emissions

Figure 6 shows the annual gas and electricity consumption, converted to carbon dioxide emissions at UK average factors used in ECON 19 (2000) of 0.052 kgC/kWh of delivered gas and 0.127 kgC/kWh (average) of delivered electricity (0.19 kg CO_2/kWh gas and 0.46 kg/kWh electricity). This gives a combined ranking of all the buildings and benchmarks in the units which best suit the UK government's policy objectives (N.B. in other countries priorities will differ, owing to differences in the national mix of heating fuels and primary energy sources for electricity generation).

The ranking of buildings for carbon dioxide emissions tells much the same story as for electricity whose carbon intensity is 2.4 times that of gas per delivered unit, but with some interesting outliers which are either high or low energy consumers of both fuels. On a building average, 71% of carbon dioxide emissions from the Probe buildings arose from normal building services (not including dedicated kitchen ventilation and computer room air conditioning systems); this proportion averaged 65% in the AC offices and 80% in the educational buildings.

For the building services in the low-emissions buildings:

- WMC becomes the lowest consumer per square metre of treated floor area; with a very similar profile to the ECON 19 Type 1 'good practice' benchmark when CO_2 emissions from the gas heating and the electric hot water are combined. Essentially there has been a trade-off between very low heating-related emissions owing to the superinsulation; and high hot water-related ones arising from the large numbers of electric water heaters, all on constantly.
- The MM FRY had similar or lower emissions than the ANV educational buildings – which the occupants also found less comfortable. However, FRY benefited from a degree of monitoring, controls upgrading and energy management not encountered in any of the other buildings. It is a very interesting exemplar, as its office occupants think its internal environment is unusually good, particularly in summer (DETR, 1998) by virtue of its thermal mass, solid walls and night cooling by mechanical ventilation only.

For the high-emissions buildings (all air-conditioned) it is instructive that HFS and ALD – the two highest (just) for their building services – were much less densely occupied than C&G, CRS and particularly TAN. Most of the excess was related to fans and to a lesser extent pumps and chillers; and largely a consequence of fabric and operational problems, which were also less easily tackled in these smaller buildings, because they had fewer on-site engineering staff.

Conclusions

The energy expert Amory Lovins has said 'much energy consumption comes from the compounding of unnecessary loads'. This was often so in the Probe buildings, where energy use was generally higher than anticipated, particularly in the buildings and areas with high levels of servicing. Normal building services accounted for between 23 and 160 kg CO_2/m^2. Other items – particularly computer rooms, catering and office equipment – added between 25% and 80% to this.

Energy performance assessment was an important part of Probe, and nearly all Probe buildings claimed to be energy efficient. However, the studies revealed less of a thorough-going approach to energy in briefing, design, construction and management than might have been expected.

While some buildings performed really well, they need to be regarded not as exotic and unattainable, but as stepping stones to further improvement. For example, even FRY – perhaps the best all-round example – and strong on thermal aspects, still fell short in lighting and control (particularly in the circulation areas where lights are on constantly during occupied hours). While its air transport efficiency was relatively good, in a review seminar in 1998, its designers said that they could design a successor with less than half the annual fan energy consumption. FRY could also be said to have been technology-driven (including independent technical advice from an energy expert) not benchmark-driven: there was little energy benchmarking in the brief, just an intention to do well.

> 'Monitoring feedback and effective motion are what create continuous improvement – but are sadly rare in UK buildings'

Monitoring, feedback and effective action are what create continuous improvement – but are sadly rare in UK buildings. Even FRY did not plan for the post-handover activities necessary to turn the design predictions into reality: this needed feedback from third parties interested in monitoring the building's performance. However, it is a credit to the client and the design team that this information was then acted upon. Frequently it isn't: indeed – with notable exceptions (e.g. Anon, 1997), only a few of the buildings surveyed in Probe have acted upon the survey results.

In moving towards sustainability, services need to work better with the building fabric to provide a safe, comfortable, healthy, productive and enjoyable environment to support the occupants' activities and equipment, through:

- Reductions in loads – through more efficient and better-controlled fabric and equipment.

- Gentle engineering – with improvements in effectiveness, efficiency and control.

- Close matches between demand and supply – seeking where possible to use information rather than energy to achieve the required conditions with minimum waste.

All need to be done in an effective and efficient manner, with attention given not only to the principal areas of the buildings, but to smaller areas and behind-the-scenes items.

Probe has helped to identify trends, and to illustrate where success is being achieved and where problems need to be addressed. Various issues have emerged:

- A tendency to full fresh-air ventilation, sometimes at high volumes and with no heat recovery; and leading to much increased demands for heating (even in summer) and humidification. Should heat recovery be mandatory for many systems, as it has been in Sweden?

- Increased use of humidification – usually with sterile steam for health reasons and often electrically-generated (with both a high energy costs and CO_2 overheads). In Probe (and other buildings known to the team), humidifiers – once present – also tended to be operated unnecessarily and wastefully. Guidance is needed on requirements for humidification, and its safe and energy-efficient provision and management.

- Widespread use of electric water heating: often a convenient option, but frequently not the lowest in terms of running costs and CO_2 emissions, particularly – as in all the Probe buildings with it – when it had no time control (except where retrofitted at RMC) and few attempts at water saving. Updated guidance on hot water systems should be considered.

- Lighting energy use tended to be lowest in the simpler buildings which had good, clear user control. While automatic systems did make some savings, most lacked compatibility with management and user requirements, brought lights on unnecessarily, and could annoy occupants. In the AC buildings, default to ON was the norm. The aspirations of MBO and DMQ to make good use of daylight were also frustrated by incompatible controls. Lighting energy use at the other ANV educational buildings, POR, CAB and APU, was relatively low, owing to good daylight, low installed power density, and reasonable control; but even here considerable potential for further savings was found. WMC's consumption was also low, but similar to the ECON 19 'good practice' benchmark for a naturally-ventilated cellular office. Overall, opportunities were missed and greater finesse in lighting controls design is required.

'Energy was often poorly speci ed in brie ng and design criteria'

More generally, the conclusions are:

- Energy was often poorly specified in briefing and design criteria. Advice on qualitative and quantitative aspects of briefing and design brief management needs improving. Energy benchmarks in the brief and during design development can provide a guide for design teams which lack an intimate knowledge of low-energy design; and be a useful tool for communication between all players.

- Intrinsically efficient technology (e.g. high frequency lighting, condensing boilers, energy-efficient IT) needs to be widely used. In the commercial buildings, no condensing boilers were found owing to their additional costs and the currently low price of gas. High frequency (HF) lighting was more common, perhaps owing to its claimed health benefits. Should not such items be regarded as essential baseline features, not added costs?

- Standards also need to be considered more carefully. For example, several of the office lighting systems still adopted the 500–600 lux standard rather than the lower LG3 one for VDU use. The occupant surveys however showed a general preference for lower illuminance levels. The two offices which (from questionnaires) occupants regarded as best lit, also had indirect lighting. If some individuals need extra light, this can often be provided more effectively on an ad hoc basis. Selecting appropriate standards should involve more of a dialogue, with greater consideration of individual requirements, environmental impact, and the specific features of the evolving design.

- Designs were prone to focus on specific low-energy features, and could lose sight of overall performance and priorities. Buildings are both symbolic and functional, but sometimes (as in ANV), symbolism could get the upper hand. Regular reviews are essential.

- There was relatively little benchmarking of solutions (e.g. boiler capacity, chiller capacity, pump capacity and specific fan power) as projects proceed, and very little connection between the values that tend to be found in completed buildings and the assumptions made in design estimation and computer models. Regular comparisons with client requirements and industry benchmarks should be undertaken, with more emphasis on the roots of energy consumption (service, capacity, efficiency and hours of utilization) (CIBSE, 1999).

- There was very little energy management in these leading buildings – even those which had low-energy briefs – so measures requiring management input were fragile. While the management might well swing into action if energy were to become a real priority, management time is an important design constraint. Straightforward robust, 'fit and forget' measures are preferable, with emphasis on reducing loads, efficient plant, effective controls, and waste avoidance. Energy management must be seen as an essential component of good management. Designers must also try to deliver systems which are intrinsically-efficient and user-friendly. Systems should not demand more from management than is likely to be available; should permit simple and efficient default operation; and if necessary warn of potential problems.

'There was . . . very little connection between the values that tend to be found in completed buildings and the assumptions made in design estimation and computer models'

- In some buildings – particularly in Probe 1 – very high allowances for internal gains from office equipment had led to oversized AC systems. In Probe 2, this had quietened-down. However, energy use by office equipment had continued to rise, owing to lengthening hours of operation. Management should encourage people to turn equipment off when not in use: unfortunately some IT departments do just the opposite!

- Scandalously high energy use by office equipment, both in use and on standby. At present customers do not seem to be interested in equipment energy efficiency as a purchasing criterion, so manufacturers do not compete in offering it. Indeed, manufacturers frequently seem to save a few pennies by selecting less efficient items – for example power supplies – which also add to harmonic distortion. It should also be easier to select energy-efficient equipment, for example through labelling and accreditation schemes. Governments should also encourage manufacturers to produce and customers to request equipment which are energy efficient when on and use the absolute minimum of electricity when off or on standby.

- High energy use in computer and communications rooms. For effective benchmarking, these need identifying and metering separately from the buildings. Often the design and operation of the systems could be more energy efficient. In particular, the need for close control can often be questioned. Systems could also often be more demand-responsive, with variable capacity operation, better sequencing, and avoiding standby units running unnecessarily.

- There were few submeters in Probe buildings. Where installed, they were seldom read – owing to the limited amount of energy management; and sometimes not even properly connected. Utility meter readings were patchy, particularly for gas. An initiative on better energy metering and reporting would help to foster better understanding and energy management, with routine sub-metering of main plant items and areas of high energy intensity such as kitchens; and computer rooms and their air conditioning. In the UK, the Regulator could consider requiring fuel suppliers to make fewer estimated readings, and to report consumption, trends and benchmarks to their customers. Building regulations could also require better provision for metering.[7]

'An initiative on better energy metering and reporting would help . . . energy management'

- Most AC buildings in Probe used large amounts of energy, particularly electricity. Some was an inevitable result of their intensity of use and equipment levels, but there were avoidable shortfalls in performance, efficiency, control and responsiveness. Heating, cooling, pumps, fans and lighting ran for much longer than designers had anticipated, owing to technical, management and control-related tendencies to default to ON. An initiative is required to improve performance, efficiency, control and management, particularly in mechanically-conditioned buildings. AC should not be demonized: there is much scope for better energy performance – as seen in good, but sadly rare, examples such as One Bridewell Street.

- Probe 2 included three mixed mode buildings. One (FRY) performed very well in energy terms, and with levels of comfort rarely found in any building. The other two (RMC and CAF) had more scope for improvement (fan energy consumption was particularly high – and often seems to be overlooked in the design of energy-efficient buildings). Nevertheless, CAF used about half as much as the similarly sized, occupied and sited AC HFS. The MM approach appears a promising alternative to AC for both energy and comfort, but with clear scope for further improving design and energy performance.

- Innovations are difficult, particularly in buildings where the prototype is often the end product. Inevitably, not everything will be right first time. The Probe NV buildings used much less energy than most of the mechanically-conditioned ones, many equalling or exceeding 'good practice' benchmarks. Some had very good performance indeed, but interestingly not without significant opportunities for further improvement. However, the ANV buildings did not seem to deliver significantly better performance than the simpler ones; and they often had shortcomings in summer-time temperatures, controls, occupant satisfaction, and higher-than-expected heating energy use owing to air leakage. There is a lot more to learn about getting the best performance from innovative approaches such as ANV. Possible downsides need to be carefully reviewed and managed.

> 'An initiative is required to improve performance, ef ciency, control and management particularly in mechanically – conditioned buildings'

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More information on Probe, the process, the studies and the conclusions, including data and downloadable reports may be found on the Probe website: http://www.usablebuildings.co.uk/Probe/ProbeIndex.html

Endnotes

[1]Since winter temperatures in the UK have been mild recently; and more of the buildings were in the southern part of the country, this had the effect of increasing gas consumption figures by an average of 15%; with a range of –6% to +34%.

[2]A referee pointed out that similar conclusions apply to UK dwellings, e.g. (Olivier and Willoughby, 1996a, 1996b).

[3]This comparison does not include C&G's gas-fired humidification; which is also at ECON 19 'good practice' levels in terms of carbon dioxide emissions.

[4]The designers report that the cost of upgrading the windows from a normal UK double-glazed specification to Scandinavian 2 + 1 triple-glazing were paid for by savings in the cost of the heating system. The authors thank one of the referees for drawing attention to this.

[5]However, even dedicated central AC systems for machine rooms can use relatively large amounts of energy, as at CRS. Often these systems also turn out to be oversized, sometimes unnecessarily closely-controlled; often inefficient in terms of refrigeration and air handling design; and wastefully operated – for example with adjacent units simultaneously humidifying and dehumidifying. Since they are seldom sub-metered, their levels of energy consumption and wastage never become apparent to management.

[6]Even when equipment is nominally off, 'leaking electricity' often occurs, with power supplies and control circuits still live and using significant amounts of energy. Auto-slumber equipment is a mixed blessing: it reinforces people's habits of not turning things off and is often far from energy-efficient (at CRS slumber only saved 10 W on the PC monitored). Even EnergyStar's criterion of 30 Watts standby per item is liberal – less than 5 W (and preferably 1 W) would be more like it. In practice, equipment is often delivered with its power-saving facilities turned off, and many users do not have the incentive to activate them; or think that screensavers are power-saving devices. In addition, IT departments often do not install or even disable them – albeit sometimes for good operational reasons. Better national and international product legislation should be considered here; but until recently the UK has shown very little leadership.

[7]While the draft of this paper was being corrected, the first steps towards this have been incorporated in proposed revisions to the Building Regulations for England and Wales.