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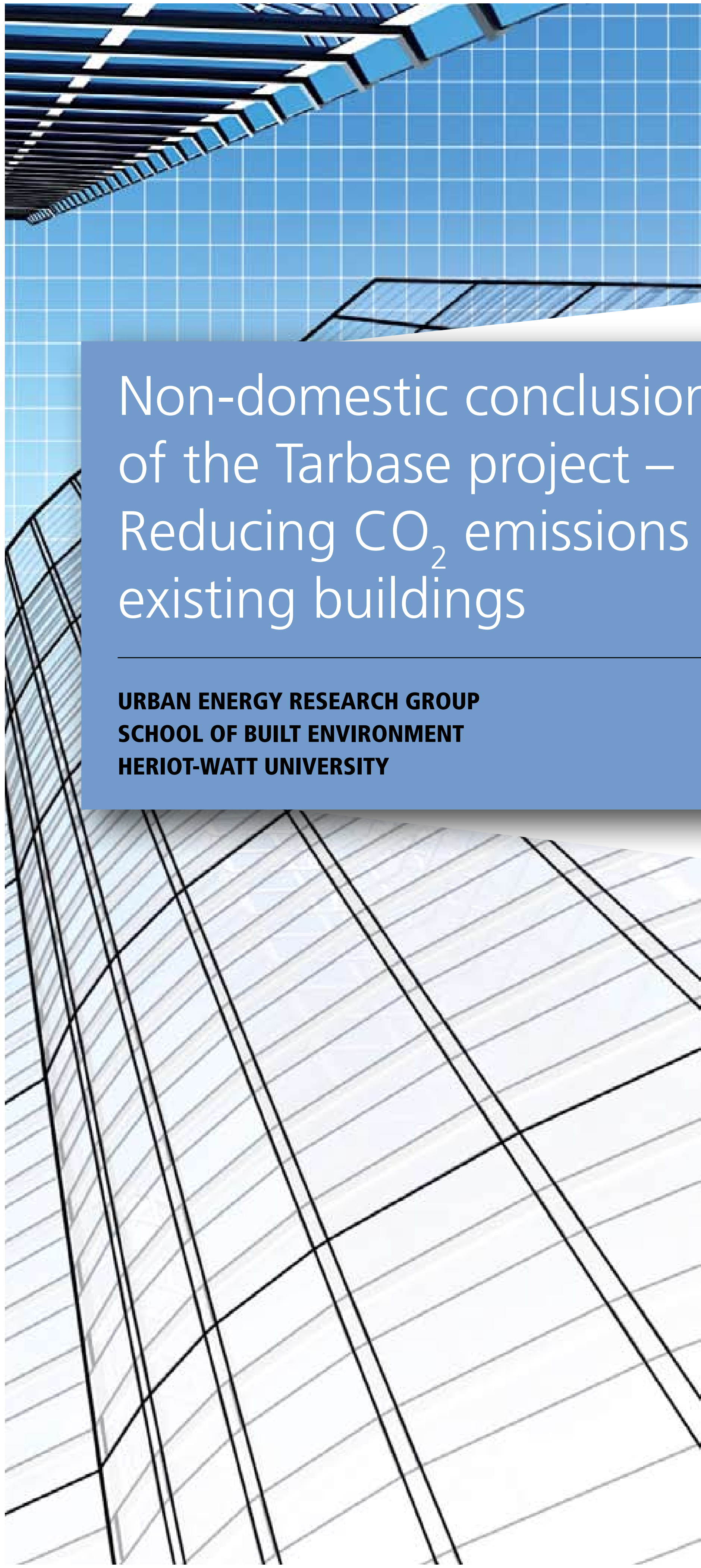

Non-domestic conclusions of the Tarbase project – Reducing CO_2 emissions of existing buildings

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tarbase
technologies for carbon reduction in existing buildings

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Summary

Tarbase (Technology Assessment for Radically Improving the Built Asset Base) is a low-carbon buildings project (part of the Carbon Vision Building Programme) funded by the Carbon Trust and the Engineering and Physical Sciences Research Council. The objective of the project is to demonstrate, by modelling existing buildings, a 50% reduction in CO_2 emissions by the year 2030. A series of existing building variants are defined that cover domestic, office, retail, education and hospitality sectors. These are then treated by measures to reduce the building CO_2 emissions including:

- adopting energy efficiency and management
- retro-fitting new technologies (concerning both the building fabric itself and the activities within)
- investigating onsite, building-integrated thermal and electrical generation.

The evaluation methodology accounts for the important temporal fluctuations in electrical and thermal loads throughout a given day, and the clear differences between sectors and within sectors. Sets of interventions to achieve specified reductions in CO_2 emissions are developed and appraised against economic and user-acceptance criteria, identifying the potential barriers to the proposed measures. The expected social trends for energy use in the different building sectors are used to inform likely changes in the way buildings are used and the consequent effect on energy consumption in the period to 2030. Similarly, the effect of a future climate and the effect of carbon intensity of electricity supply on the CO_2 emissions are assessed for each building. The approach taken enables building-specific measures to be assessed for, in principle, any building.

The report is divided into four sections. Section A discusses the various ways in which energy is used in non-domestic buildings, builds up energy consumption profiles and explores the contributions that can be made by changes to equipment and appliances, lighting, heating, ventilation, air-conditioning and to the building fabric, together with the role of renewable energy sources. Section B presents a series of case studies in which the buildings used as exemplars are described. Results of the demand-side carbon reducing interventions are presented in a standard format for ease of comparison. Section C considers the effect of renewable energy sources. Finally, a detailed cost analysis is given in Section D.

The main conclusions of the work are as follows:

1. The stock of non-domestic buildings is very heterogeneous both within and between sectors and emission reduction approaches should be tailored to specific buildings. Overall, CO_2 reductions of more than 50% present a highly challenging target for existing buildings.
2. The internal activity of non-domestic buildings is crucial and the efficiency of small power and lighting should be improved before any other measures are taken. Particularly in offices, IT equipment and lighting cause heat gain profiles which must be understood before choosing HVAC and building fabric refurbishments, because reduced heat gains mean reduced cooling requirements, which may change the building from being cooling-dominated to heating-dominated and this would need a different fabric refurbishment strategy.
3. There is potential for overheating in schools, which may drive a trend to mechanical cooling and ventilation, with an associated CO_2 emissions penalty that could be avoided by sensible building

design and correct management of IT equipment and lighting.

4. There is real potential for reducing lighting energy consumption in non-domestic buildings through improving technologies but the trend towards halogen spot-lighting in shops has a negative effect and should be discouraged.
5. Open fronted display refrigerators in supermarkets are a major source of CO_2 emissions and contribute to heating energy consumption through local cooling.
6. On-site energy generation can only achieve significant savings in larger non-domestic buildings if very large systems are installed and these are difficult or impossible to justify economically. Integration with the existing network infrastructure may help but the goal should be an overall reduction in the CO_2 intensity of delivered energy.
7. Capital and whole life cycle costs of technologies needed for large emissions reductions (especially beyond 50%) in non-domestic buildings are high and there is not sufficient attraction for landlords and managers to imagine the suite of technologies described in this report being adopted on a mass scale across the country.
8. Despite the uncertainties inherent in economic analyses of building refurbishments with new and emerging technologies, there needs to be considerable reductions in capital costs as a result of substantial investments in research, development, training and installation.
9. There are indications that in some sectors the added monetary and aesthetic value of a "green" building is significant to the organisation occupying that building, either as owner-occupier or tenant. This is useful since modest energy bill savings are unlikely to drive stock-wide refurbishment in the private sector.
10. The goal of "net-zero" carbon non-domestic buildings will not be achieved, by any definition, without dramatically reducing the energy consumption of small power and lighting, since few buildings will be able to satisfy their electrical energy demand through PV, wind and CHP supplies. The ambitious policy targets for non-domestic energy use are not currently commensurate with the empirical trends of usage in the sector.

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SECTION A

Potential for carbon saving in the non-domestic sector

A1 DEMAND SIDE ENERGY REDUCTION MEASURES

Foreword

This section describes a series of technologies and measures that would be suitable for reducing the energy demand in various non-domestic buildings. If refers to building variants which are defined by the case-studies in section B, and the reader should make cross-references as appropriate.

Detailed measures for reducing the carbon emissions of non-domestic buildings can be quite diverse in their application, due to the varied nature of the non-domestic stock. However, there are several areas of common ground across a large proportion of the stock, which will now be described. Firstly, there are initial savings to be made through the introduction of energy management and improved technology within the area of information technology, particularly desktop computers, monitors and servers. There is further scope for savings through the use of energy efficient lighting, a technology that is currently showing steady progress in terms of lighting efficacy (i.e. the lumens per watt of a lighting fixture). With these improvements made, we must then account for the significant change in internal heat gains (from the reduction in small power and lighting usage) and re-assess the heating and cooling requirements. Subsequent fabric and glazing improvements must be relevant to this "new" building, where the assumed internal activity is now quite different. This relationship, between the internal activity and heating/cooling requirements, is absolutely paramount to understanding low-energy non-domestic buildings. Fabric and HVAC measures that might be suitable for a high internal gain building might not be so successful for a low internal gain building.

A1.1 SMALL POWER AND IT EQUIPMENT

While non-domestic buildings have small power equipment and appliances that can be specific to a particular type of building (e.g. machinery in a factory or whiteboards in a school), there is a certain degree of homogeneity throughout the stock in that most buildings will have a significant number of office-type appliances. As will be seen in Sections D and E, personal computers, monitors and photocopying/printing usage are likely to be responsible for a large proportion of the building carbon emissions. Table 1 summarises these changes.

***Table 1** – Summary of small power interventions for non-domestic variants*

	2005 Baseline	2030 intervention
PC	Standard desktop (70W)	Power management (and 60W machine)
Monitor	CRT screen 61W	Power management and Cholesteric LCD (7W)
Printing/ copying etc	Separate printer/copier/fax/ scanner	Multi-function machine replaces copiers*
Servers	FIle and web servers always	Switch off non-vital file servers after hours

**also reduces the number of separate printers and eliminates separate fax machines and scanners. "On" power consumption of MF machine is 720W c.f. 1354W of conventional photocopier.*

A1.1.1 PERSONAL COMPUTERS

It could be argued that personal computers (PCs), particularly in the office sector, are close to saturation point in the workplace, with one PC per person being most common. Subsequent discussions will look at increased usage in schools, but it is firstly assumed that, outside the schools sector, the number of desktop computers will not increase (though neither will they decrease). The definition of a desktop computers is open to a huge number of variations however, including what they are used for and where they are used (with laptop and mobile computing becoming more prevalent outside the office building). Industry research has centred on technologies such as thin-client servers, removing processing power from the desktop to a central plant, mobile computing and changing the immediate environment of a worker to incorporate personalised IT technologies[1,2]. Some of these changes would produce noticeable energy reductions while others aim to improve worker access to IT technology and potentially increase the total IT energy consumption.

To allow a like-for-like comparison, a similar type of usage has been assumed in both 2030 and 2005, in that people are going into offices to work a full day. Clearly, a dramatic change in working practices (people working from home and not requiring a permanent workstation) would make the comparison between a 2005 office and 2030 office largely irrelevant – in such a case carbon emissions might be displaced from one building to another but not necessarily reduced.

For the non-domestic variants it is assumed that a small decrease in power consumption might be possible for the desktop computer, from 70W to 60W. This allows for improved efficiency while accounting for the fact that computer processor power tends to increase with time so very large power reductions might not be achievable. Energy management, i.e. switching things off when not in use and also allowing for PCs to vary power consumption depending on the task being carried out (e.g. reading a CD or DVD will temporarily increase the power consumption), can produce far greater energy savings. This is summarised in work by Lawrence Berkeley National Laboratory and US Department of Energy[3,4]. This change can produce savings of approximately 70% per computer. There are clearly, as with all IT equipment in a working environment, user-behaviour issues that have to be addressed here. Some of these issues could be bypassed to an extent, in that mandatory energy management software could be applied to such equipment, thus making such energy saving potential independent of the actual user.

Savings can also be made from server/network computing (see Table 1). Generally, web and office servers are left on 24 hours a day in most non-domestic buildings. However, noticeable energy savings can be made by identifying non-essential servers that can be switched off at night and weekend. It has been estimated elsewhere[3] that 40% of office servers (i.e. non-web servers such as printing servers which can account for 42% of all servers) can be switched off at night and weekend, which would reduce energy consumption of server equipment by 8%.

A1.1.2 MONITORS

Many offices are already seeing an upgrade in display technology, with a move towards liquid-crystal display (LCD) monitors rather than cathode-ray tube (CRT). With advancements in display films and backlight technologies, the power consumption of computer monitors, with encouragement from legislation, could be reduced significantly by 2030. For example, cholesteric LCD screens[5] do not require a backlight to operate – they merely reflect the ambient light in the room. This dramatically reduces the power consumption of the screen (such a monitor is predicted to have an "on" power consumption as low as 7W). Combined with good energy management, a cholesteric LCD monitor could have an energy saving of 89% when compared to a CRT monitor with poor energy management[3].

A1.1.3 PHOTOCOPYING/PRINTING

In the area of paper output, there is already a movement towards "multifunction" units, i.e. machines that can carry out photocopying, printing, faxing and scanning. As well as the practical advantages of such a system, the machine does not have to be left in a standby or idle mode for such long periods of time (such modes are essential for keeping the components of a copier or printer warm, so that they are able to fix ink to paper without the user waiting for long periods of time for the machine to warm up). The energy savings can therefore be significant, estimated as a 38% saving across all printing, copying, faxing and scanning.

There have, for some time, been discussions of paperless offices, with a predicted improvement in resolution of electronic images and so the introduction of e-paper (thin, portable electronic displays similar to the cholesteric screens mentioned above). This is yet to be seen and it will be assumed here that paperless offices will not be the norm by 2030.

A1.2 LIGHTING

To determine lighting energy consumption for the non-domestic buildings (for both 2005 baseline and future 2030 scenarios), a simple lighting model was developed[6]. In summary, Equation 1 calculates the electrical power *P* used, for a given lighting technology, to meet a given design illuminance:

$$P = \frac{E_i A_s}{UF.MF.BF.\varepsilon}$$

(1)

where E_i is the internal illuminance of the building area in question, A_s is the area of horizontal surface to be illuminated (in m²), UF the utilisation factor (essentially the percentage of emitted lighting that reaches a horizontal surface), MF the lighting maintenance factor (accounting for degradation, age and condition of lighting), BF the ballast factor/efficiency and ε the lighting efficacy (in lm/W). This calculation can be repeated for areas with different design illuminances.

If daylighting is present, the internal illuminance E_i (in lux) from daylighting alone can be estimated from Equation 2:

$$E_i = \frac{E_e \tau C A_g \theta O}{100 A_T (1 - R^2)}$$

(2)

where E_e is the external illuminance (in lux), τ is the glazing transmission, C the correction factor due to dust and maintenance, A_g the glazing area (in m²), θ the vertical angle of visible sky from the horizon (in degrees), O the orientation factor of glazing, A_T the total room surface area (in m²) and R the average reflectance of all room surfaces. With adequate information representing climate data[7], the hours that E_i exceeds the design internal illuminance (from daylighting alone) can be estimated and so, for a given working day, the hours of electrical lighting required calculated. However, daylighting in non-domestic buildings depends on the energy management and working practices of the occupant organisation(s), with many non-domestic buildings using lighting throughout the day, all year round.

As well as energy management, in particular switching off the lights outside occupancy (which can produce large and easily achievable savings), technology is again key to producing carbon savings. Fluorescent lighting, for a 2005 office baseline, might range from 70lm/W (for T12 fluorescent tubes) to 100lm/W (for T5 fluorescent tubes). Such lighting might also be seen in schools. Retail, however, will tend to have more diverse lighting, with halogen lighting (which can be as low as 20-25lm/W) often present. The use of this latter technology is of some concern in the retail sector, such as clothes shops, (as well as some domestic buildings). It is sometimes promoted as "energy saving", in that it has slightly improved efficacy when compared to older incandescent light bulbs. This is somewhat misleading – if halogen bulbs are used instead of fluorescent lighting then lighting energy use will rise significantly. Furthermore, due to the spotlight halogen product (i.e. GU10 fixtures) being quite small, far too many of the fixtures are installed, leading to very bright rooms, with poor lighting energy efficiency and a significant level of heat gain. Such technologies should be discouraged as a general lighting option – if spotlights are required, GU10 compact fluorescent lighting bulbs or LED fixtures (see below) are available with significantly improved efficacies and these can be a like-for-like replacement for spotlight halogens.

Despite this choice of lighting, there are certainly grounds for optimism in the area of non-domestic lighting. As well as the "easy win" of turning lights off at night and weekend, the efficacy of future lighting technologies show signs of substantial improvement. Tubular fluorescent lighting is already exceeding 100lm/W and light-emitting diodes (LED) are being championed as being the future of energy-efficient lighting in all sectors. This technology is predicted to exceed 150lm/W by 2030[8] which will achieve very large savings in all non-domestic sectors if implemented. Although lagging behind in terms of efficacy, organic light-emitting diodes (OLED) are also showing potential, providing an even more versatile form of lighting that could be produced more cheaply and with lower embodied energy than conventional LED lights.

In the case of current LEDs and OLEDs, there is a small question over the colour-rendering index at high efficacies, i.e. achieving a "white" light that is also energy efficient. While this is unlikely to be a long-term problem, it might limit the very high-end predictions of LED lighting efficacy by 2030 (where some sources mention figures close to 200lm/W[9]). It is therefore assumed in this study that all non-domestic lighting achieves 150lm/W by the year 2030, with the nominal technology being LEDs.

A1.3 INTERNAL HEAT GAIN PROFILES

While inefficient appliances/equipment and lighting are directly responsible for high carbon emissions in the non-domestic sector, they also have a huge influence on the size of cooling (and heating) loads, as well as affecting user comfort issues. This is quantified further in section 2.4, but the internal heat gain profile resulting from internal activity (equipment, lighting and metabolic gains from the occupants themselves) should not be oversimplified. The shape of such a profile and how it coincides with external heat gains (from air temperature and solar radiation), will indicate when an overheating problem might exist (for buildings, such as schools, that might not have cooling systems), or when a cooling plant might be required to reach maximum output.

The use of lighting is relatively simple to estimate, as discussed in section A1.2. However, with a diverse use of appliances and equipment in some non-domestic buildings, a strategy is required to produce an hourly daily profile for all small power usage in a given building. This is achieved by, firstly, identifying all the equipment that might be present in the building (from design guides and empirical data[10]). In the case of offices, individual electrical demand profiles are assumed for PCs and monitors, which make up the majority of the small power equipment usage for these buildings. These individual demand profiles are then summed together but allowing for a diversity factor so that, for example, computers are switched on at slightly different times to prevent an unrealistic power spike (this can be achieved by starting the PC or monitor demand profile in stages at 8:00, 8:30, 9:00, and 9:30 rather than all of them starting at 9:00). Other small power appliances and equipment (such as photocopiers and printers) are averaged throughout the day (as these usage patterns are more constant and their small variation is less of an issue to the total electrical demand). This electrical demand profile can be equated to the heat generated by lighting and small power[11] and so, after accounting for sensible heat gains from occupants, a total heat gain profile produced for a given day. Figure 1 is an example of such a profile for the VO1 office variant (see section B for the description of this building).

(a)

(b)

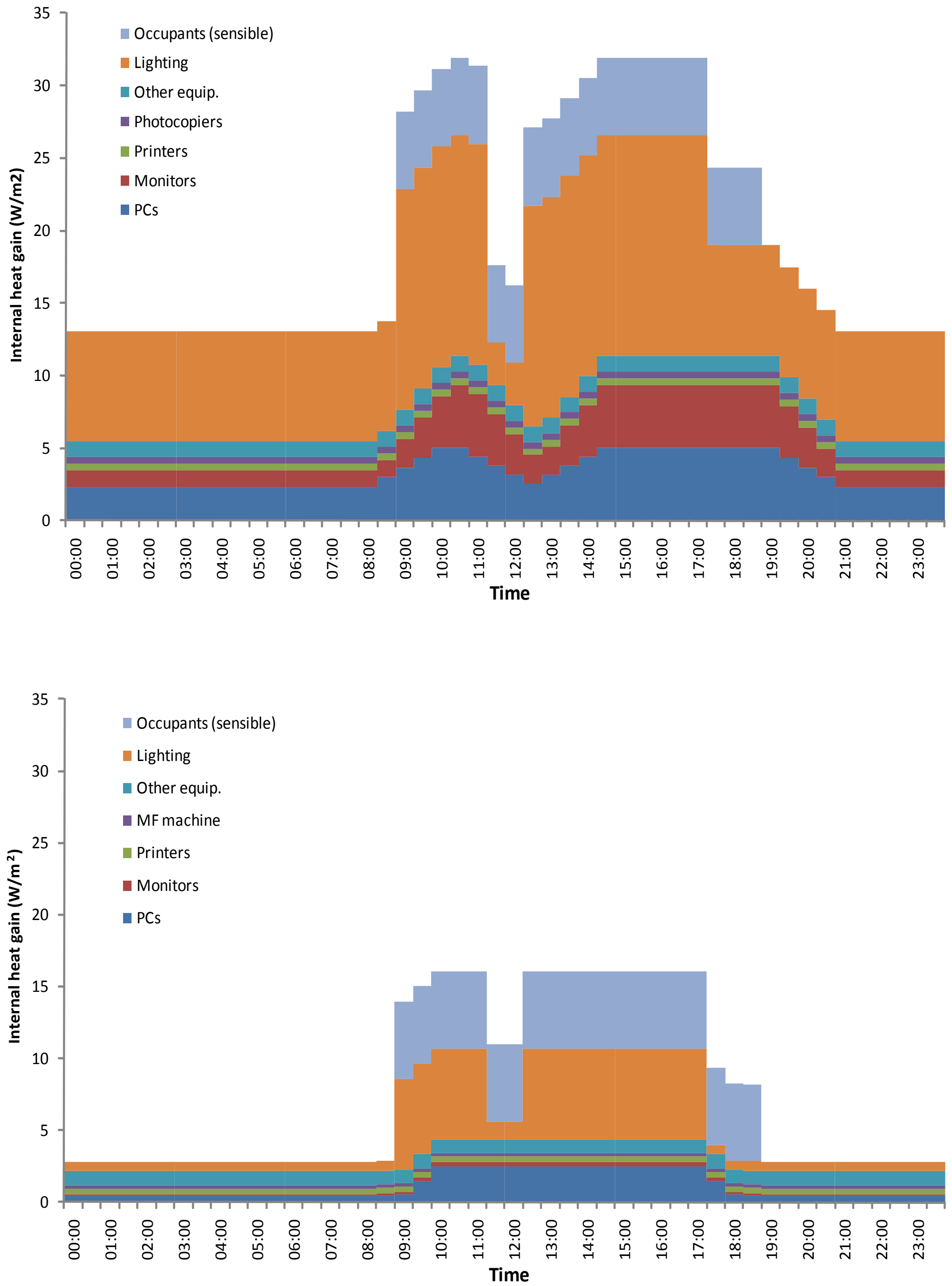


Figure 1 *– Estimated internal heat gain profile for four-storey office variant (VO1) for a January day for (a) 2005 baseline and (b) 2030 scenario*

This demonstrates the previously asserted point – that the internal activity of the building, after the demand-side changes, has been changed to such a degree that it is necessary to re-evaluate any subsequent carbon savings measures. So Figure 1(b) is no longer a "2005 office" and should not be treated as such when considering HVAC and fabric measures. This will be amplified in subsequent sections.

Figure 1 is therefore an example of internal gain profiles that can be used for simulating 2005 and 2030 variants. Profiles are constructed in a similar way for all the non-domestic variants under consideration.

A1.4 BUILDING FABRIC MEASURES

With electrical demand measures applied to the building, the next step is to consider the space heating requirements. If internal heat gains have been reduced, this must be accounted for in subsequent simulations of building's heating and cooling energy requirements. While such measures reduce the reliance on cooling (if present) or the problems of overheating (if cooling systems are not present), the space heating requirements will now be significantly higher. So, although retrofitting insulation to a high internal gain office (such as the 2005 baseline VO1 office, section B) might not reduce carbon emissions significantly (as heating consumption might already be low), the same measure for a lower internal gain office (such as a 2030 version of the same office) might be more worthwhile. This is now explored with the following building fabric measures.

A1.4.1 INSULATION

Changing the fabric of a non-domestic building will obviously have issues relating to cost and disruption to the user of the building. If the energy-saving benefits of such a measure are small, then an occupant organisation might not be inclined to carry out the refurbishment due to these negative impacts.

As far as simulating building heating and cooling requirements, the change in fabric essentially involves two factors: the thermal transmittance or U-value of the building and the thermal mass of the building. The former is relatively simple to calculate for a known material and is generally the prime motivation for improving building fabric (ignoring aesthetic considerations). The latter is unlikely to be used as a reason for retrofitting new building fabric because, as well as the economic considerations, it would involve significant changes to the building structure, requiring exposed thermal mass (such as concrete) in ceiling areas. It is assumed that optimising building thermal mass (which, when applied in conjunction with intelligent ventilation strategies, can reduce peak heating and cooling requirements) has more potential for new non-domestic buildings. We are therefore left with retrofit changes to building fabric as being a measure to reduce heat loss through walls, floor and roof (effect on infiltration rate is explored in section A2.3) – though the unintentional change in building thermal mass will be accounted for in the dynamic simulations that are carried out.

The intention of this study was to be ambitious with U-value targets while not proposing technologies that might not achieve wide market penetration. Technologies such as vacuum-insulation panels have existed for some time but have not yet shown enough promise as a retrofit measure for building elements. The assumption is therefore made that any retrofit to walls, floors or roof will involve adding a material (either externally or internally) to reduce the U-value. A suitable insulation for retrofitting might be expanded polystyrene (EPS). The effect of applying this to a 4-storey office variant (VO1) is given in Table 2, where it is assumed that external insulation is feasible (although often not possible with listed buildings and glass-curtain walled offices).

It is important to understand that radically improving thermal insulation for a non-domestic building can have a detrimental effect. A high internal heat gain building (such as a high density office) can lose this unwanted heat through fabric heat loss and air infiltration (see section A1.4.3). While this effect is undesirable during the heating season of a building, "poor" building fabric can provide free cooling during the summer, in that heat transfer can occur more easily between the cooler outside air and the overheated internal air. If the cooling loads are higher than the heating loads in the building in question over the course of the year, it is possible to increase the total building energy consumption through ill-planned retrofit insulation measures, with the undesirable high internal gains from equipment, people and lighting being trapped in the building. However, if changes to the internal activity have already taken place (see sections A1.1

***Table 2** – Overview of 2005 and 2030 building fabric for 4-storey office variant (VO1 in section B)*

	2005		2030	
	Description	**U-values (W/m²K)**	**Description**	**U-values (W/m²K)**
Walls	Concrete panel, air, mineral fibre, block, plasterboard	0.65	External EPS (150mm) with concrete render (13mm)	0.15
Floor	Carpet, underlay, floorboards, minearl wool, clinker and earth	0.27	Replace mineral wool with EPS (100mm)	0.22
Roof	Felt, insulation, concrete, air and plaster	0.87	Replace mineral wool (100mm) with EPS (200mm)	0.14
Glazing	Double glazed	2.75	Replace double glazing with Ar-filled triple glazing, low-e coating	0.78

to A1.3), then the building is more likely to be heating-dominated (as opposed to a 2005 high density office building which might be cooling dominated). This means that a higher percentage of the internal heat gains will be useful, i.e. throughout the course of the year they are more likely to reduce the building's heating energy consumption than exacerbate the cooling problem. Once this initial change has been made to small power and lighting, there will be, from an energy saving (although not necessarily an economic) perspective, more justification for making fabric improvements. The same argument will apply to glazing refurbishments, although here there will be an added benefit of solar gain reduction and so there exists the potential to reduce heating and cooling consumption in one measure.

A1.4.2 GLAZING MEASURES

Also shown in Table 2 is the effect of a change in glazing. With the baseline 4-storey office having standard double glazing, a noticeable improvement is predicted if these are replaced with triple-glazed argon-filled windows (with a low emissivity coating). Again a relatively conservative approach has been taken, with technologies such as electrochromic glazing (varying the solar transmission of a window electronically) and photovoltaic glazing (windows embedded with photovoltaic cells) deemed too expensive to achieve high market penetration in the near future. However, triple-glazed argon-filled windows for all appropriate offices would still be a challenging target in the UK, due to expense and issues with installation. Also, while this technology is suitable for some non-domestic buildings, other buildings are unlikely to see such a retrofit measure. Again, listed buildings and glass-curtain wall buildings are not necessarily suitable for such a major refurbishment. Therefore, the chosen glazing technologies for the different non-domestic variants (see section B) are often "sub-optimal", in that they must satisfy other building requirements relating to the structure and aesthetic quality of the building.

A1.4.3 REDUCING INFILTRATION

Whether seen as an individual measure, through the introduction of draughtproofing, or seen as a consequence of radically changing the building fabric, reducing the infiltration rate of non-domestic buildings can be an effective measure when aiming to reduce building heating consumption. Again, there is the need to understand internal activity – an airtight, high density office is likely to have a significant overheating problem whereas a poorly airtight equivalent, although having a higher heating consumption, will have warm internal air displaced by cooler external air at a greater rate. There might be times when the poorly airtight building has warmer external air displacing cooler internal air (during times of very high external temperatures) – however, in the UK this is rare even if it is a significant factor in warmer climates.

In summary, the measures that have been suggested for reducing small power and lighting energy consumption (and the associated heat gains), will reduce (although not eliminate) the overheating problem of an airtight non-domestic building. Therefore, it might be justifiable for an office with "2005 baseline" equipment and lighting to be allowed to have relatively high infiltration rates and high U-values, but a 2030 office (with low power equipment and lighting) is more likely to see the benefit of retrofit fabric measures of the type discussed in section A1.4.

A2 HVAC OPERATION

Heating, ventilation and air-conditioning (HVAC) systems consume significant energy in the office and retail sectors though, in the UK, cooling and mechanical ventilation are currently quite rare for schools (see section A3.2.2 for a discussion on how this might change by 2030).

A typical building services approach to sizing the HVAC systems[12] is carried out for each Tarbase variant. This tends to result in oversized systems that are, as in reality, designed to reduce any risk of failure. It is important to account for this when simulating buildings as the resulting part-loads of the respective HVAC systems can be quite low, which will affect their efficiencies.

The non-domestic buildings of section B are simulated using dynamic building software[13] to obtain heating and cooling requirements (i.e. required outputs of the chosen HVAC systems). These simulations are informed by the transient internal heat gain profiles mentioned in section A1.3, each profile being unique to the specific building and being quite different between 2005 and 2030 simulations.

These hourly heating and cooling requirements are then passed through bespoke Tarbase boiler and chiller models to estimate the heating and cooling energy consumption (and associated carbon emissions). This approach therefore allows for an hourly change in part-load efficiency throughout the entire year (for the systems as sized).

A2.1 SIZING HVAC SYSTEMS

Although a building simulation might suggest, for example, that the maximum heating requirement at any time is 200kW, this alone does not indicate how large the boiler (or boilers) would be. Building services engineers would not base such an estimation on the simulation of one year – to ensure that, in this case, the boiler is large enough, the approach used usually involves taking worst-case design guides (e.g. lowest external temperature, lowest (or zero) internal gains etc) and sizing a boiler to match this condition. Oversized systems are therefore common as this sizing approach does not account for transient internal gain profiles (with, for example, heat gains from lighting, people and equipment offsetting much of the perceived heating requirement). A similar approach is taken with cooling systems, with an air-conditioning system sized to meet a coincidence of maximum internal and external heat gains.

This situation is far from ideal but unlikely to change in the near future – building services engineers cannot take the risk that a designed system might fail as a result of being too small. However, with design guides used for estimating peak heat gains, a change in internal activity (as a result of changing lighting and equipment technology) should be reflected in these design guides. Table 3 lists the office, retail and school variants with estimated sizes of systems for 2005 baseline scenarios. It can be seen that multiple boilers and chillers have been used for larger buildings, to allow for an improved part-load performance.

***Table 3** – Chosen HVAC system sizes for non-domestic buildings for 2005 baseline (see section B for variants)*

Variant	TFA (m2)	Heating (kW)			Cooling (kW)				Ventillation	
		Simulated peak*	**Boiler rating**	**Pump****	**Simulated peak**	**Chiller rating**	**Pump****	**Fans****	**No. of fans*****	**Total (kW)**
4-Storey Office (VO1)	4000	173	2 x 152	5	272	2 x 197	7.5	11.6	2	3.5
5-Storey Office (VO2)	3000	175	2 x 156	5	314	2 x 268	7.5	10	2	2.6
6-Storey Deep Plan Office (VO3)	5400	317	2 x 174	5	333	2 x 264	7.5	15	3	4.8
6-Storey Shallow Plan Office (VO4)	5400	323	2 x 187	5	457	2 x 351	7.5	18	3	4.8
Small Office (VO5)	120	10.4	1 x 22	0.5	9.1	1 x 15	0.5	0.4	1	0.4
Estate Agent (VR1)	60	3.6	1 x 9	0.5	3.1	1 x 5	0.5	0.2	1	0.2
Convenience Store (VR2)	150	17.6	1 x 29	0.5	13.9	1 x 24	0.5	0.6	1	1.0
Clothes Shop (VR3)	450	21.3	2 x 18	0.5	34.4	2 x 26	0.5	1.8	1	1.4
Supermarket (VR4)	10950	377	2 x 302	20	402	2 x 239	20	44	10	14.4
Small primary school (VS1)	840	48	2 x 46	2	-	-	-	-	-	-
Medium primary school (VS2)	1328	146	2 x 97	3	-	-	-	-	-	-
Medium secondary school (VS3)	7566	453	2 x 323	5	-	-	-	-	-	-
Large secondary school (VS4)	9198	492	2 x 413	8	-	-	-	-	-	-

** result of simulation, i.e. required output of system*
*** approximately sized electrical pumps/fans for boiler and chiller units*
**** one "fan" includes a supply and extract ventilation fan*

***Table 4** – effect on heating and cooling system sizes of changes to scenario and location for 4-storey office variant (VO1)*

	% change in system rating c.f. 2005 baseline					
	2005 + Equipment refurbishments		2030 + Equipment refurbishments		2030 + Equipment and fabrik refurbishments	
	Heating	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**
London	40	-27	34	-19	11	-35
Cardiff	42	-30	36	-22	19	-38
Birmingham	34	-22	30	-15	3	-32
Manchester	39	-27	33	-20	15	-36
Edinburgh	44	-34	38	-27	11	-43

As a demonstration of the sensitivity of HVAC (in this case boiler and chiller) system size, Table 4 shows the change in boiler and chiller ratings as the result of selected refurbishments in different locations for the 4-storey office variant (more detailed scenarios for the individual variants are listed in sections A4 and B). All systems, for all scenarios, are still significantly oversized (and so allow for the large margin of error that would be intentionally designed for) but they account for the fact that, for example, a very low internal gain building would not require the same size of cooling system as a high internal gain building. Conversely, to maintain the same margin for error, reducing internal gains would suggest a larger boiler is required. It should be noted that the change in designed system size, which imagines a worst-case point in time, will not necessarily exactly match the change in total annual energy consumptions of those systems between each scenario, which are calculated from dynamic simulations. This is further explored in sections A2.4 and A4.

Annual "domestic hot water" energy consumption, i.e. for kitchen and toilet areas, is assumed to meet typical benchmarks of 12kWh/m^2 for all offices and retail buildings[10]. The consumption for schools is based on estimations of water usage per pupil and the energy required to heat such a volume[14]. The above is factored into the boiler sizing.

A2.2 HVAC TECHNOLOGY OPTIONS

Some of the technologies available for heating, ventilating and cooling a building become more difficult when dealing with existing non-domestic buildings. Firstly, onsite CHP was discounted for the non-domestic variants as most of the office and retail buildings tend to have high electrical demands and relatively low (compared to, say, domestic buildings) thermal demand per unit floor area. School buildings tend not to have the operational patterns that might suit CHP, with intermittent usage throughout the year. Tri-generation, where cooling, heating and electricity are supplied or part-supplied by one system, might, initially, suggest a way of making this work. For example, the project has previously looked at absorption chillers being used with onsite CHP systems[15]. It was found that, for such a system to produce significant carbon savings, the coefficient of performance of the absorption chiller (which takes the waste heat from the CHP unit that is not required by the thermal demand of the building) would need to be very high (in the region of 1.0, which would relate to a triple-effect absorption chiller that is still quite far from being commercially available). In the aforementioned research, it was calculated that the electrical efficiency of the CHP unit would have to reach 46%, extremely high for an onsite system (though larger, near-site, district solutions might reach this goal if neighbouring buildings had energy demands that were suitable).

The advantage of such tri-generation systems in the non-domestic sector is that, with the thermal output of the CHP unit being used for both the space heating (and perhaps hot water) demand and the cooling demand (via the absorption chiller), a CHP unit with a high heat output to electrical output ratio (which is the case for most current technologies) might actually work. However if, as demonstrated in section B, we perform energy saving refurbishments such that the space heating and cooling demands of the building are significantly reduced, then the justification for tri-generation (and indeed any radical, and un-economic, change to heating and cooling the building) begins to disappear. There may, however, be more of an opportunity for tri-generation in industrial buildings. In such cases, even after energy-saving refurbishments, there may be a significant thermal demand from industrial processes, which might make both co-generation (i.e. conventional CHP) and tri-generation more worthwhile as carbon-saving options.

Other options might include the use of night-time cooling, which can also be optimised through the use of exposed thermal mass (see also A1.4.1). Essentially, the building can jettison heat at night (through the use of mechanical fans) when a set temperature is exceeded, so that the building is cooler the following morning when workers enter the building. If, for example, exposed concrete ceilings are used in the building, these can be used to absorb any undesirable heat during the day and so the peak temperature of the building is shifted. The heat, rather than being re-radiated into the building, can be removed outside via the night-time ventilation system (this can involve vented cavities within the concrete thermal mass structure). While this is an interesting approach for new buildings, and has been modelled by the project team elsewhere[15], it is very difficult to imagine such a system being retrofitted on a large scale and so it has not been included as an intervention for all the Tarbase variants (though is discussed as a parallel option in Figure 2 and below).

The foregoing discussion suggests that, for a building that still has a significant electrical demand from small power and lighting but relatively modest heating and cooling loads (which is the case for many of the Tarbase non-domestic variants for the 2030 scenarios), altering the heating or cooling technologies becomes less of a priority. In relation to this an exercise has been carried out, through demand-side measures, to produce buildings (in particular offices) that have a near-zero cooling requirement (see accompanying work for more detail[16]). This approach for the 4-storey office is shown in Figure 2. The graph shows the coolth requirement, effectively the heat that would have to be removed throughout the year to maintain comfort temperature. The calculations are based on results of simulation at hourly temporal precision throughout an entire year using ESP-r dynamic simulation software. The different refurbishment steps taken are similar to the technologies mentioned already in this report (i.e. the changes to small power, lighting, fabric and glazing – thermal comfort is discussed further in section A3.1). It would suggest that, in the UK, far more can be achieved through cooling load management, and focussing on what processes are actually producing the heat, rather than suggesting expensive and invasive retrofit technologies that are needed to remove this heat.

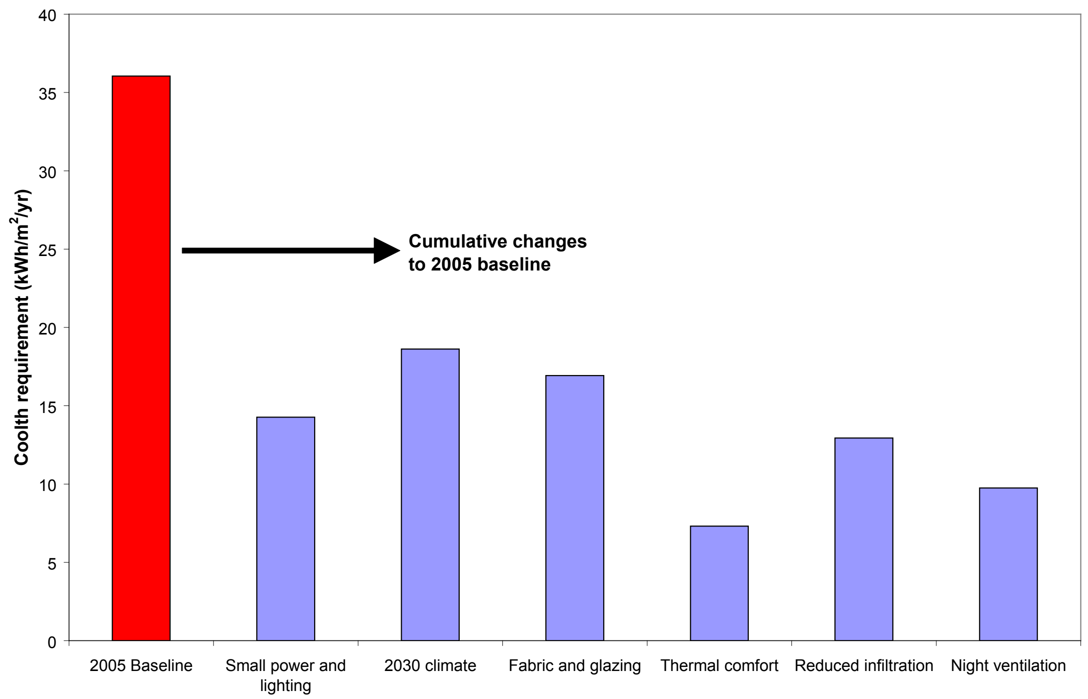


***Figure 2** – Cumulative effect on cooling requirement of changes to baseline of 4-storey office (VO1) in London location*

The variants in section B, as a result of the above arguments, only compare non-condensing gas boilers with condensing boilers and air-source heat pumps (see section A5 for the latter).

Mechanical ventilation, which is assumed to be present in all baseline office and retail variants (though not school variants), can in theory be reduced through passive approaches, i.e. providing vents or stack systems to encourage air movement from outside. Again, this has been investigated for new buildings[15], showing some small carbon savings, but it is slightly more difficult to justify when retrofitting a building. There is also a risk of failure when passive ventilation is designed to satisfy all air change requirements in buildings that are becoming increasingly airtight – there is already a growing problem in maintaining air quality in schools, where mechanical air-conditioning and ventilation has traditionally not been used (see also section A4.3).

A2.3 MECHANICAL VENTILATION HEAT RECOVERY

Both cross-flow and thermal wheel systems can be used with mechanical ventilation systems to recover heat (Figure 3). Thermal wheel systems are assumed to be an appropriate intervention strategy for the non-domestic variants of the Tarbase project, with an average heat recovering efficiency of 70%, though this can vary with part-load operation and temperature gradients. A large proportion of the office heating load is due to ventilation heat loss so the potential of heat recovery is significant. A simple model is used to quantify the use of this system alongside the existing heating and cooling systems, for a ventilation rate of 10l/s/person, as provided by the existing mechanical ventilation system.

The reduction in thermal requirement (i.e. reduced boiler usage) can be significant (as quantified in Sections C and D), though the "coolth" recovery from the same systems was found to be negligible. This is mainly due to internal temperatures being significantly higher than external temperatures during the majority of the cooling season, which reduces the potential for coolth recovery.

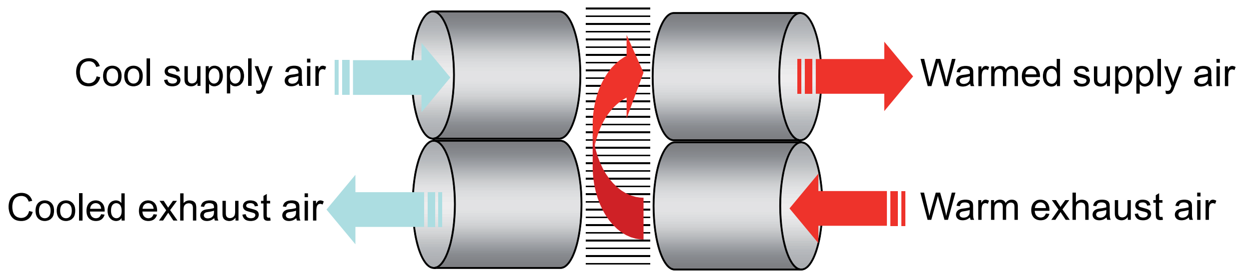


***Figure 3** – Description of heat recovery in a mechanical ventilation system.*

A2.4 THE EFFECT OF INTERNAL GAINS ON HEATING AND COOLING LOADS

The importance of internal activity in heating and cooling non-domestic buildings has already been highlighted. Further Tarbase modelling work has investigated this for office, retail and school buildings[17,18,19,20,21].

Figure 4 shows the energy use (kWh per m^2 of total floor area) for heating and cooling the 4-storey office variant in different locations and for different scenarios (negative axis refers to cooling energy; positive axis to heating energy).

Detail of the scenarios are given in sections B and C for variant VO1 in the London location (Figure 4 includes the first three intervention packages). The calculations account for typical efficiencies of a gas boiler and chiller (with respective distribution systems). It is noticeable that, after making the changes to "equipment" (i.e. small power and lighting), the office (in the London location) has changed from being cooling dominated to heating dominated (i.e. the difference between the dark blue bar and red bar). While the predicted 2030 climate offsets this change slightly (yellow bar), the comparison emphasises the importance of internal activity on cooling loads in

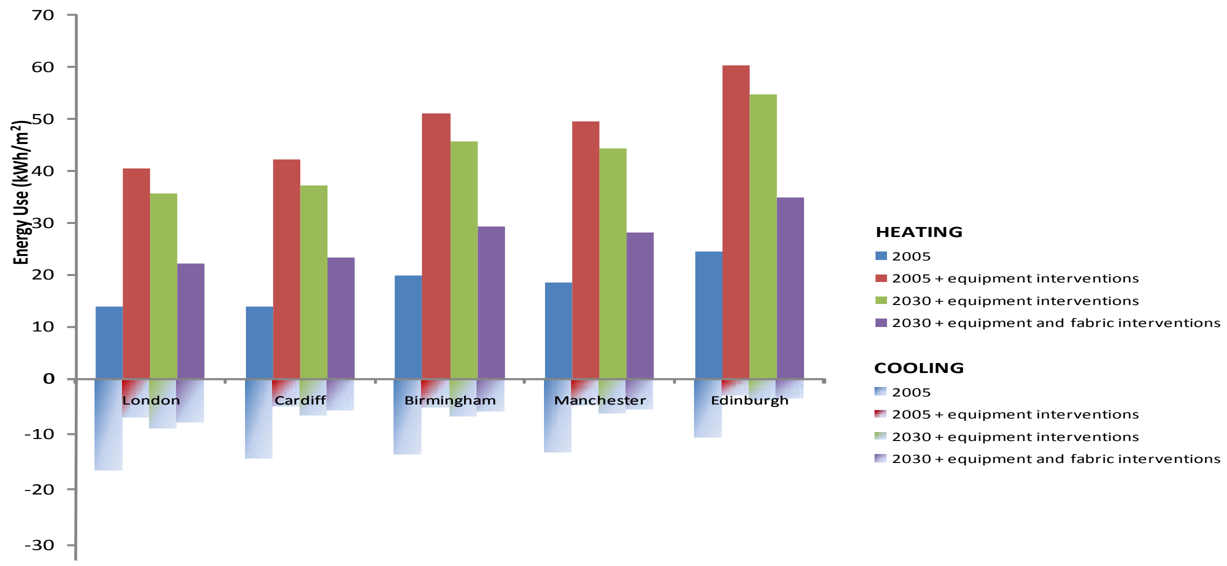


***Figure 4** – Simulated heating and cooling energy requirements for 4-s torey office in different locations for different scenarios*

UK offices. While it is understandable that research into non-domestic buildings in southern Europe and the Middle East often looks at ways of changing the building fabric (and glazing) to reduce the cooling load, it is suggested that this should not be the priority in most UK non-domestic buildings. The fabric changes that are made (the light blue bar) are as listed in Table 2. With the office building now having an increased heating requirement, due to reduced internal heat gains, such measures have more of an impact – it is debatable whether the same fabric measures would be worth applying to the 2005 baseline office (dark blue bar).

A similar theme is seen throughout the other four locations, although it is clear that the Edinburgh version of the office would have a noticeably different balance between heating and cooling. This building would be heating-dominated throughout all scenarios, suggesting fabric measures would have an even greater impact. Even here, where the cooler climate would result in lower cooling loads, the effect of reducing equipment loads is significant to the cooling energy consumption.

This exercise suggests that, in the main, UK non-domestic cooling systems do not exist purely to offset thermal discomfort due to climatic variations – our use of the buildings, and the small power and lighting within, has to be changed if we are to reduce cooling loads of existing non-domestic buildings. This will now be explored further for offices and schools.

A3 THERMAL COMFORT IN NON-DOMESTIC BUILDINGS

The definition of a "comfortable" interior can vary with building (e.g. a school can be quite different to an office) but also with occupant subjectivity. Quantifying this is therefore non-trivial, although empirical work in the office sector does exist that can aid our approximations. Using such information to create optimised cooling strategies, which account for variations in external temperature and the reaction of the user to this variation, can have a significant effect on the calculated cooling energy consumptions.

In the school sector the situation is quite different, with buildings traditionally assumed to operate without mechanical ventilation or cooling (though we are perhaps starting to see a deviation from this model with newer buildings). With a warming climate, increased internal small power, and a dramatic change in building fabric (with U-values being reduced and airtightness improved), school buildings are vulnerable to overheating.

A3.1 THERMAL ADAPTATION IN OFFICE BUILDINGS

In the building interventions for offices listed in Sections B and C, a measure entitled "adaptive comfort" is included. All office buildings are assumed to meet the 21 to 23°C comfort criteria often specified in design guides[10] – so a cooling system will be activated if the internal temperature exceeds 23°C and a heating system will be activated for temperatures below 21°C. This approximation assumes a very rigid control system to heating and cooling buildings. In practice control can be more flexible and the adaptive comfort intervention addresses this as follows.

Thermal comfort in offices is an area of substantial research though, in practice, quite difficult to determine. Monitoring the actions of individuals that become uncomfortable in a given working environment can be as much about psychology as building physics (for example, an individual might feel uncomfortable due to working conditions, air quality or daylight etc and yet "feel" that they need to alter the temperature controls to improve their comfort). Work by Nicol and Humphreys[22] and at Strathclyde University[23] has attempted to quantify suitable comfort temperatures for office workers and the point at which an occupant might act to improve his/her comfort. This postulates a relationship between the temperature outside a building (over a previous time period) and the comfort temperature within the building, based on actual data collected in an office environment. While not detailed here, this approach is used to identify the "adaptive comfort" measure. It also applies to heating the building, though only a small difference is seen between using this adaptive comfort algorithm in the simulation and using a 21°C heating set-point. In the case of cooling the difference is quite significant (also explored in other Tarbase work[16]). The adaptive comfort intervention essentially assumes that, when achieving comfort conditions, the building temperature controls will follow the thermal comfort algorithm as defined.

A3.2 OVERHEATING AND AIR QUALITY IN SCHOOLS

There has been a country-wide programme to re-build or refurbish schools in the UK. This will affect the energy use and operation of school buildings in a way that is intended (such as reducing heating consumption through improved insulation) but also through unintended consequences (such as overheating and the need for mechanical cooling). The Tarbase school variants, as listed in section B, assume that there is no mechanical ventilation (design air-change targets of 10l/s/person are assumed to be met passively through the use of openings and vents) or cooling present, as is still often the case in reality. However, to highlight the likelihood of overheating in such buildings, a parallel study[20] was carried out looking at the internal temperatures of the teaching areas of two of these variants (a primary school (VS1) and a secondary school (VS4) – teaching areas of these variants are highlighted in Section B). These variants were also placed in two locations, Edinburgh and London, to investigate the effect of local climate. Internal heat gains profiles were constructed using the method outlined in section A1.3 and infiltration assumed to be 0.3 air changes per hour (with window openings and vents closed).

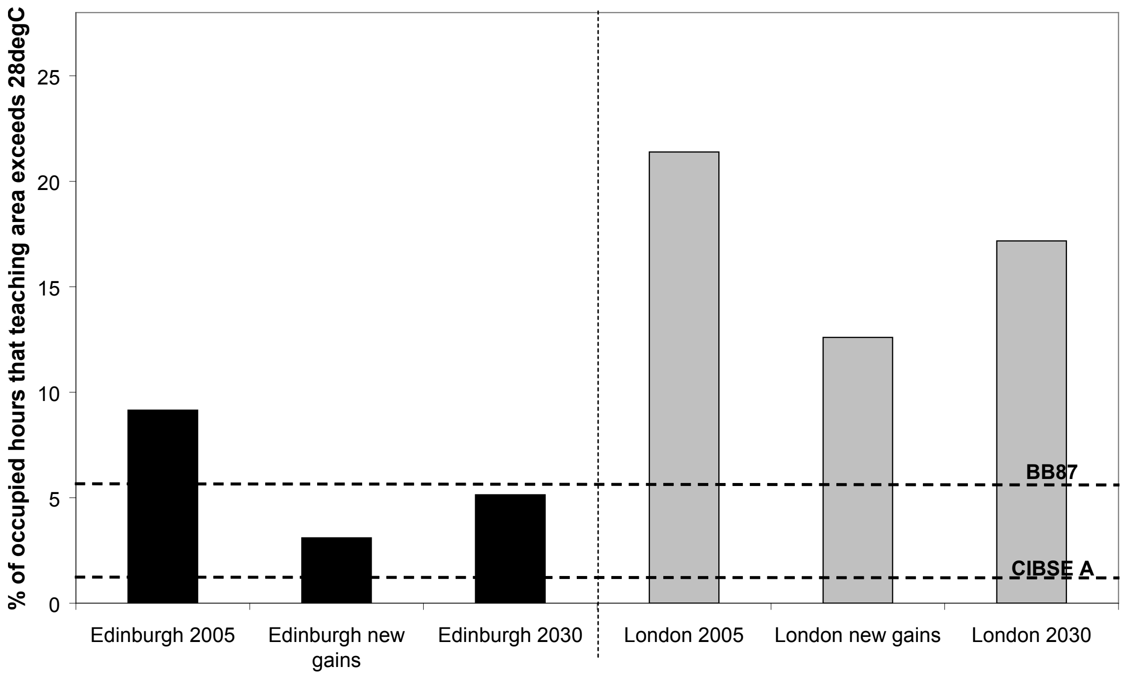


Figure 5 *– Percentage of total occupied hours in teaching spaces at over 28°C for the primary school in six scenarios*

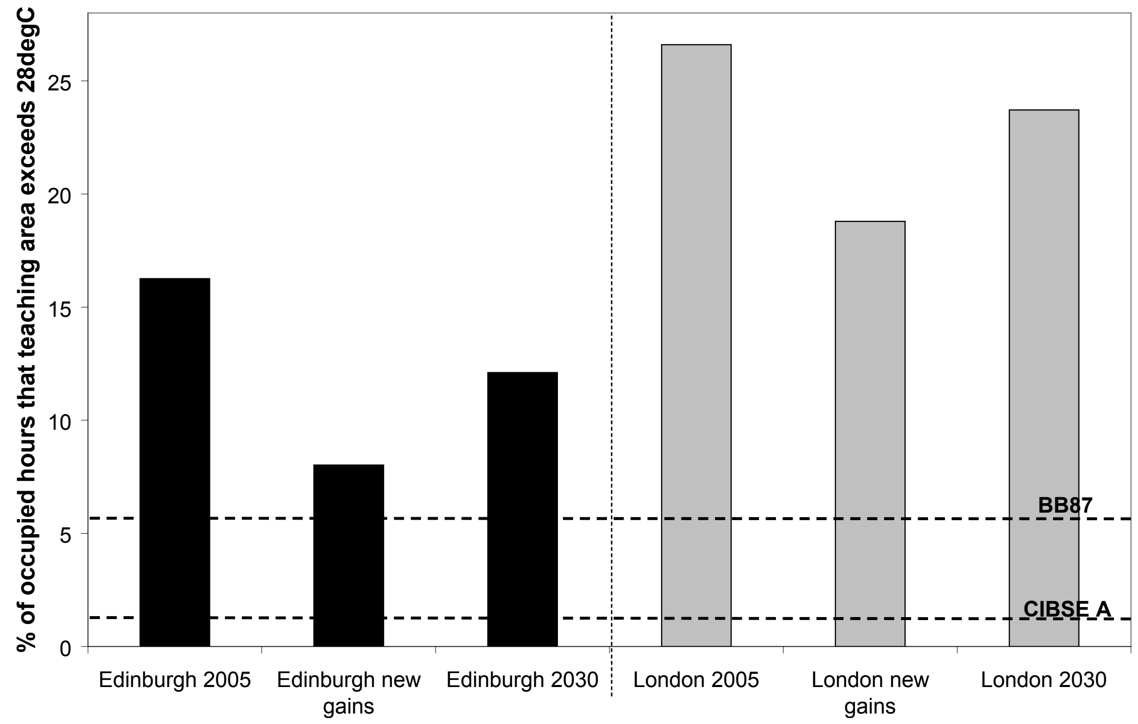


Figure 6 *– Percentage of total occupied hours in teaching spaces at over 28°C for the secondary school in six scenarios*

This 2005 baseline was then altered to account for a change in small power and lighting usage (based on the suggested Tarbase technological interventions and seen as "new gains" in Figures 5 and 6) and also for a change in climate, based on predicted climate change by the year 2030[24] compared to a current climate[25]. Overheating is defined using two previous studies[10,26], with the former suggesting an overheating problem if 1% of occupied hours exceed 28°C and the latter suggesting a limit of 80 hours per year (equivalent to 5.6% of a school year). The predictions, following the simulations of the building variants, are given in Figure 5 for the primary school and Figure 6 for the secondary school (note also that these schools have different locations when presented in Section B). The "Edinburgh 2030" and "London 2030" scenarios account for the "new gains" scenario in a 2030 climate.

Overheating, as defined, occurs for most scenarios and is a particular problem for the London secondary school. This is partly because the two chosen school variants are of relatively recent construction (see Section B) and therefore retain internal heat gains (and are less draughty) than many older school buildings. The results of Figures 5 and 6 therefore only apply to modern schools that might correspond to the current Building Schools for the Future Programme. Most of this overheating, which was registered only if it occurred in the teaching area during term time (accounting for holidays and weekends), occurs between May and September, with June and July being the problem months (the schools will be closed for teaching in August). The substantial drop between the 2005 baseline and "new gains" scenarios implies that a significant proportion of this overheating could be offset by a change in small power and lighting loads. As will be detailed later, the Tarbase approach for IT usage in the school is to replace desktop computers with low power laptops, thus ensuring that pupils can gain access to IT technology but without an excessive energy penalty. In reality, unless legislation is introduced to the contrary, electrical demands, and therefore internal heat gains, are likely to increase as electronic whiteboards and other IT technology achieve wider penetration throughout the education sector. This can only exacerbate the overheating problem.

To investigate other solutions, the buildings were re-simulated with increased ventilation (20l/s/person – which would have to be met through mechanical systems) and solar shading around all windows (represented by a 0.8m external shade installed at the top of all windows). These two measures were chosen as being workable solutions for most schools, although clearly other measures exist.

Figure 7 shows the results of these further simulations. Solar shading has only a small effect on the overheating, suggesting that internal gains are indeed the main problem. Mechanical ventilation shows a noticeable improvement but, at 20l/s/person, is likely to bring with it other comfort issues, with air change rates now being too high. Even with increased ventilation and shading, the secondary school variant in London is predicted to have 12% of teaching hours over 28°C. It would, in such cases, perhaps be advisable to introduce some form of cooling (ideally a passive or semi-passive system such as undercroft or borehole cooling), rather than rely on very high levels of ventilation to displace the warm air.

It is also interesting that, in Figures 5 and 6, the existing 2005 scenario is showing the greatest overheating risk (although, it should be emphasised, the future scenarios are ideal Tarbase projections of what could happen – not necessarily firm predictions of what will happen). With recent investigations[27,28] into the general air quality and internal conditions of schools (including carbon dioxide concentrations as well as thermal comfort) and the rapid change in the buildings themselves, the internal environment of schools is likely to come under increased scrutiny. It is perhaps fair to suggest that ventilation and cooling systems may become more common as we gain greater understanding of this area – and therefore we will see an unintended energy and carbon penalty. The report on this study[20] contains more detail and discussion.

A4 TOTAL ENERGY DEMANDS OF NON-DOMESTIC BUILDINGS

Before considering the effect of carbon-saving interventions (section B), the predicted energy consumption of the non-domestic variants must be considered as a baseline prior to refurbishments. It should be emphasised that, although the methodology is informed by empirical studies and data collected from real buildings, all results are based on simulations. It is quite common for simulation-based results to underestimate the heating and cooling energy consumption of buildings, as poor energy practice can be difficult to quantify within a simulation exercise. While it is relatively simple to account for lights being left on at night (and the lighting energy consumption of the variants do indeed allow for this), it is more difficult to allow for the fact that, for example, occasionally the heating is left on overnight or windows are left open during the heating season because a certain room feels uncomfortable to the occupants. This should be borne in mind when looking at the results of any simulation exercise. As a result, the predicted energy

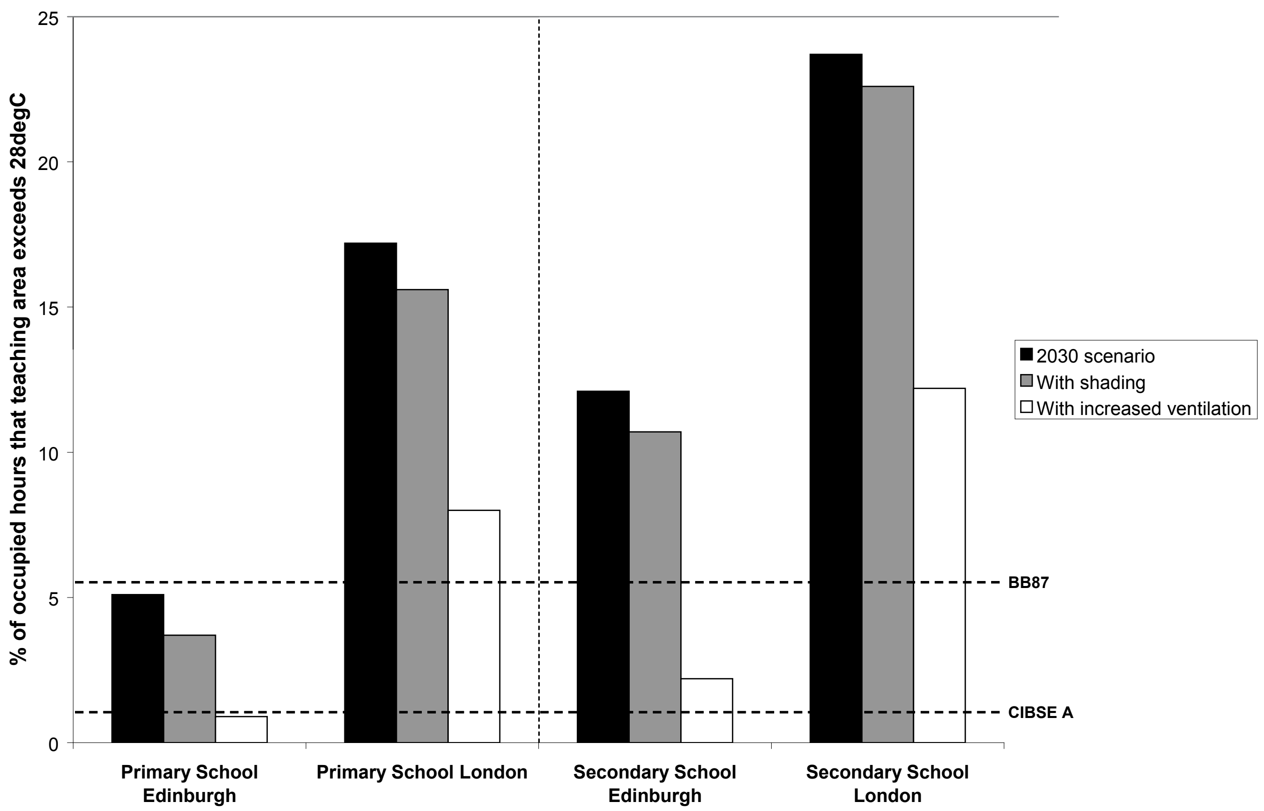


***Figure 7** – Reduction in overheating for 2030 climates in school variants*

consumption figures will show a greater similarity to other simulation-based studies[29] than to purely empirical studies of individual buildings.

A4.1 OFFICES

Although most people have an idea of a working office that is quite generic, significant variations can occur when accounting for detailed operation. Whilst there are often common themes throughout most of the energy usage patterns in the office sector, the advantage of using a variant-based analysis is that slightly different energy-saving strategies become evident for different buildings. However, it becomes clear that to make very large energy and carbon savings in the office sector, the issue of IT equipment and lighting must be addressed. Solely looking at HVAC systems and fabric measures, as well as being difficult to implement due to costs and disruption during installation, cannot be the basis for an effective strategy for reducing carbon emissions throughout the entire office stock.

A4.1.1 DAILY DEMAND PROFILES

The method used for constructing lighting and small power usage, along with output of the hourly simulation for heating and cooling requirements, enables electrical and thermal demand profiles to be constructed for a given day. This will vary throughout the year due to a change in air-conditioning and boiler usage, electrical lighting operation (due to daylighting variation) and the electrical fans and pumps associated with air-conditioning and heating the building. As an example of predicted office energy patterns, Figures 8 and 9 show electrical (half-hourly) and thermal (hourly) profiles for 3rd January and 27th July respectively. The electrical demand profile includes all electrical energy use (lighting, small power and HVAC associated) while the thermal demand represents space heating and domestic hot water usage (DHW), with DHW assumed to be constant throughout the day and the year across the whole of the building.

The winter electrical profile is dominated by small power and lighting, with an allowance made for some IT technologies to be turned off during lunch break. There is a large out-of-hours energy usage due to poor energy management of IT equipment and lighting – it is suggested that this is representative of real life. It is common for IT managers in companies to ask for desktop machines to be left on (though perhaps this practice is slowly changing – and is accounted for in the 2030 interventions for IT equipment). Furthermore, monitors are left in screensaver modes in the belief that these are energy-saving – this is

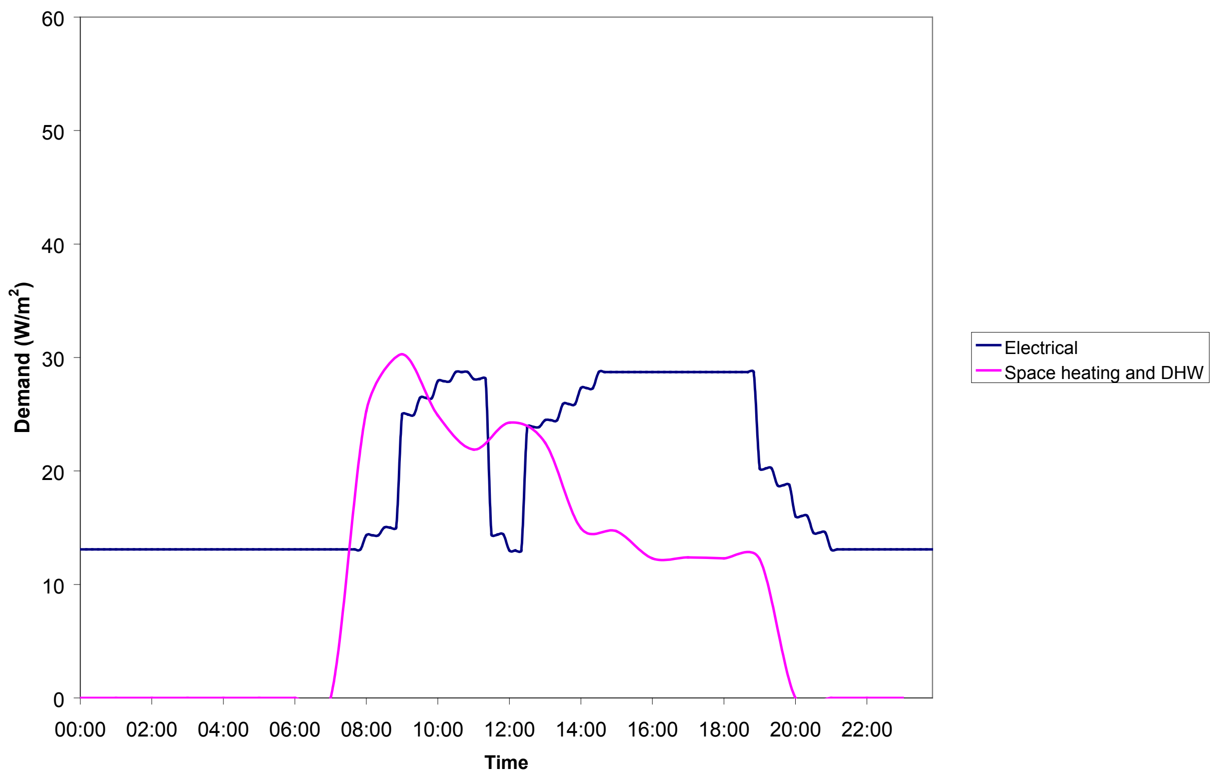


***Figure 8** – Total demand profiles for 4-storey office variant (VO1) on 3rd January 2005*

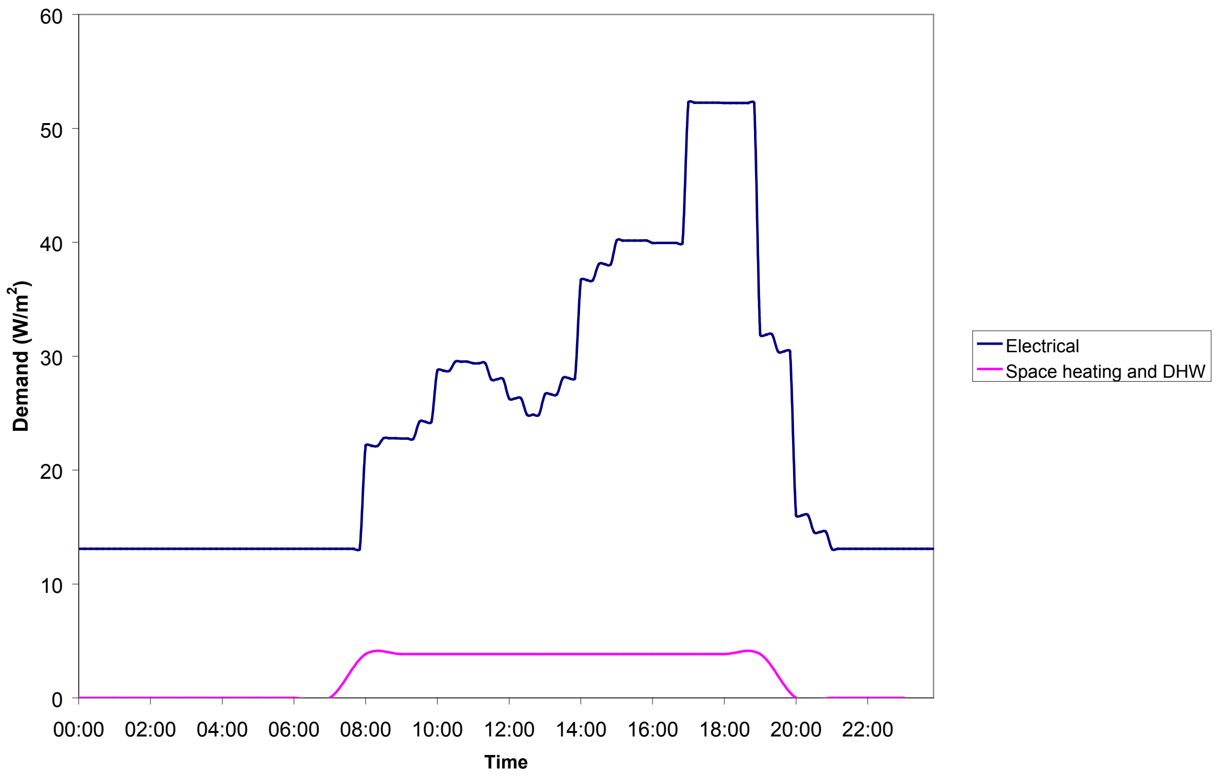


Figure 9 *– Total demand profiles for 4-storey office variant (VO1) on 27th July 2005*

actually not true as a monitor in such a state can actually be in "active mode", operating at somewhere near the power rating of the unit.

The winter thermal profile shows the boiler using significant energy in the morning, heating up the building after it has lost heat throughout the night and early morning. (N.B. A simple operating strategy has been adopted for the boiler where it is switched on at 08:00 – in practice, energy managers may choose a longer start-up period depending on the building in question). As the building heats up, and the external temperature increases, the boiler output is reduced. Also, with the VO1 variant being a concrete panel building of relatively high thermal mass, the building absorbs some of this initial heat (as well as the rising internal heat gain) and re-radiates it at a later time, hence the boiler usage after 16:00 is half that of the peak morning value.

The summer electrical profile is significantly higher than the winter equivalent, with air-conditioning being used extensively. Lighting energy use is reduced, although the sudden increase at 17:00 suggests daylight does not satisfy all the lighting requirements throughout the day (unsurprising for a deep-plan building). As well as the lights coming on, this increase in electricity in the second half of the day is also related to the thermal mass of the building – a build-up of heat from various heat gains (from small power and occupants as well as solar gains) can result in greater loads on the air-conditioning system. The building does not require space heating for this day, so the thermal demand just consists of DHW.

While this method cannot account for the smaller fluctuations of real non-domestic electrical and thermal demands, they do indicate where energy is being used (and therefore where it might be wasted). It is also useful to understand peak power requirements of buildings (as opposed to just using annual energy requirements), particularly from the point of view of energy providers, be it offsite or onsite. With regards to the latter, these profiles can be used when looking at the supply-demand matching problems that can exist when using the onsite generation technologies (where a large percentage of onsite generation ends up as being exported to the grid). Real energy demand profiles are being measured as part of a follow-up study to add to this analysis.

A4.1.2 ANNUAL ENERGY CONSUMPTION

The energy consumptions of the baseline office buildings are mostly dominated by lighting and small power usage, thought this varies subtly between the variants (with occupancy patterns, climate and construction being different). Figure 10 shows the total annual energy consumption of the five 2005 office buildings by unit total floor area. "Fans and pumps" refers to the fans and pumps used with the air-conditioning system and boiler and also includes mechanical ventilation. The "cooling" category is for the chiller consumption only.

The differences between the buildings can be explained by considering the definitions of the variants. The warm climate of VO1 (based in London), combined with slightly less efficient lighting (70lm/W T12 fluorescent instead of 100lm/W T5 fluorescent), results in a small heating consumption and a cooling consumption that is higher than most other variants. VO2 is based in Cardiff, which has relatively warm summers, but is an older building with relatively poor U-values. It also has a very shallow-plan shape (i.e. a long building with a high wall area to volume ratio) and so the heating consumption is higher than VO1, though the lighting energy consumption is less, due to increased daylighting. VO3 and VO4 are identical relatively modern office buildings, based in Manchester, except that VO3 is deep-plan (i.e. a square footprint) and VO4 shallow-plan. With a cooler climate, and slightly lower internal heat gains (with more efficient lighting), the heating energy consumption is more noticeable for these buildings. For the same reason, cooling energy consumption is quite low in both buildings, though it is marginally higher for the shallow-plan building as, with the shallow-plan design, there is more glazing (as there is a higher wall to volume ratio). VO4 also has a reduced lighting energy consumption as, with the higher glazing area, there is more daylighting. Finally, VO5 is a solid wall sandstone building and so, being also based in the cooler climate of Edinburgh, has the highest heating energy consumption per unit floor area (the electricity consumption of the pump used with the boiler results in a high "fans and pump" energy consumption also). This heating energy consumption might be expected to be even higher but the variant also has a high occupant density, so internal heat gains are noticeably higher (and likewise small power energy usage is increased). Cooling is relatively small and the level that exists will be mostly due to these high internal heat gains (with an occupancy of 8m² per person compared to 14m² for the other offices).

These baselines indicate the areas where low-carbon interventions should concentrate. Clearly, lighting and small power usage needs to be addressed (hence these being the first interventions in Section B) and heating is subsequently likely to be an issue for most, if not all, variants once this internal heat gain has been reduced. The

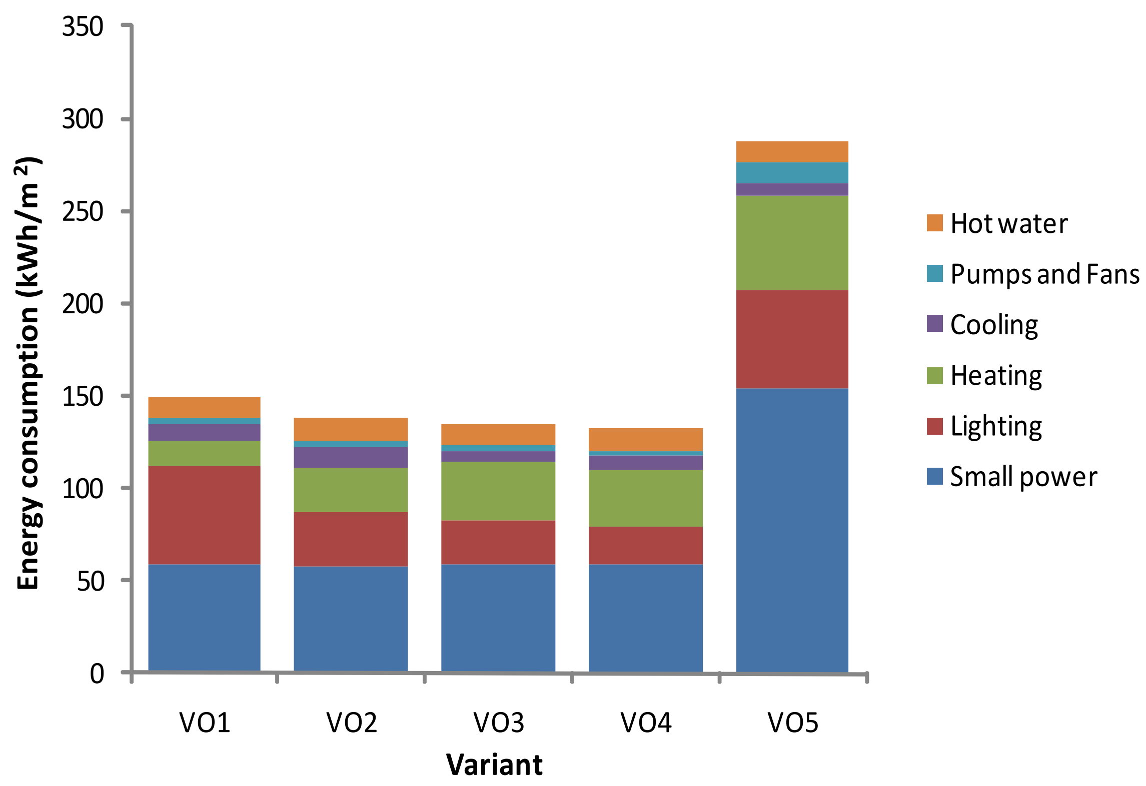


Figure 10 *– Predicted energy consumption of the baseline office variants (defined in Section B)*

extent to which cooling is a problem can only be addressed after carrying out the other interventions – some of these interventions (such as reducing internal heat gains and using glazing with reduced solar transmission) reduce the cooling problem whilst others (such as reducing infiltration rates and increasing insulation) aggravate it.

A4.1.3 EFFECTS OF INTERNAL BLINDS

As a note to the above discussion, the effect of internal blinds should not be ignored. It has been assumed that the use of such blinds is minimal for the baseline office buildings (and this assumption is carried through to Section B). However, the offices were re-simulated to estimate the effect of internal blinds on baseline lighting, air-conditioning and heating energy consumption. These simulations assume that blinds are kept closed for the working day and so there is less solar gain, which decreases annual cooling requirements but increase heating requirement and electrical lighting usage. This assessment is not meant as an exhaustive investigation into different methods and operation of internal shading – such an investigation would have to account for user-behaviour in real-life offices and account for the fact that solar glare (i.e. light discomfort) is the biggest reason for using blinds, not necessarily thermal discomfort, and this is outside the scope of the project. Figure 11 is therefore a first approximation of the effect of introducing internal blinds to the five office variants.

The results are largely intuitive with the buildings most affected by the change being those with the highest glazing area per unit floor area (i.e. VO2 and VO4). The results are not strictly comparable between buildings, because climate and internal activity are different for each variant. For example, VO2 would probably show a greater increase in cooling energy usage but, as it has poor U-values and a higher infiltration rate than VO3 and VO4, it is less likely to overheat. These values can be used as indicative correction factors for all subsequent energy consumptions, but the role of internal blinds (as opposed to fixed external shading) is very difficult to quantify without empirical evidence of their use and measured data and their effects.

A4.1.4 CHANGING BASELINE IT TECHNOLOGY

Another possible change to the baseline (before any carbon-savings interventions are to be added) might be the choice of IT equipment, specifically monitors. It has been assumed for all baseline non-domestic buildings that 61W CRT monitors are the standard screens in use (remembering that this is for a 2005 baseline). There is

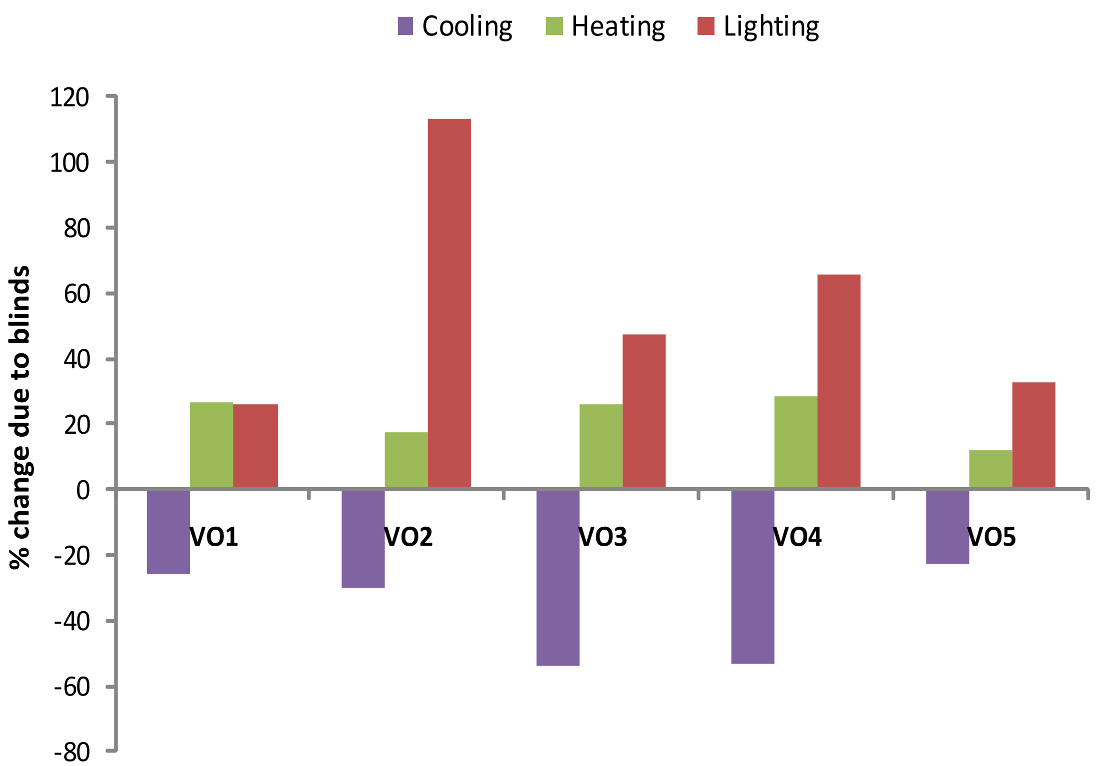


Figure 11 *– Predicted changes in annual cooling, heating and lighting energy consumption due to the introduction of internal blinds for all glazing*

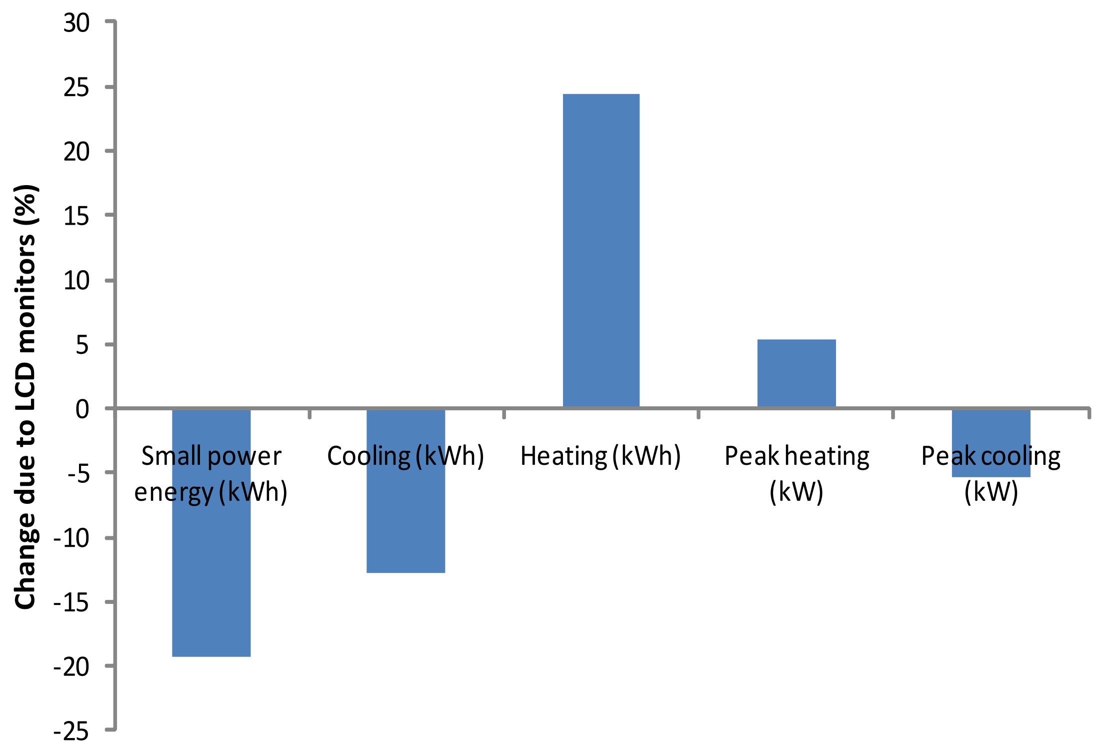


Figure 12 *– Predicted change due to replacing 61W CRT with 12W LCD monitors for variant VO1*

now, however, a steady increase in the use of LCD screens. Such changes occur rapidly as IT equipment is routinely updated every 3 to 5 years by most organisations. To account for this recent change, the 4-storey office (VO1) was re-simulated with LCD monitors (at 12W – this is not the same as the 7W cholesteric LCD monitors used for the 2030 small power equipment intervention). This, as well as reducing the small power energy usage, affects the heating and cooling of the building, an effect that is magnified due to the large number of units in all the office variants. Figure 12 gives the predicted change in these quantities, as well as indicating the change in peak heating and cooling requirement (in kW), which would affect the sizing and operation of the respective heating and cooling systems.

There is a significant change in small power energy consumption and so, with the resulting change in internal heat gains, the annual heating and cooling energy consumption will be modified. As with the previous section, these results can be used as indicative correction factors to modify the baseline results of section A4.1.2 (and Figure 10).

A4.2 RETAIL

While the energy use of office buildings can vary significantly depending on internal activity and construction, retail buildings are even less homogeneous. Even within a specific category, such as supermarkets, the operation between different buildings might be quite diverse (in the case of supermarkets, just using integral or remote refrigeration can make a large difference, as well as HVAC systems being quite different from one company to the next). Such a category of building can be difficult to benchmark such that annual energy consumption (in kWh/m^2) is difficult to generalise. Therefore, the results shown here (like all Tarbase results) are not meant to represent the entire stock, but are predicted for each building variant as defined.

Furthermore, retail buildings are likely to have quite different activities within them. Supermarkets, in particular, typically have a sales area (split between refrigerated and non-refrigerated), storage area and office area. Each area has different occupancies, comfort temperatures, internal heat gains, lighting requirements and, therefore, different energy consumptions. This is accounted for, where relevant, in the simulations of the retail buildings.

A4.2.1 DAILY DEMAND PROFILES

As with the section on the office sector, retail demand profiles will now be demonstrated for a chosen variant over specific days to identify the energy patterns that are predicted to exist. Figures 13 and 14 show the demand

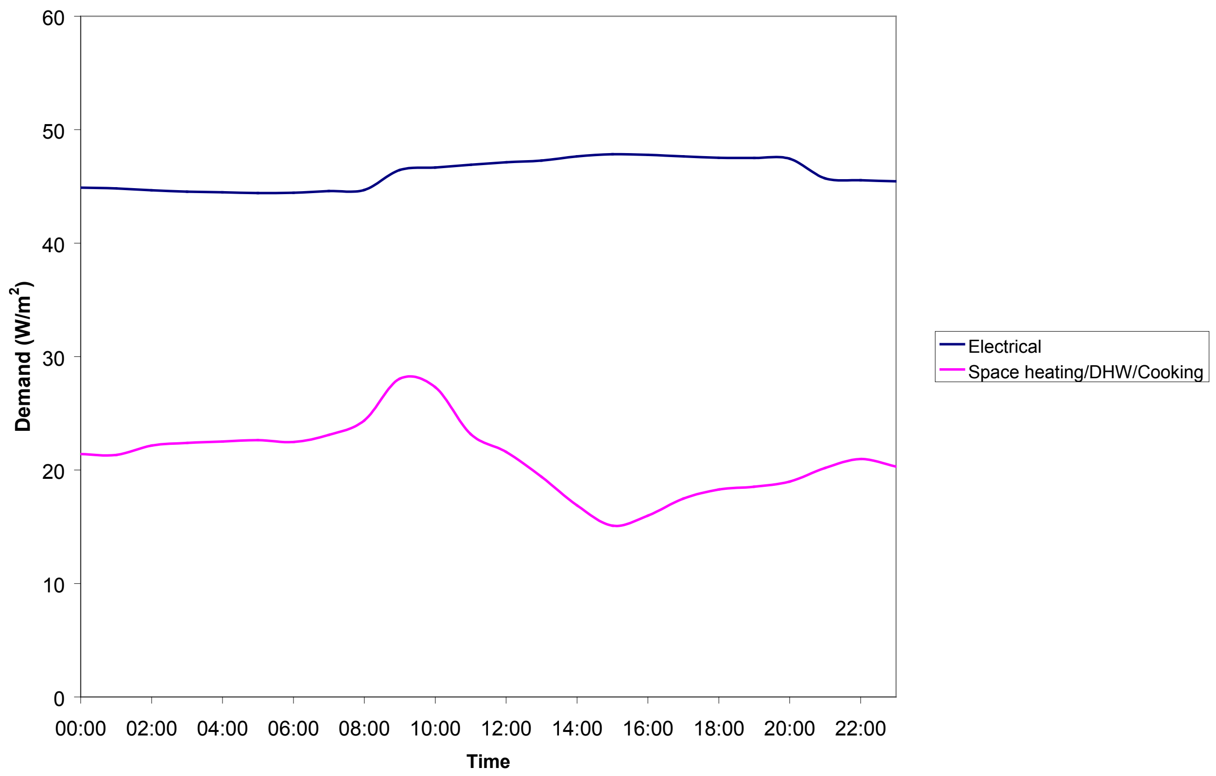


Figure 13 *– Total demand profiles for supermarket retail variant (VR4) on 3rd January 2005*

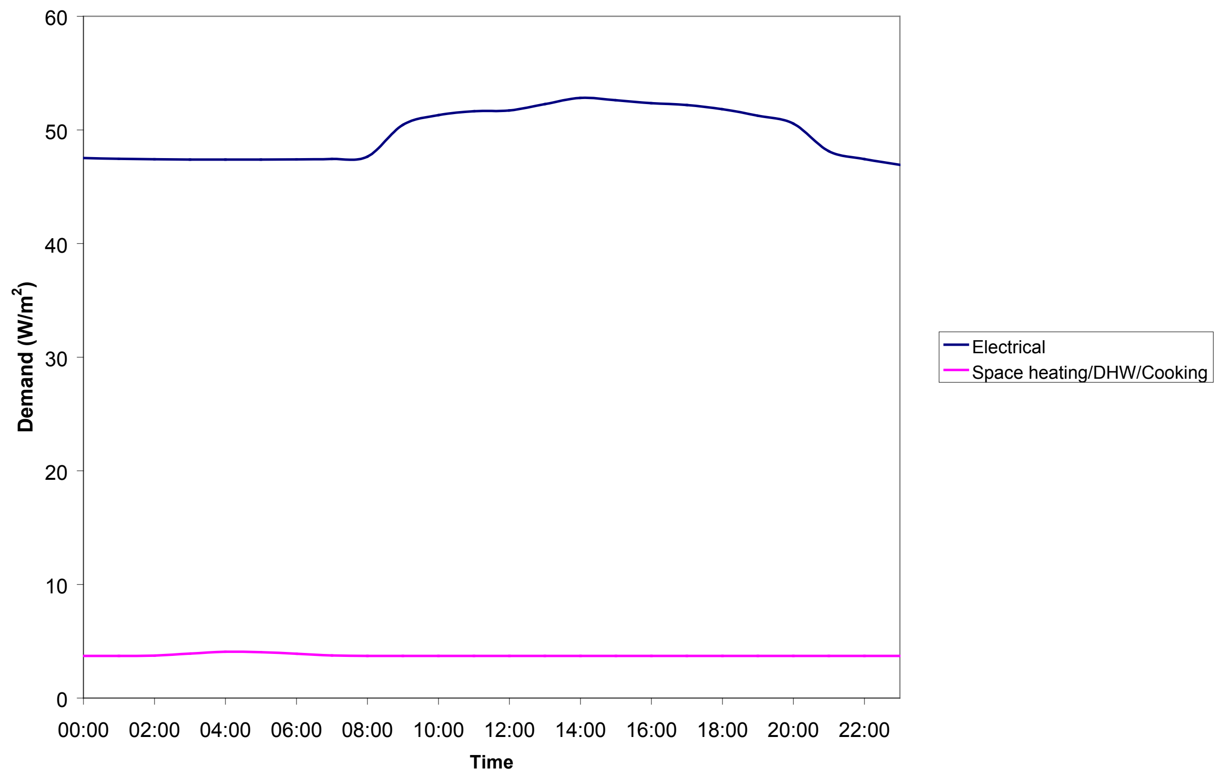


Figure 14 *– Total demand profiles for supermarket retail variant (VR4) on 27th July 2005*

profiles of the supermarket building (VR4) for winter and summer respectively, with the variant itself discussed in Section B.

The winter electrical profile (blue line in Figure 13) is fairly flat – this is due to the dominance of refrigeration and lighting. With the supermarket variant being open for 24hours a day, the lighting and refrigeration is assumed to be operating over this entire time (there is a small drop in lighting energy use outside normal working hours due to workers in the office area switching lights off). The winter gas usage profile (i.e. including space heating, hot water and in-store bakery cooking) shows a peak in the morning, when external temperatures are still low and internal heat gains have yet to contribute towards internal temperature (although this effect is less pronounced than for an office building due to the constant operation of the building). A rise in occupant metabolic gain (see section A4.2.3) and external temperature reduces the space heating requirement during the day, before a rise is seen towards the evening (as with all variants, these simulations use real climate data and fluctuations are specific to that day).

The summer electrical profile (blue line in Figure 14) is, like the winter profile, quite flat, though there is an added daytime electrical load due to air-conditioning throughout the building. There is also an increase as the refrigeration units (with power consumption modelled to change with temperature and humidity[30]) are having to work harder to maintain the required storage temperatures for food. The space heating demand is close to zero, with the only gas usage being due to the hot water and cooking requirement (assumed to be relatively constant throughout the day).

Such flat electrical and thermal loads are generally advantageous in terms of the running of a boiler or onsite electrical generation system. However, these loads are also consistently high (in the region of 50W/m²) and so onsite generation will struggle to meet anything like a significant proportion of this electrical demand profile.

A4.2.2 ANNUAL ENERGY CONSUMPTION

Figure 15 shows the total annual energy usage of all the retail variants. VR1, is a high-street estate agent and shows similar energy usage patterns to the office variants, being dominated by small power (mostly IT equipment) and lighting. The lighting in the other retail variants is slightly higher (per unit total floor area) due to slightly less efficient lighting (such as the use of halogen lighting in the clothes shop, variant VR3). This is a significant problem for lighting in the retail sector – while general store lighting (often fluorescent) might be quite efficient, there is a desire for the aesthetic of spotlights (usually halogen, though compact fluorescent lighting equivalents are sometimes used) and display lighting. This can increase lighting energy consumption considerably. Heating can be more of a problem than the energy values of Figure 15 suggest – for buildings with electric heating (whether radiant or warm-air systems) the carbon penalty of using grid electricity can be significant. This is true for both variants VR2 and VR3, as detailed in Section B.

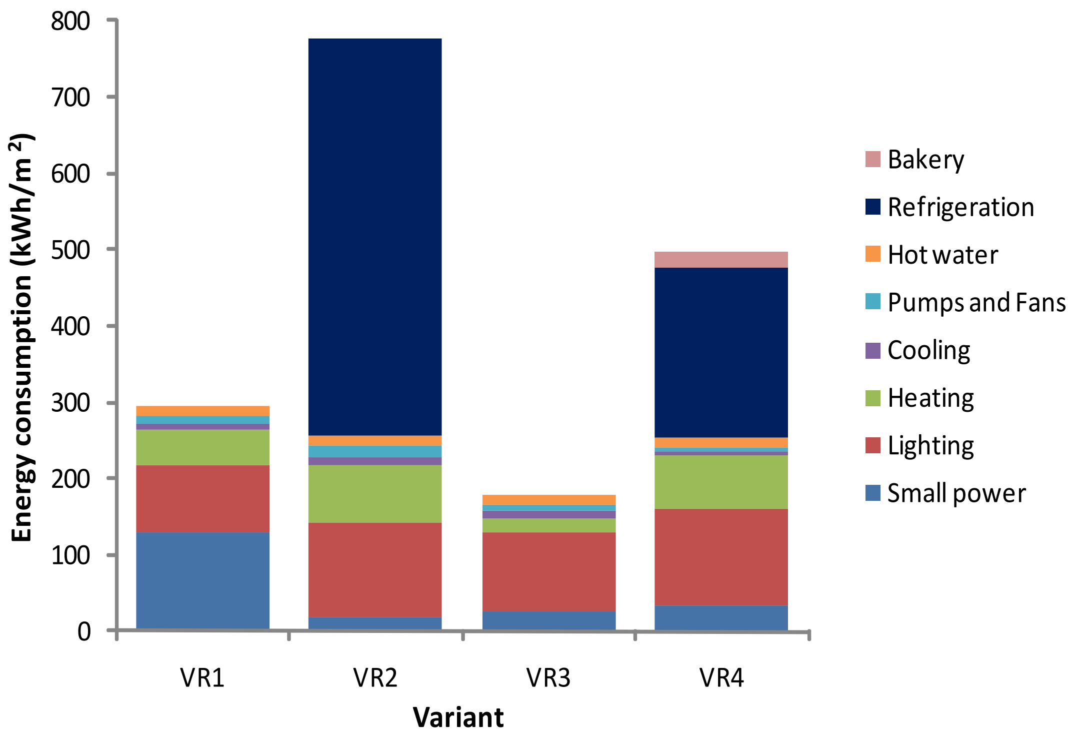


Figure 15 *– Predicted energy consumption of the baseline retail variants*

For buildings with refrigeration (such as the convenience store VR2 and the supermarket VR4), it is clear that this becomes the dominant energy use. VR2 uses integral refrigeration (which would reject heat inside the building) and VR4 uses remote refrigeration with a central compressor on the outside of the building (more common for large supermarkets). The convenience store is assumed to have a large percentage of its floor area dominated by such units (which includes low temperature L1-type and high temperature M1-type[31] display refrigerated cabinets), whereas the supermarket, although having a very large total refrigeration load, also has a large percentage of its floor area devoted to non-food items. The simulation of buildings with incidental cooling gains from refrigeration will not be discussed in detail but has been documented in detail elsewhere by Tarbase[21].

For retail buildings with refrigeration, large-scale carbon savings will not be achieved without addressing this refrigerated energy use. While the COPs of refrigerated units are improving over time, reducing this energy use is likely to involve some form of energy management, such as the use of cabinet blinds. An alternative strategy might be to use some form of tri-generation (see section A2.2), although the low temperatures required (particularly for freezer units) can reduce the efficiency and applicability of absorption chiller technology.

For retail buildings without refrigeration, the dominance of lighting is, in some respects, less of a problem. As discussed for offices, there is certainly scope for lighting efficacy to improve significantly, both through the current fluorescent technologies but also with the adoption of near-future technologies such as LEDs. This will have a noticeable effect on the total building energy use (and carbon emissions).

The building fabric of different retail buildings can be as diverse as the activities within. They range from a retail shed-type construction, as seen with the clothes shop variant (VR3) and the supermarket (VR4), to the more traditional buildings of the estate agent (VR1) and convenience store (VR2). The latter two are presumed to be relatively recent conversions from domestic properties in high streets or residential areas.

A4.2.3 SUPERMARKET OCCUPANCY

As part of the study on retail buildings, a data collection exercise was carried out to monitor the occupancy of a supermarket building over the course of a day. The number of people entering and leaving a large supermarket building over 24 hours was measured every hour, thus giving an average number of people in the building per hour. In addition to this, to account for different occupancies throughout the week, an estimate was provided by the supermarket for the expected total number of shoppers in the building every day (Table 5). The "normalised factor" quantifies the number of people in a given day compared to the average number per day for an entire week. The average weekday and weekend day normalisation factors (0.96 and 1.10 respectively) could then be used to morph the collected data to represent typical week and weekend days (which can then be used in the simulation).

Table 5 *– Expected shoppers at local Edinburgh supermarket (sales area 5000m2)*

	Expected total shoppers	Normalised factor	5-day/2-day averages
Monday	8000	0.862	
Tuesday	7500	0.808	
Wednesday	8500	0.915	0.958
Thursday	9500	1.023	
Friday	11000	1.185	
Saturday	10500	1.131	1.104
Sunday	10000	1.077	

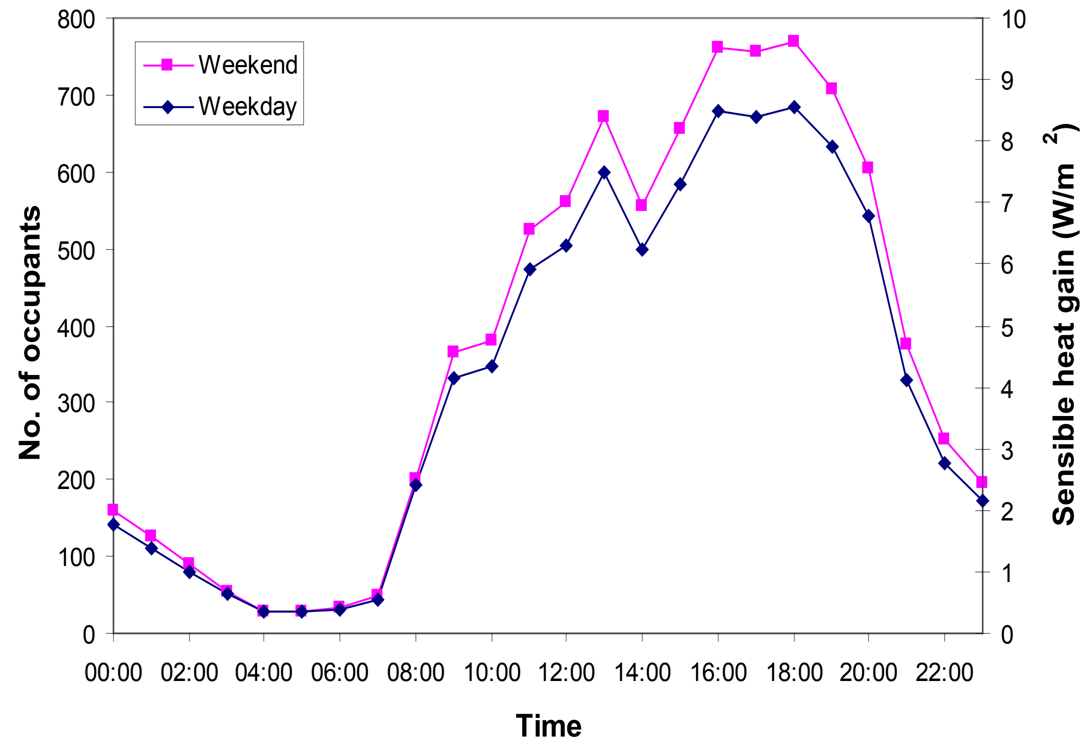


Figure 16 *– Weekday and weekend occupant profiles for supermarket*

The normalised results for the measured store are shown in Figure 16. This can be used to estimate the sensible and latent heat gains generated in the building from occupants (the former relating to dry-bulb temperature and the latter wet-bulb). With an estimated number of staff (128 during daytime and 20 during the night) and assuming a sensible heat gain of 75W per person[10], a total occupant heat gain profile can be estimated, as shown by the secondary y-axis of Figure 16. Converting the number of people into W/m^2 heat gain means that this profile can be applied to any supermarket of this type. The process is repeated for latent heat gain, assuming 55W per person[10]. These inputs, along with internal heat gain characteristics of the small power and lighting, can be used to describe the internal activity within the simulation.

A4.3 SCHOOLS

Energy use in the schools sector can be relatively homogenous between buildings of a similar construction. While variations occur due to use of IT technology (particularly electronic whiteboards) and general energy management, there is also a clear difference between older buildings (such as solid wall Victorian schools) and more modern constructions, particularly those emanating from the Building Schools for the Future programme. The variants used in this study are chosen with the year 2030 in mind – namely, what current school buildings will still be standing in 20-25 years time? This approach identifies newer buildings, which are designed to be reasonably energy-efficient and built for use over a long period of time (of the order of 60 years) and older listed buildings (which will be kept as historic buildings) as being appropriate as building variants.

A4.3.1 DAILY DEMAND PROFILES

It is to be expected that primary school and secondary school buildings have slightly different demand profiles, particularly with a difference in the scale of IT equipment being used. However, particularly with regards to electrical demand profiles, similar patterns of energy use will be seen throughout the school sector. Figures 17 and 18 show the predicted electrical and thermal demand profiles of the largest secondary school variant (VS4), for winter and summer respectively.

The winter electrical profile is assumed to be relatively constant throughout the school day, with higher values between 9am and 2pm due to electrical usage in the kitchen (electrical usage in the kitchen is included in

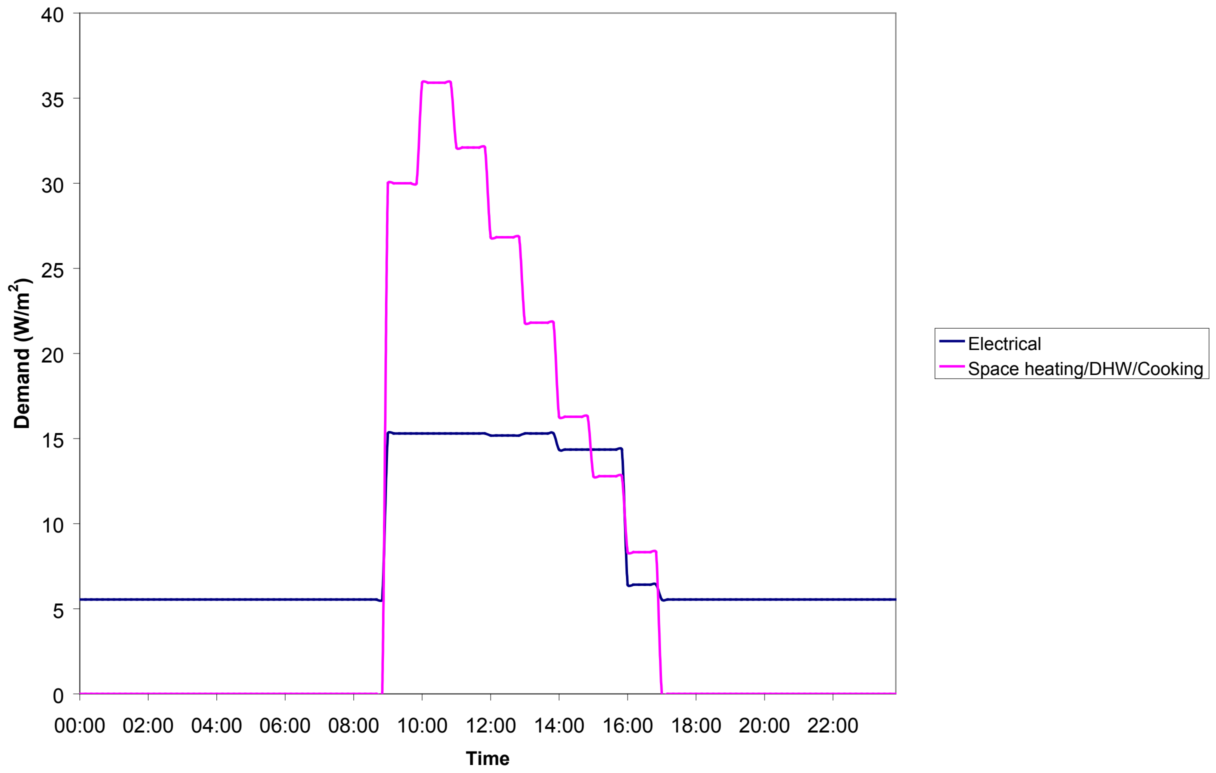


***Figure 17** – Total demand profiles for large secondary school variant (VS4) on 5th January 2005*

the electrical profile whereas gas usage in the kitchen is included in the space heating/DHW/cooking profile – the balance between these has been quantified using published guidelines[32]). Lights are assumed to operate throughout the day, with a proportion of these left on at night forming, with equipment loads, a night-time electrical load of over $5W/m^2$. The winter thermal profile (for space heating, hot water and kitchen gas usage) is dominated by space heating, with the boiler providing a large amount of heat in the morning before reaching desired temperature

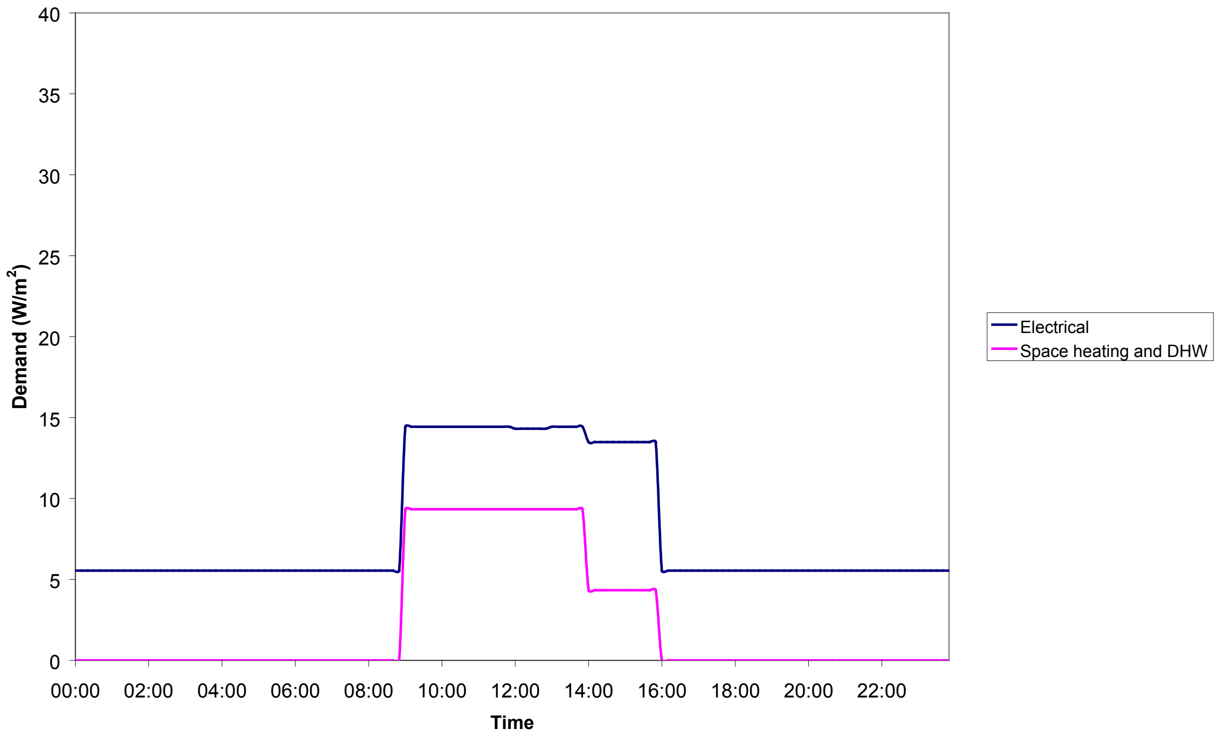


***Figure 18** – Total demand profiles for large secondary school variant (VS4) on 19th July 2005*

and, with rising internal gains and external temperatures, the boiler usage decreases throughout the day.

The summer electrical profile is similar to the winter profile (although slightly lower due to the electrical pump associated with the boiler not being required for space heating). It is possible that lighting energy use would be reduced, though it has been assumed here that lighting is still being used throughout the day (to enable a suitable visual environment for the entire building at all times – essential for a school building). The absence of space heating leaves gas usage being due only to cooking and hot water. With these assumptions, the electrical energy use in school buildings is fundamentally different to most other non-domestic buildings in that there is greater energy usage in the winter. It has already been suggested (see section A3.2) that this might soon change as mechanical cooling becomes necessary in school buildings.

A4.3.2 ANNUAL ENERGY CONSUMPTION

Figure 19 shows the total energy consumptions of all the school variants. There is a consistency throughout the chosen variants, apart from the vastly increased heating consumption of VS2, the pre-1900 construction primary school. This is a solid wall building based in Edinburgh, and so has a far greater heat loss problem than the other school variants. The similarity in the space heating usage of the other variants is explained by the similar choice of constructions (for reasons discussed earlier regarding the need to choose buildings that would still be standing in 2030). VS1, the smaller primary school based in Cardiff, is unlikely to have a greatly different heating requirement (per unit floor area), from the secondary schools in London (VS3) and Birmingham (VS4). This does suggest that, when the Building Schools for the Future Programme has been completed, a generic approach could be adopted for further reducing school carbon emissions that will be relevant to a large proportion of the stock (due to building homogeneity). This is not necessarily the case for other sectors of the non-domestic stock.

The concern is that, as previously discussed, IT equipment usage will increase dramatically (thus directly increasing the size of the blue area in Figure 19) and so introduce a cooling energy usage that, traditionally in schools in the UK, has not been seen as an issue. That such problems might occur immediately after a large-scale building refurbishment programme is even more of an issue, but this study would strongly recommend appropriate legislation to ensure that internal heat gains be minimised so that low-carbon schools can still provide suitable internal teaching environments throughout the year.

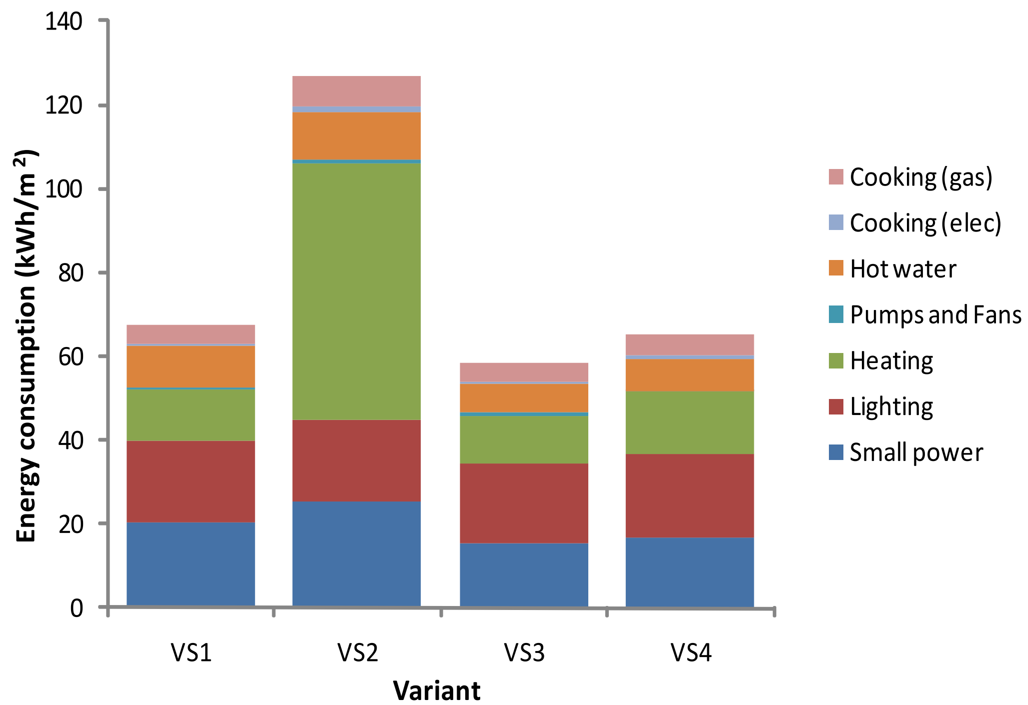


***Figure 19** – Predicted energy consumption of the baseline school variants (defined in Section B)*

A4.4 HOTELS

In addition to the detailed sector analysis performed on offices, schools and retail buildings, the project also carried out a study on hotel buildings[33]. This work followed a similar methodology as already detailed, using dynamic simulation with appropriate information for internal activity and building services. Two hotels were studied; an older building that has already undergone a certain level of refurbishment and a new hotel built to more recent building regulations.

The main finding was that it could be technically, though not necessarily economically, feasible to reduce emissions by 50% without compromising guest comfort. This was achieved through the implementation of changes to small power and lighting, mechanical ventilation heat recovery, wall insulation (external cladding for the newer hotel, internal for the older hotel with a more historic facade), argon-filled triple glazing and a reduction in infiltration. Solar thermal panels were also modelled for these buildings to provide some of the hot water requirements, which can be considerable for buildings with high laundry usage.

Taking an optimistic view regarding the installation and ability of the building owner to pay, the new hotel was modelled with baseline carbon emissions of 525 tCO_2 that was reduced to 183 tCO_2. The older hotel had a baseline of 280 tCO_2 that reached a post-retrofit value of 133 tCO_2. The aforementioned reference[33] discusses the sensitivity of this modelled energy usage with other factors and compares the results with actual surveys of hotel buildings.

A5 ONSITE GENERATION

The visibility of onsite generation often results in such technologies being near the front of the queue for low-carbon building refurbishments. This is even more so for non-domestic buildings, with the organisations that own such buildings wanting to project a greener image. However, there are several factors that make onsite generation less suitable for non-domestic buildings. Firstly, as a result of often being multi-storey buildings, the roof to floor area ratio of non-domestic buildings can be quite low. This means that there is less room for the rooftop technologies of solar thermal, solar photovoltaic and small and micro wind turbines. With the use of IT equipment being so widespread, air-conditioning being in present and lighting being used for very long periods of time, electrical energy use of non-domestic buildings can be vast. These two factors (large electrical loads and relatively small roof areas) can result in onsite generation only satisfying a small percentage of electrical energy use and so carbon savings will be small.

Using CHP and tri-generation has already been discussed (section A2.2) and while some approaches show potential, most technologies would point towards district solutions as being more appropriate.

A5.1 SOLAR AND WIND ONSITE GENERATION

Table 6 shows the chosen photovoltaic (PV), onsite wind and solar thermal options for the non-domestic variants. These technologies are modelled using bespoke models developed during the project[34,35]. Considering the size of most of the systems used, it is clear that this type of onsite generation cannot really be described as micro-generation. Very large systems have been identified, in most cases representing the largest installation that would be feasible. The results, in that regard, are therefore optimistic. However, it is expected that the selected solar and wind technologies will improve by the year 2030 (in both capital cost and efficiency). Arguably, this improvement would have to be quite dramatic for PV and wind turbines to become an economical strategy for reducing carbon emissions throughout the entire non-domestic stock, rather than just being applied to a few exemplar buildings.

Solar PV systems are approximately sized on the available roof area and total electrical energy use of the building (so a total electrical energy use and a large roof area would be more likely to choose a larger PV installation). However, it is likely to be economics that restricts the sizes of PV. Rooftop wind turbines (assumed to reach a maximum of 1.5kW each) are installed such that they do not interfere with other turbines, which restricts the number that would be suitable for a given roof area. The school variants are assumed to have enough ground to install a larger 20kW turbine, which will generally have an improved capacity factor when compared to smaller turbines. Solar thermal units are sized to meet 50% of the annual "domestic" hot water energy demand. For the supermarket variant (VR4) and the primary school variants (VS1 and VS2), solar thermal has not been considered. In the case of the supermarket, the hot water energy usage is quite small and so solar thermal does not reduce total

Table 6 *– Summary of onsite generation systems for non-domestic variants*

Variant	Photovoltaic		Onsite wind		Solar thermal	
	Description	Annual yied (kWh)	Description	Annual yied (kWh)	Description	Annual yied (kWh)
VO1	200m² monocrystalline, 27kW peak, 30.~ from horizontal, South facing, London	25840	10 x 1.5kW rooftop turbines at hub height of 16.3m (av. wind speeds: urban 2.3m/s; rural 5.6m/s)	4110 - 31360		20770
VO2	200m² monocrystalline, 27kW peak, 30.~ from horizontal, South facing, Cardiff	27570	8 x 1.5kW rooftop turbines at hub height of 24.5m (av. wind speeds: urban 2.5m/s; rural 6.1m/s)	4377 - 28620		15740
VO3	300m² monocrystalline, 40kW peak, 30.~ from horizontal, South facing, Manchester	36430	8 x 1.5kW rooftop turbines at hub height of 24.2m (av. wind speeds: urban 2.5m/s; rural 6.1m/s)	4340 - 28620		28670
VO4	300m² monocrystalline, 27kW peak, 30.~ from horizontal, South facing, London	36430	8 x 1.5kW rooftop turbines at hub height of 24.2m (av. wind speeds: urban 2.5m/s; rural 6.1m/s)	4340 - 28620		28670
VO5	30m² monocrystalline, 4kW peak, 30.~ from horizontal, South facing, Edinburgh	3350	2 x 1.5kW rooftop turbines at hub height of 14m (av. wind speeds: urban 2.2m/s; rural 5.4m/s)	730 - 5910		1240
VR1	No available rooftop for onsite photovoltaic		No available rooftop or ground for onsite wind		Sized to meet 50% of annual hot water requirements where hot water usage is reasonably consistent (and a significant energy user) throughout the year	n/a
VR2	50m² monocrystalline, 6.8kW peak, 30.~ from horizontal, East facing, Birmingham	5430	2 x 1.5kW rooftop turbines at hub height of 6m (av. wind speeds: urban 1.7m/s; rural 4.2m/s)	330 - 3780		1800
VR3	50m² monocrystalline, 54kW peak, 30.~ from horizontal, South facing, London	6500	4 x 1.5kW rooftop turbines at hub height of 13m (av. wind speeds: urban 2.2m/s; rural 5.3m/s)	1380 - 11460		5380
VR4	400m² monocrystalline, 6.8kW peak, Flat on roof, Manchester	43500	1 x 20kW near site turbine at hub height of 12.5m (av. wind speeds: urban 2.2m/s; rural 5.3m/s)	4760 - 44150		Variant deemed unsuitable
VS1	50m² monocrystalline, 6.8kW peak, Flat on roof, Cardiff	6420	2 x 1.5kW rooftop turbines at hub height of 6m (av. wind speeds: urban 1.7m/s; rural 4.2m/s)	330 - 3780		3626
VS2	100m² monocrystalline, 13.5kW peak, 30.~ from horizontal, East facing, Edinburgh	9740	2 x 1.5kW rooftop turbines at hub height of 13m (av. wind speeds: urban 2.2m/s; rural 5.3m/s)	690 - 5730		6168
VS3	400m² monocrystalline, 54kW peak, Flat on roof, London	47040	1 x 20kW near site turbine at hub height of 12.5m (av. wind speeds: urban 2.2m/s; rural 5.3m/s)	4760 - 44150		25120
VS4	400m² monocrystalline, 54kW peak, Flat on roof, Birmingham	45020	1 x 20kW near site turbine at hub height of 12.5m (av. wind speeds: urban 2.2m/s; rural 5.3m/s)	4760 - 44150		30390

Wind turbine annual yields give range between the predicted urban and rural wind speeds

building carbon emissions by a large degree. In the case of the primary school variants, there is the problem of both intermittent usage throughout the year and intermittent usage throughout the day – a greater number of occupants (such as with the secondary school variants) would result in a smoother hot water demand profile and improve the performance of a solar thermal system. This does not rule out solar thermal completely for these variants but the other non-domestic variants are considered as being more suitable. No rooftop renewables are used with the estate agent variant (VR1) due to the premise being situated below other premises (in this case below the small office variant (VO5)).

The inputs used for the solar and wind models are empirically-based. The PV model uses CIBSE Test Reference Year climate files[25] that are morphed to account for a future 2030 climate[24]. As well as global and diffuse radiation inputs (re-calculated for the inclination of the solar PV panel), the model also accounts for dry-bulb temperature (and its effect on the PV efficiency).

As discussed in section A5, the wind turbine model uses manufacturers' power curves with wind speed data collected at Heriot-Watt University for a sheltered and non-sheltered site (approximated as urban and rural locations respectively). These 10-minutely wind speeds are then extrapolated for other altitudes using the wind shear formula[36].

Generally, non-domestic onsite generation systems have a greater percentage of generated energy used onsite, and less exported, than for domestic equivalents. This is partly due to the high electrical loads throughout the year as well as fewer fluctuations over small timescales (where, for example, a kettle switching on will not register on the electrical demand profile in the way that it would for a domestic demand profile).

The carbon savings achieved by each of the identified interventions on each building variant are quantified for different grid carbon intensities in Appendix II.

A5.2 HEAT-PUMP OPTIONS

The project developed both air-source and ground-source heat pump models for use in any domestic or non-domestic building, based on climate files, system specification and thermal demands (nominally on an hourly basis). The models work in similar ways and output hourly COPs throughout the year (accounting for climatic variations and part-load efficiencies) and electrical energy use of the system.

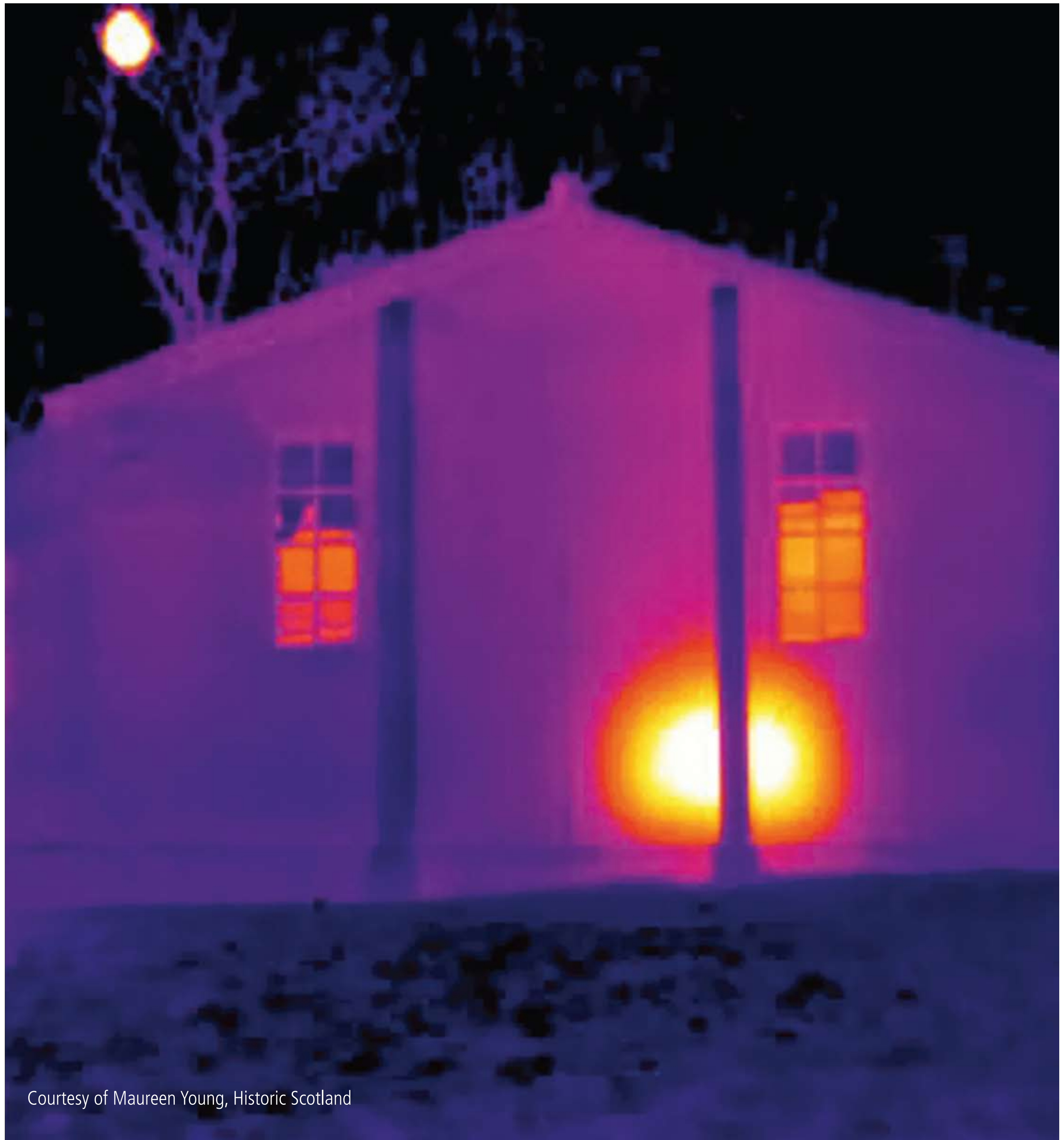
The air-source heat pump (ASHP) model[37] identified office and retail buildings as being suitable applications providing there was a significant heating requirement in the building (not always the case in some of the defined non-domestic variants). While the system was also being used for cooling, there was no carbon saving benefit to cooling the building with an ASHP as compared to a modern air-conditioning system (the carbon savings are then all about how the ASHP in heating mode compares to the baseline heating system, for example a gas boiler). The sensitivity of the carbon savings to grid carbon intensity was also explored in the aforementioned study.

The ground-source heat pump (GSHP) model[38] suggested that large-scale carbon savings were more likely for new domestic buildings that install underfloor heating (which allow for substantially higher COPs). The problem with retrofitting into a non-domestic building is that the carbon savings might not actually be significant when compared to a highly efficient condensing gas boiler. The effect of grid carbon intensity is again important – will the GSHP be using peak daytime (and carbon intensive) electricity or will it be controlled to take less "dirty" electricity during the night, storing this heat, and distributing through the building during the day to meet the requirement. If large carbon (and running cost) savings are not apparent, the rationale for installing a GSHP system into an existing building begins to diminish, particularly if the building has undergone other refurbishments (such as mechanical ventilation heat recovery and building fabric improvements) to reduce the heating requirement to the point of it being a minor concern.

GSHPs are therefore not considered for the non-domestic buildings within this study. ASHPs have been investigated for variants VO2, VO3, VO4, VR2 and VR3, the latter two variants using such technology in the baseline version.

SECTION B

Building exemplars with demand-side carbon-saving interventions



Courtesy of Maureen Young, Historic Scotland

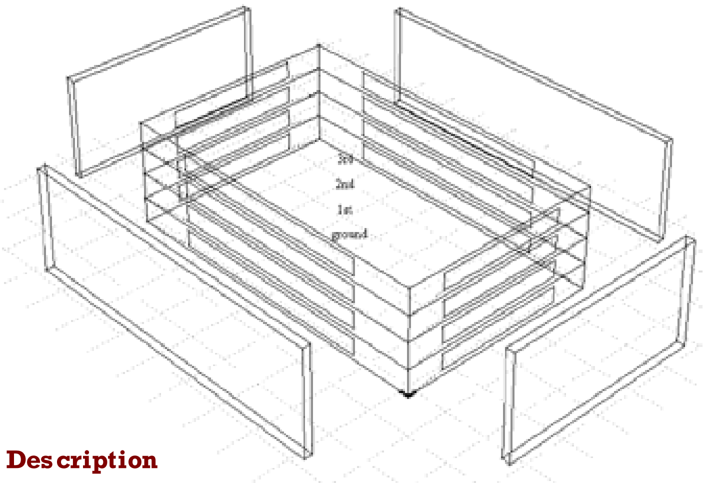
FOREWORD

This section presents the carbon saving interventions and their effects on the energy consumption and CO_2 emissions of each of the building variants, in a standardised and concise format. For each case study, the building itself is described and the small power and total energy consumptions in 2005 (baseline) and 2030 (after climate change and interventions have been applied) obtained from the simulations are presented. Different packages of demand-side carbon-saving measures have been proposed for different buildings and, for selected variants, an extra layer of detail has been provided by describing intermediate intervention steps to achieving the final goal. These are presented as cumulative measures and so all changes to the internal activity etc are accounted for in subsequent simulations. This is a crucial point when assessing appropriate carbon-saving strategies for individual buildings – what might be a sensible measure for a baseline 2005 building can have a negligible or detrimental effect on the same building once the internal activity has changed. Different measures can clash with each other and so simulating a "bundle" of interventions is more important than simulating individual measures and then summing the measures. It is also incorrect to assume that a measure will always reduce the building carbon emissions by the same percentage.

The additional effect of onsite generation is included in the graphical output of section C. All CO_2 calculations in this section are based on carbon intensity factors of 0.19kgCO_2/kWh for gas-based energy usage[39] and 0.52kgCO_2/kWh for grid electricity[40] (for both imported and exported electricity).

Non-Domestic building CO_2 savings:

Office variant VO1



Dimensions

Width: 25m

Length: 40m

Height: 4 x 3.7m

Total floor area: 4000m^2

Age: 1981-1985 construction

Description

4-Storey office building, situated in London, with occupancy of one person per 14m^2 (resulting in 286 occupants). Operating hours are Mon-Fri, 9am to 7pm.

Construction

Concrete panel building with wall, floor and roof U-values of 0.65W/m^2K, 0.27W/m^2K and 0.87W/m^2K respectively. Standard double glazing (40% of external wall area) of 2.75W/m^2K. Infiltration rate of 1.0ach (i.e. poor air-tightness)

HVAC systems

2 x 147kW non-condensing boilers for heating, with 2 x 194kW chiller units for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 5.4W/m^2; Lighting 15.2W/m^2; Small power 11.4W/m^2

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ External insulation of expanded polystyrene (EPS) with concrete render

⇒ EPS also used for floor (100mm) and roof (200mm) replacing existing mineral wool

⇒ Triple-glazed argon windows (U-value 0.78W/m^2K), with low-e coating, replacing existing double glazing

⇒ Infiltration reduced from 1ach to 0.5ach

- **HVAC**

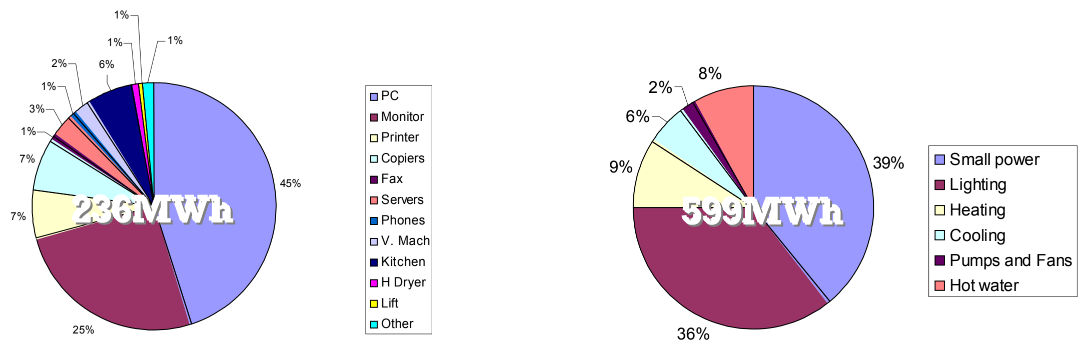
⇒ Condensing boiler replaces non-condensing boiler

⇒ Mechanical ventilation heat recovery (MVHR)

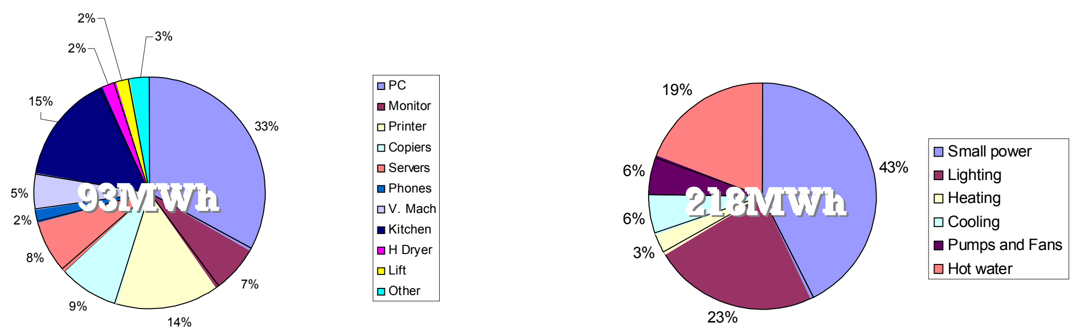
⇒ Adaptive comfort approach to cooling

⇒ Reduction in internal gains (see "Small Power and Lighting")

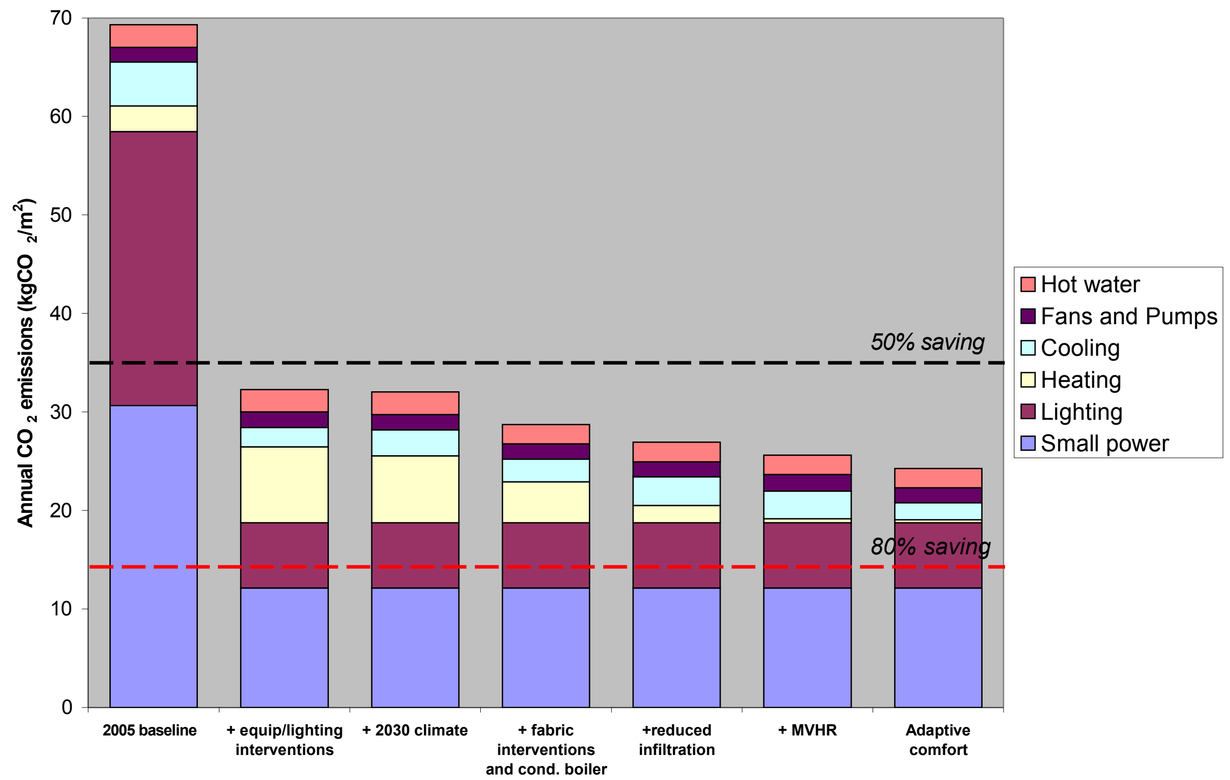
2005 small power and total energy consumption



2030 small power and total energy consumption

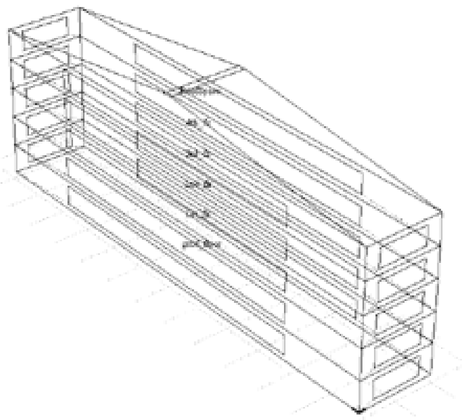


Final CO_2 savings



Non-Domestic building CO_2 savings:

Office variant VO2



Dimensions

Width: 10m

Length: 60m

Height: 5 x 4.5m

Total floor area: 3000m²

Age: Pre-1900 (with modern refurbishment)

Description

5-Storey office building (originally converted from Victorian warehouse), situated in Cardiff, with occupancy of one person per 14m² (resulting in 257 occupants). Operating hours are Mon-Fri, 9am to 7pm.

Construction

Brickwork building, with cavity, with wall, floor and roof U-values of 0.50W/m²K, 0.31W/m²K and 0.34W/m²K respectively. Single-glazing (40% of external wall area) of 5.1W/m²K. Infiltration rate of 0.34ach

HVAC systems

2 x 156kW non-condensing boilers for heating, with 2 x 268kW chiller units for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 6.4W/m²; Lighting 16.9W/m²; Small power 11.2W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ Internal wall insulation of expanded polystyrene (EPS) replacing mineral wool

⇒ EPS also used with floor (100mm) and roof (200mm) replacing existing insulation

⇒ External shading applied above glazing (0.8m width)

⇒ Single-glazing replaced with thin cavity double-glazing (U-value 2.9W/m²K)

- **HVAC**

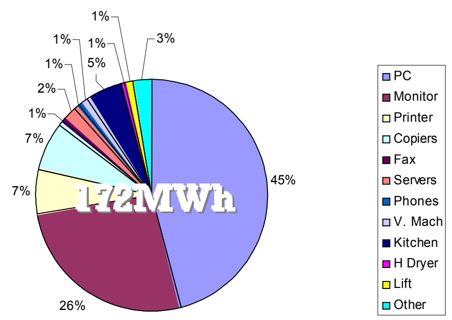
⇒ Condensing boiler replaces non-condensing boiler

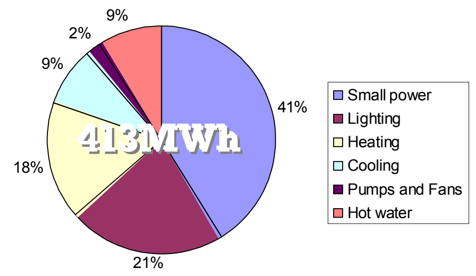
⇒ Mechanical ventilation heat recovery (MVHR)

⇒ Adaptive comfort approach to cooling

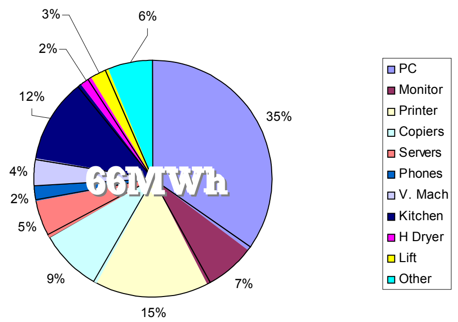
⇒ Air-source heat-pump (alternative option to boiler and chiller for heating and cooling)

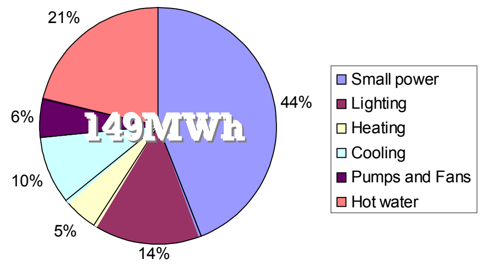
2005 small power and total energy consumption



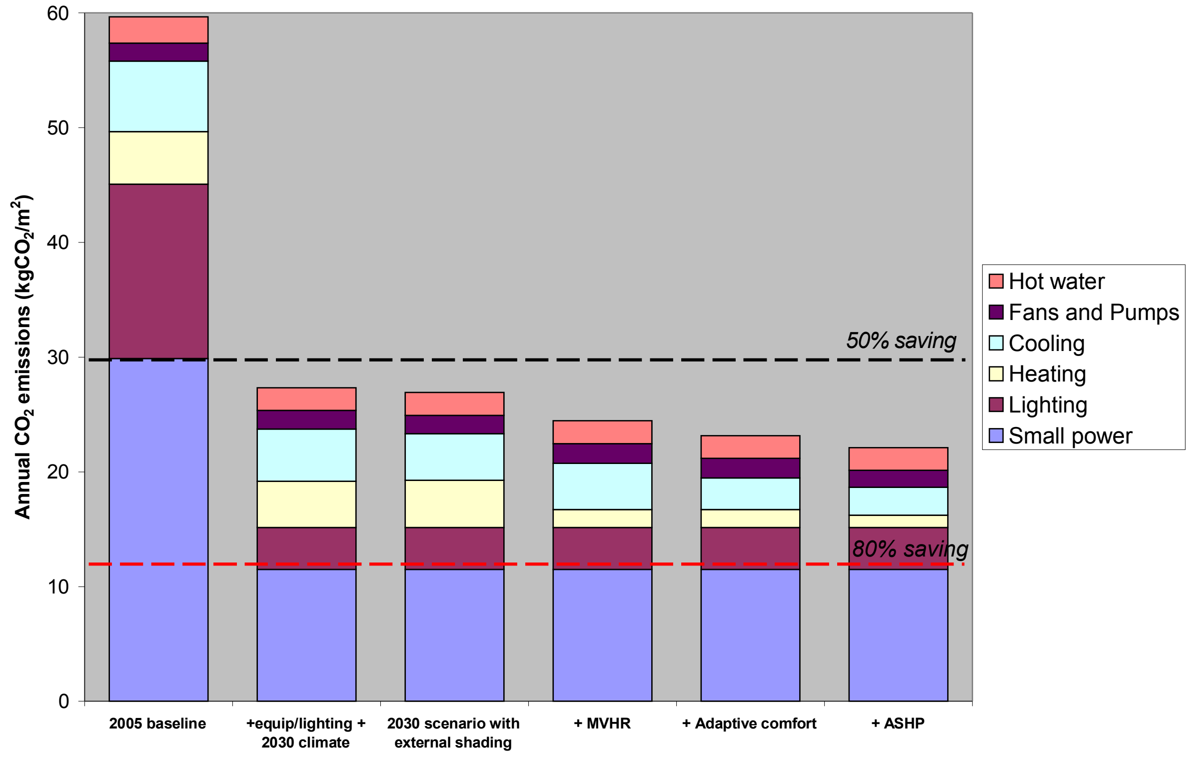


2030 small power and total energy consumption



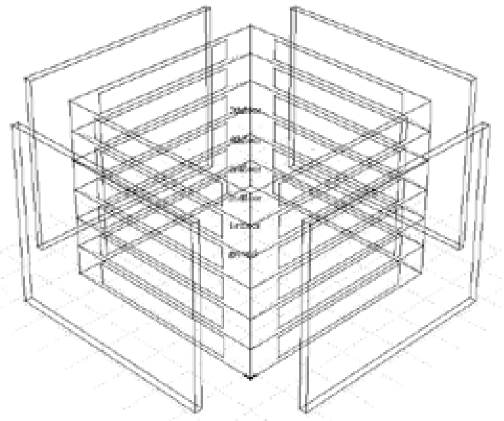


Final CO_2 savings



Non-Domestic building CO2 savings:

Office variant VO3



Dimensions

Width: 30m

Length: 30m

Height: 6 x 3.7m

Total floor area: 5400m²

Age: 1986-1990 construction

Description

6-Storey deep-plan office building, situated in Manchester, with occupancy of one person per 14m² (resulting in 386 occupants). Operating hours are Mon-Fri, 9am to 7pm.

Construction

Glass curtain wall building, with wall, floor and roof U-values of 0.44W/m²K, 0.27W/m²K and 0.37W/m²K respectively. Double-glazed façade (with effective glazing ratio of 50% of external wall area) with U-value of 2.75W/m²K. Infiltration rate of 0.44ach.

HVAC systems

2 x 174kW non-condensing boilers for heating, with 2 x 264kW chiller units for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 5.4W/m²; Lighting 9.4W/m²; Small power 11.4W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T8 fluorescent tubes (100lm/W)

- **Fabric**

⇒ Internal wall insulation of expanded polystyrene (EPS) replacing mineral wool

⇒ EPS also used in floor (100mm) and roof (200mm) replacing existing insulation

⇒ Option of adding anti-sun film applied to glazing (reducing solar transmission by 60%)

- **HVAC**

⇒ Condensing boiler replaces non-condensing boiler

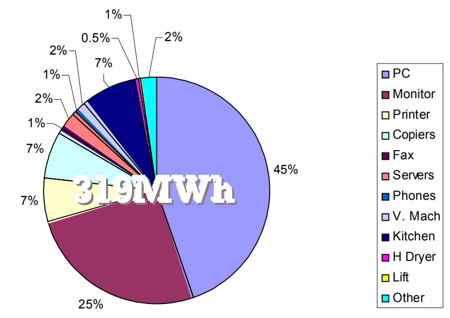
⇒ Mechanical ventilation heat recovery (MVHR)

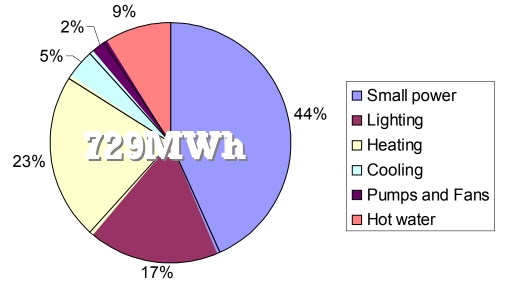
⇒ Adaptive comfort approach to cooling

⇒ Air-source heat-pump (alternative option to boiler and chiller for heating and cooling)

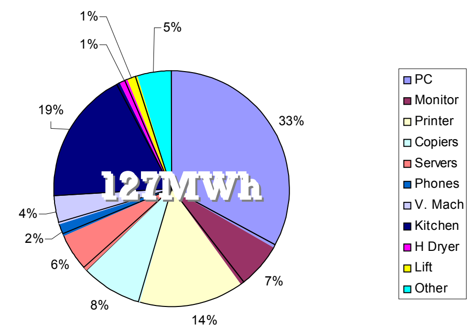
⇒ Reduction in internal gains (see "Small Power and Lighting")

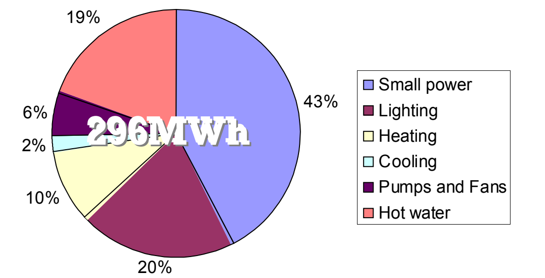
2005 small power and total energy consumption



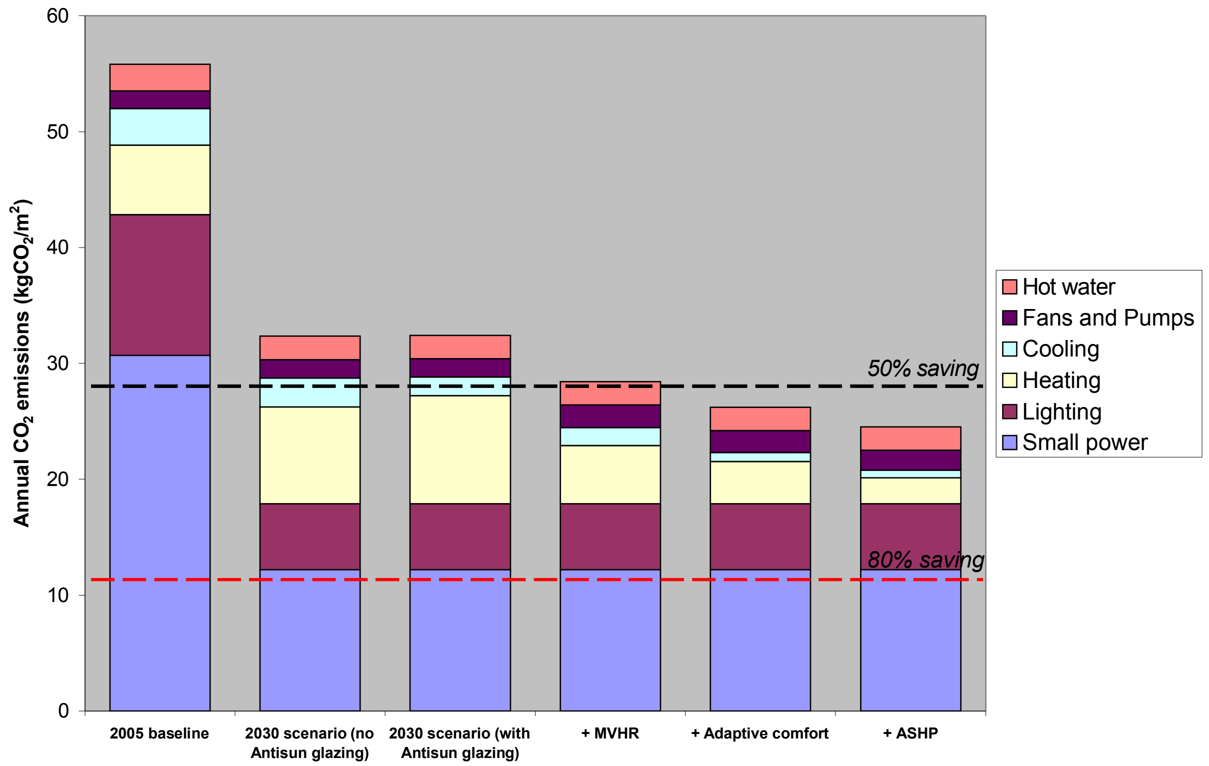


2030 small power and total energy consumption



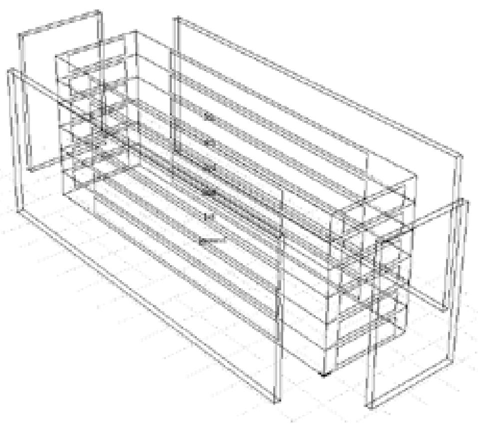


Final CO_2 savings



Non-Domestic building CO_2 savings:

Office variant VO4



Dimensions

Width: 15m

Length: 60m

Height: 6 x 3.7m

Total floor area: 5400m^2

Age: 1986-1990 construction

Description

6-Storey shallow-plan office building, situated in Manchester, with occupancy of one person per 14m^2 (resulting in 386 occupants). Operating hours are Mon-Fri, 9am to 7pm.

Construction

Glass curtain wall building, with wall, floor and roof U-values of 0.44W/m^{2}K, 0.27W/m^{2}K and 0.37W/m^{2}K respectively. Double-glazed façade (with effective glazing ratio of 50% of external wall area) with U-value of 2.75W/m^{2}K. Infiltration rate of 0.44ach.

HVAC systems

2 x 187kW non-condensing boilers for heating, with 2 x 351kW chiller units for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 5.4W/m^2; Lighting 9.4W/m^2; Small power 11.4W/m^2

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T8 fluorescent tubes (100lm/W)

- **Fabric**

⇒ Internal wall insulation of expanded polystyrene (EPS) replacing mineral wool

⇒ EPS also used in floor (100mm) and roof (200mm) replacing existing insulation

⇒ Option of adding anti-sun film applied to glazing (reducing solar transmission by 60%)

- **HVAC**

⇒ Condensing boiler replaces non-condensing boiler

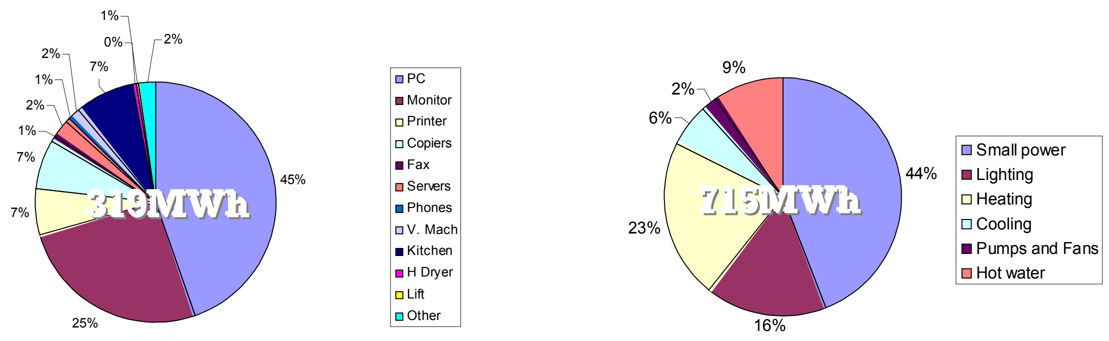
⇒ Mechanical ventilation heat recovery (MVHR)

⇒ Adaptive comfort approach to cooling

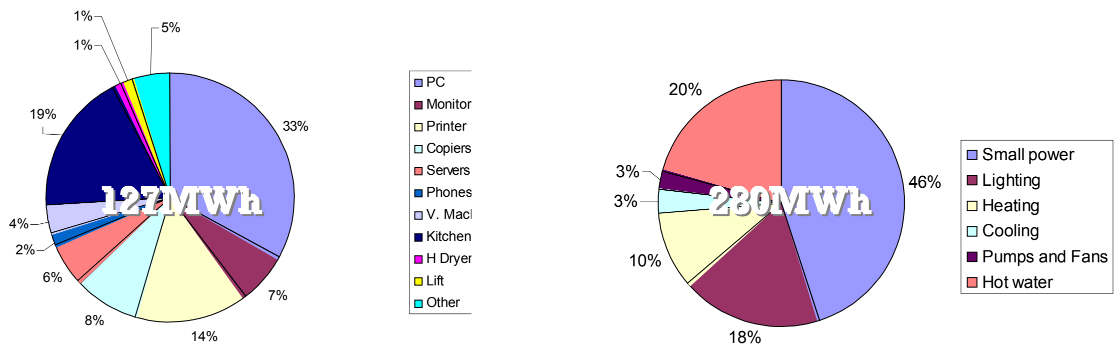
⇒ Air-source heat-pump (alternative option to boiler and chiller for heating and cooling)

⇒ Reduction in internal gains (see "Small Power and Lighting")

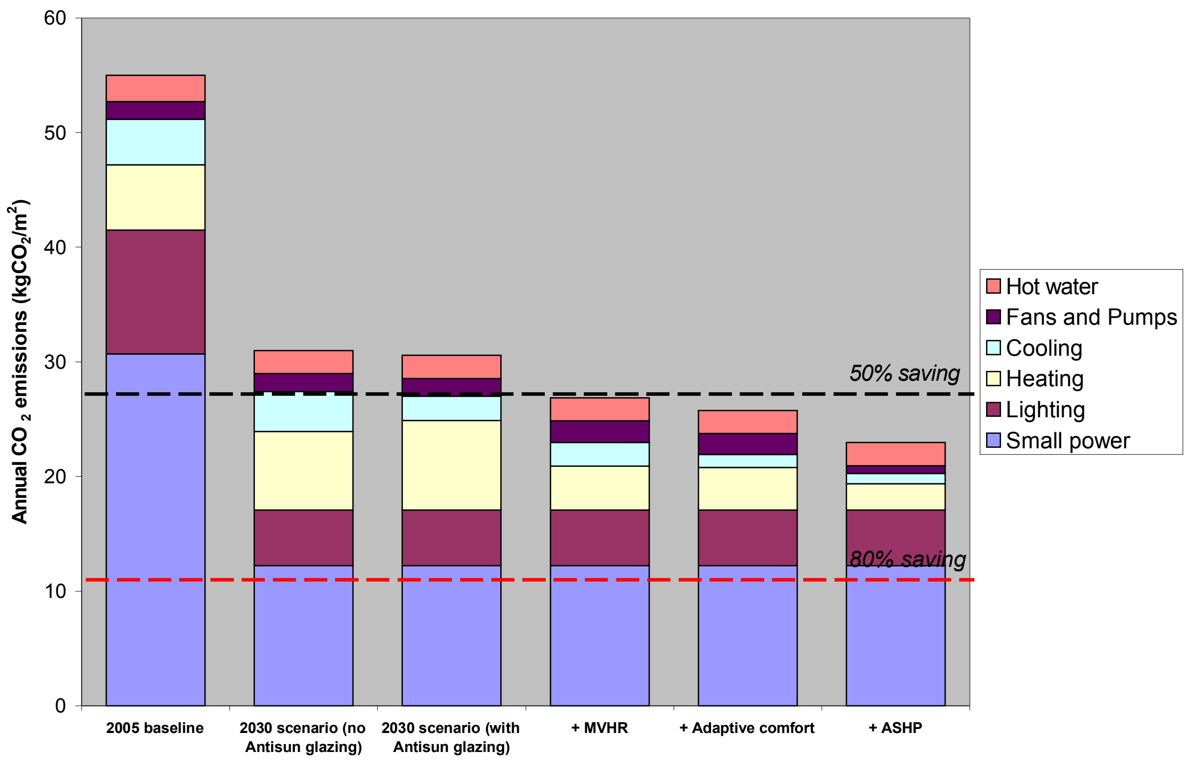
2005 small power and total energy consumption



2030 small power and total energy consumption

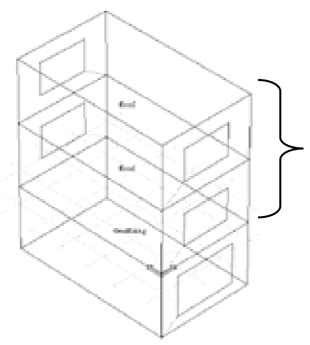


Final CO_2 savings



Non-Domestic building CO2 savings:

Office variant VO5



Dimensions

Width: 6m

Length: 10m

Height: 2 x 4m

Total floor area: 120m²

Age: 1900-1918 construction

Description

Terraced 2-Storey office (above estate agent—not included in variant), situated in Edinburgh, with high occupancy of one person per 8m² (resulting in 13 occupants). Operating hours are Mon-Fri, 9am to 7pm.

Construction

Solid wall sandstone building, with wall and roof U-values of 2.71W/m²K and 0.33W/m²K respectively (floor adjoins with estate agent). Single-glazing façade (with glazing ratio of 25% of external wall area) with U-value of 5.4W/m²K. Infiltration rate of 0.58ach.

HVAC systems

1 x 22kW non-condensing boiler for heating, with 1 x 15kW chiller unit for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 8.1W/m²; Lighting 15.8W/m²; Small power 25.7W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ Internal wall insulation of expanded polystyrene (EPS) added

⇒ EPS also used in roof (200mm) replacing existing insulation

⇒ Single-glazing replaced with thin cavity double-glazing (U-value 2.9W/m²K)

- **HVAC**

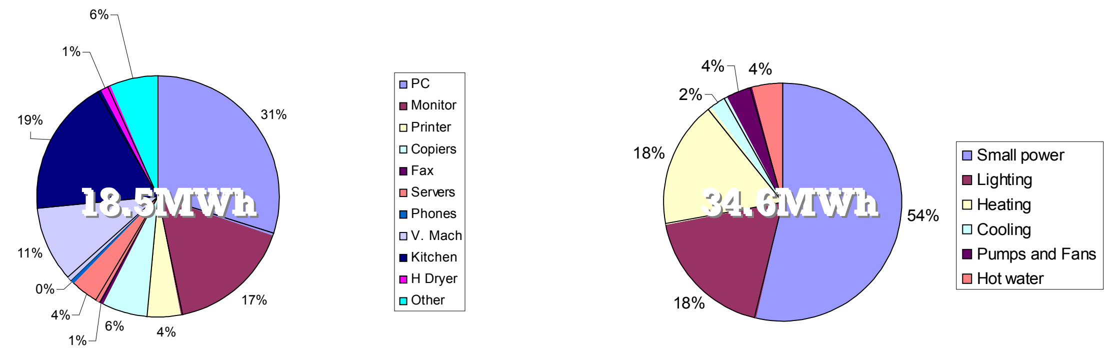
⇒ Condensing boiler replaces non-condensing boiler

⇒ Mechanical ventilation heat recovery (MVHR)

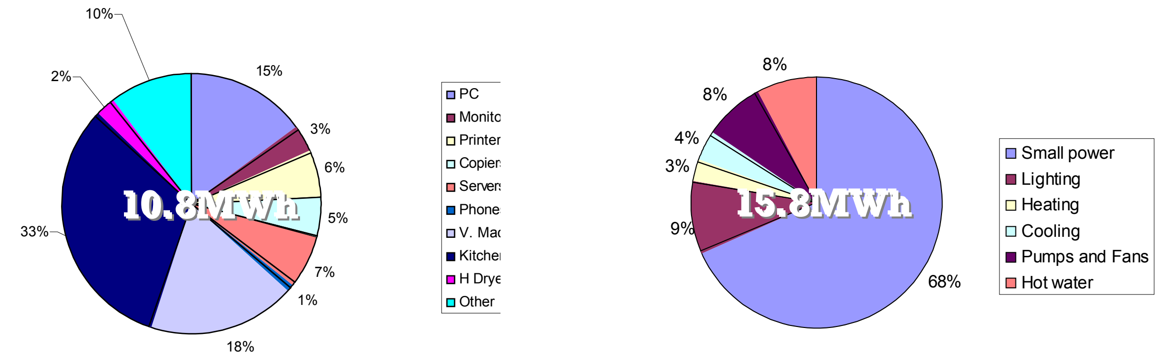
⇒ Adaptive comfort approach to cooling

⇒ Reduction in internal gains (see "Small Power and Lighting")

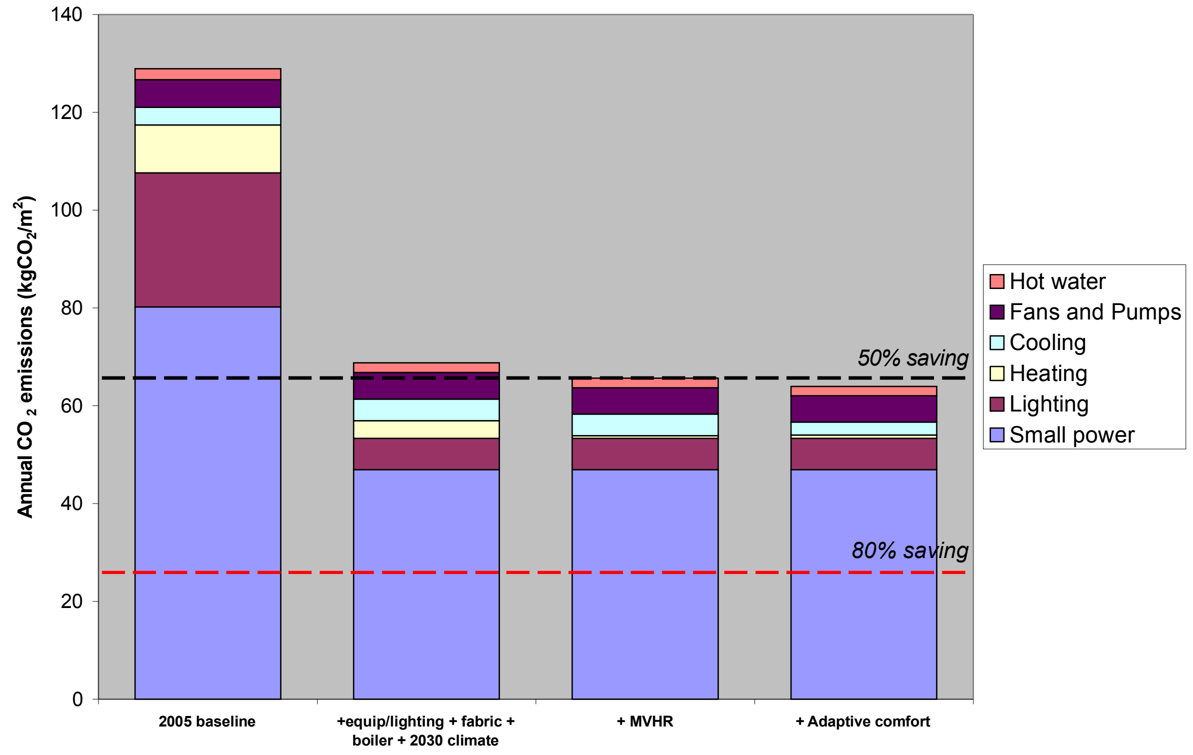
2005 small power and total energy consumption



2030 small power and total energy consumption

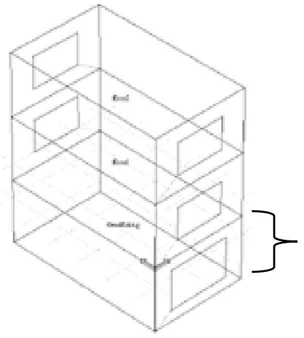


Final CO_2 savings



Non-Domestic building CO2 savings:

Retail variant VR1



Dimensions

Width: 6m

Length: 10m

Height: 1 x 4m

Total floor area: 60m^2

Age: 1900-1918 construction

Description

Terraced ground floor estate agent (below two-storey office), situated in Edinburgh, with five staff and two customers present at any one time. Operating hours are Mon-Sat, 9am to 7pm.

Construction

Solid wall sandstone building, with wall and ground U-values of 2.71W/m^{2}K and 0.76W/m^{2}K respectively (ceiling adjoins offices above). Single-glazing (with glazing ratio of 40% of front façade only) with U-value of 5.4W/m^{2}K. Infiltration rate of 0.58ach.

HVAC systems

1 x 9kW non-condensing boiler for heating, with 1 x 5kW chiller unit for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 8.8W/m^2; Lighting 16.6W/m^2; Small power 19.6W/m^2

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT energy management (including switching non-essential servers off overnight)

⇒ Cholesteric LCD monitors replace CRT monitors

⇒ Reduced PC usage with more efficient processor

⇒ Multifunction machine used for all printing/copying/scanning

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ Internal insulation of expanded polystyrene (EPS) added to walls

⇒ EPS also added to floor, replacing mineral wool

⇒ Single-glazing replaced with thin cavity double-glazing (U-value 2.9W/m^{2}K)

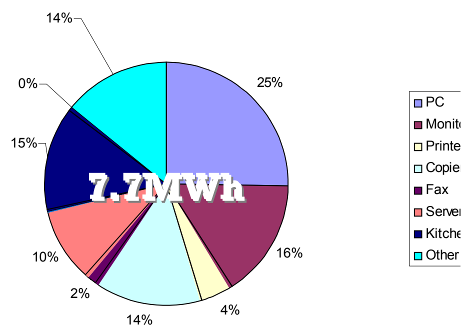
- **HVAC**

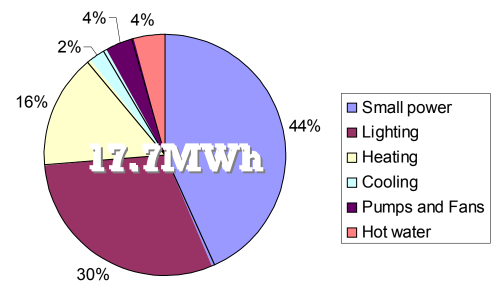
⇒ Condensing boiler replaces non-condensing boiler

⇒ Mechanical ventilation heat recovery (MVHR)

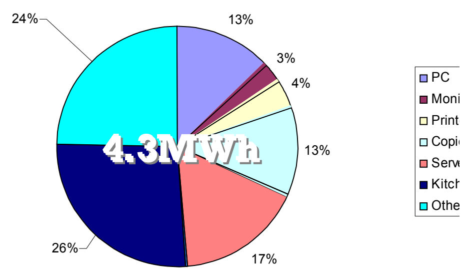
⇒ Reduction in internal gains (see "Small Power and Lighting")

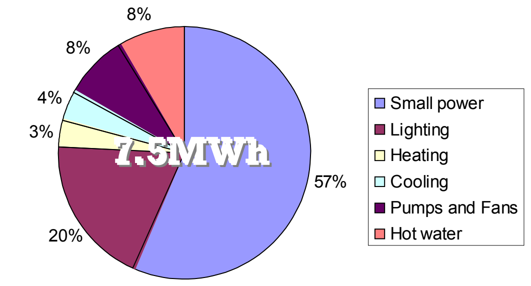
2005 small power and total energy consumption



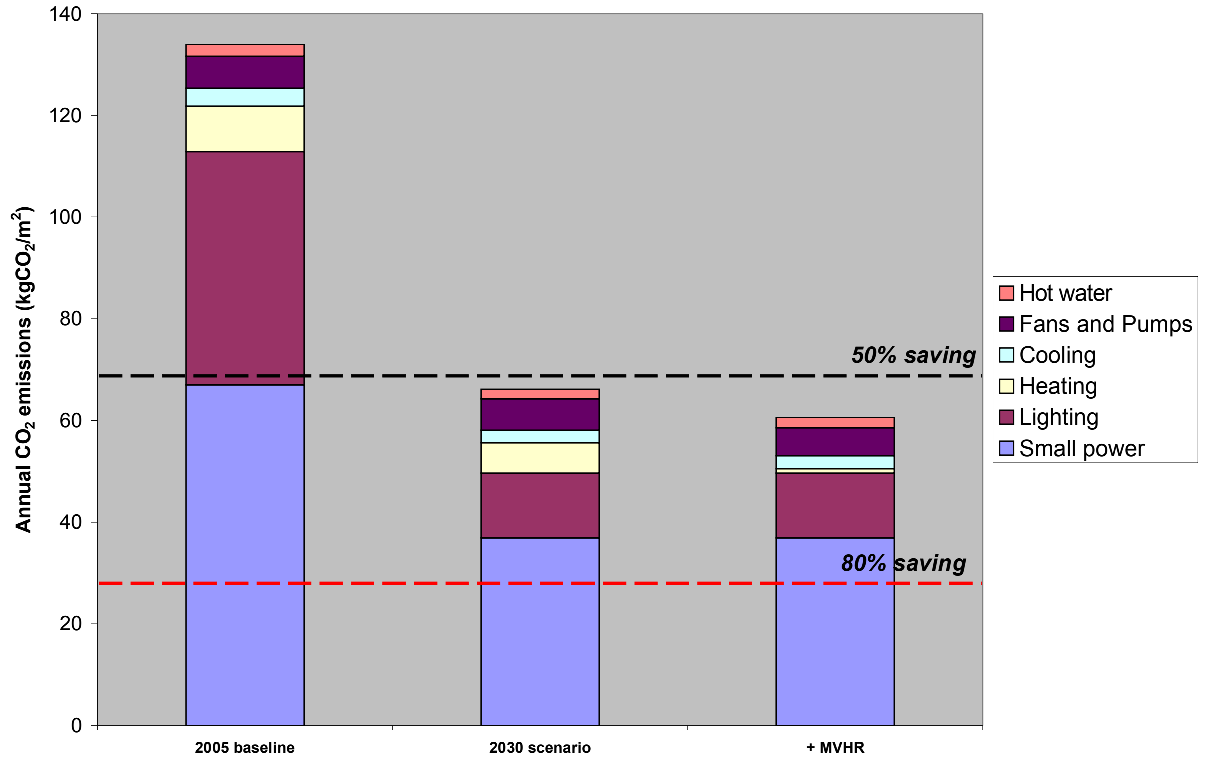


2030 small power and total energy consumption



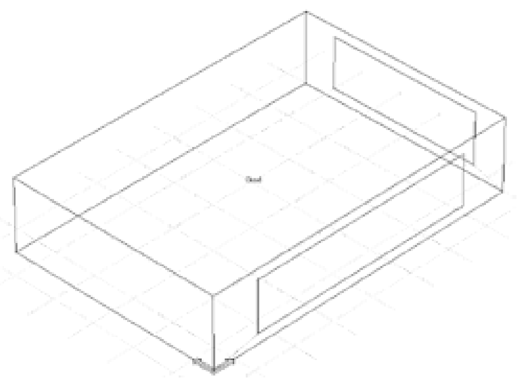


Final CO_2 savings



Non-Domestic building CO2 savings:

Retail variant VR2



Dimensions

Width: 10m

Length: 15m

Height: 1 x 3.5m

Total floor area: 150m²

Age: Pre-1900

Description

Cornershop convenience store, situated in Birmingham, with thirty staff and customers present at any one time. Building includes 8m² storage area. Uses 5.8kW of integral chiller cabinets and 3.1kW of freezer units. Operating hours are seven days a week, 8am to 10pm.

Construction

Pre-1900 brickwork building, with wall, floor and roof U-values of 1.45W/m²K, 1.1W/m²K and 0.34W/m²K respectively. Single-glazing (with glazing ratio of 50% of two external walls) with U-value of 5.4W/m²K. Infiltration rate of 0.58ach.

HVAC systems

Electric radiant heaters for heating and cooling with air-conditioning system (nominal COP of 3.7 at standard test conditions). Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains are: Occupant 15.0W/m²; Lighting 20.2W/m²; Small power 2.5W/m² (not including refrigeration—these units are "integral" with heat rejected internally so there is no net cooling/heating effect)

Carbon-saving interventions

- **Small Power, Refrigeration and Lighting**

⇒ IT and "office" type energy management (see office variants)

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

⇒ Apply night-blinds and covers to all refrigeration and freezer units

- **Fabric**

⇒ Internal insulation of expanded polystyrene (EPS) added to walls

⇒ EPS also added to floor and roof, replacing existing mineral wool

⇒ Single-glazing replaced with thin cavity double-glazing (U-value 2.9W/m²K)

⇒ Infiltration reduced from 1ach to 0.5ach

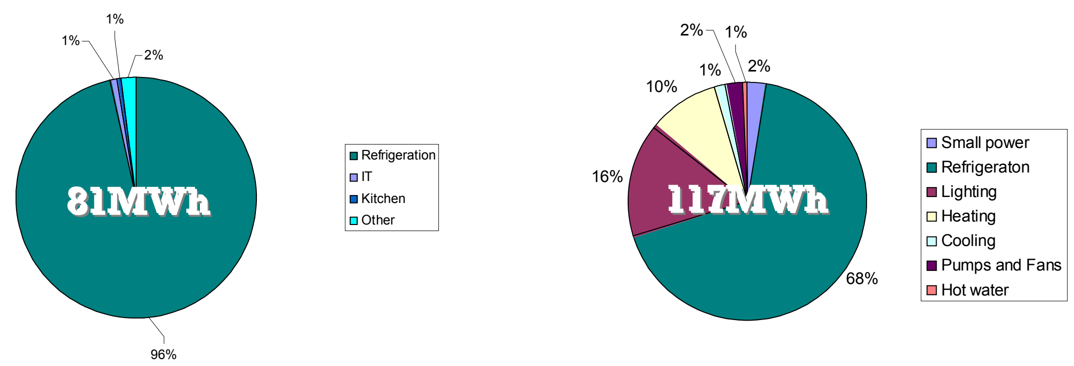
- **HVAC**

⇒ Air-source heat pump replacing electric heaters for space heating

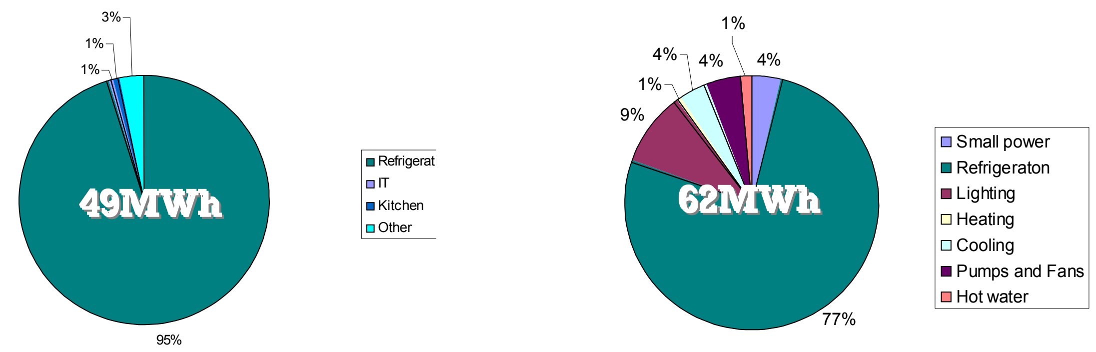
⇒ Mechanical ventilation heat recovery (MVHR)

⇒ Reduction in internal gains (see "Small Power and Lighting")

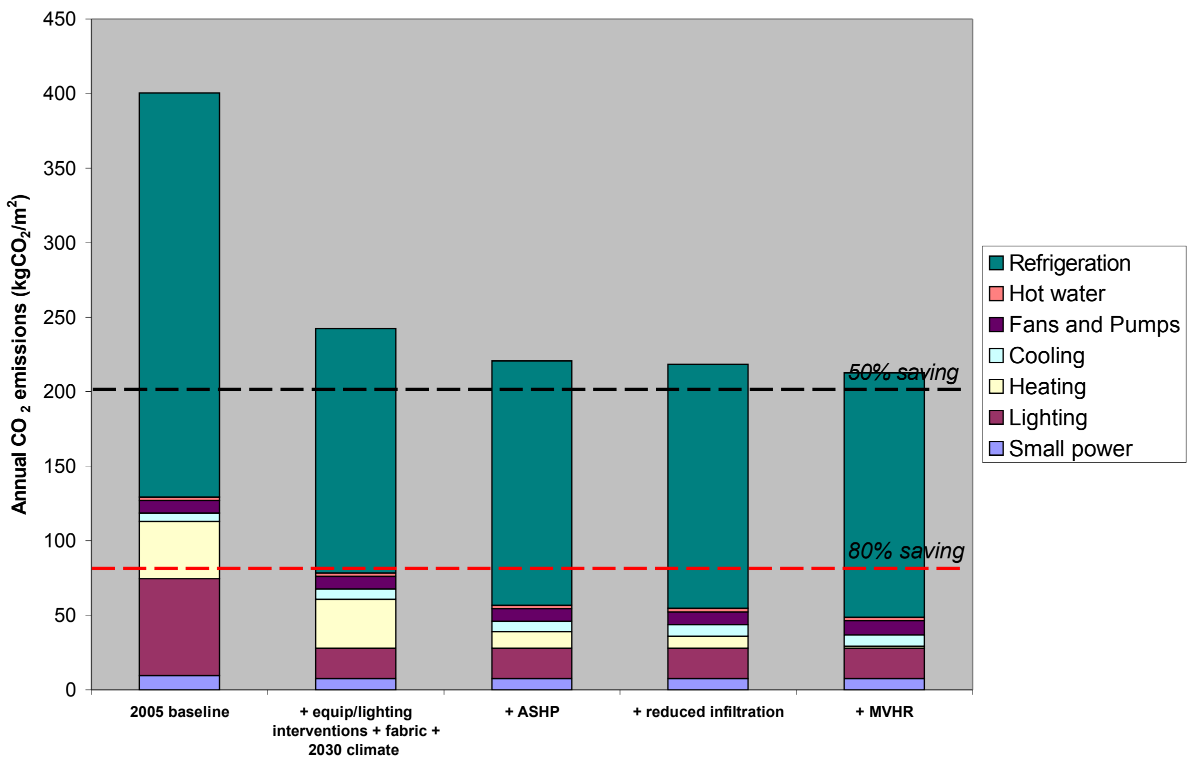
2005 small power and total energy consumption



2030 small power and total energy consumption

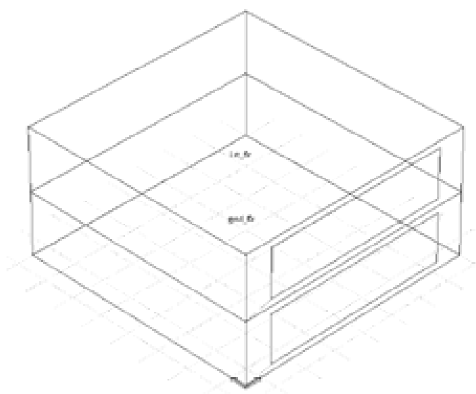


Final CO_2 savings



Non-Domestic building CO2 savings:

Retail variant VR3



Dimensions

Width: 15m

Length: 15m

Height: 2 x 4m

Total floor area: 450m²

Age: 1986-1990

Description

Terraced clothes shop in "out-of-town" shopping centre, situated in London, with 45 staff and customers present at any one time. Building includes 50m² storage area, 25m² office area and 150m² sales area. Operating hours are seven days a week, 9am to 7pm.

Construction

Concrete panel building, with wall, floor and roof U-values of 0.65W/m²K, 0.46W/m²K and 0.96W/m²K respectively. Single-glazing (with glazing ratio of 60% on front wall only) with U-value of 5.4W/m²K. Infiltration rate of 0.25ach.

HVAC systems

Electric radiant heaters for heating and cooling with air-conditioning system (nominal COP of 3.7 at standard test conditions). Mechanical ventilation is used to provide 10l/s/person. Mechanical ventilation is used to provide 10l/s/person. Hot water uses electric point-of-use water heating.

Internal gains

Peak gains (averaged over all areas) are: Occupant 7.5W/m²; Lighting 19.8W/m²; Small power 3.3W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT and "office" type energy management (see office variants)

⇒ LED lighting (150lm/W) replaces T5/T8 fluorescent tubes (100lm/W) and halogen lights (20lm/W)

- **Fabric**

⇒ External insulation of expanded polystyrene (EPS) with concrete render added to walls

⇒ EPS also added to floor (replacing mineral wool) and roof cavity

⇒ Triple-glazed argon windows (U-value 0.78W/m²K), with low-e coating, replacing existing single-glazing

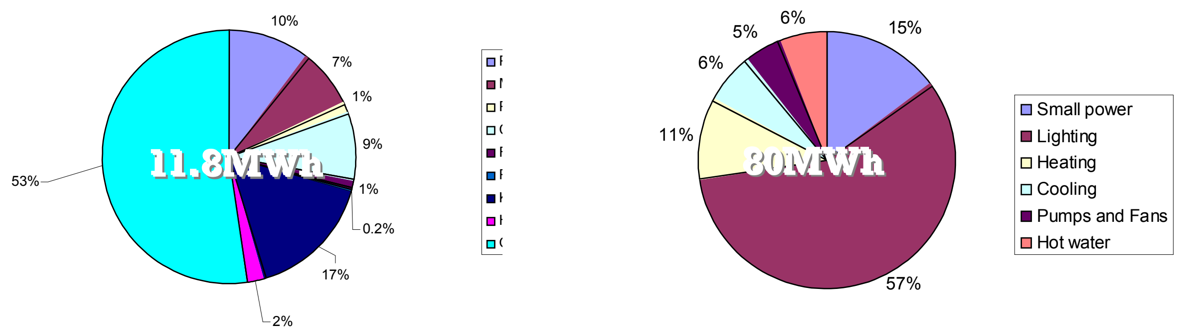
- **HVAC**

⇒ Air-source heat pump replacing electric heaters for space heating

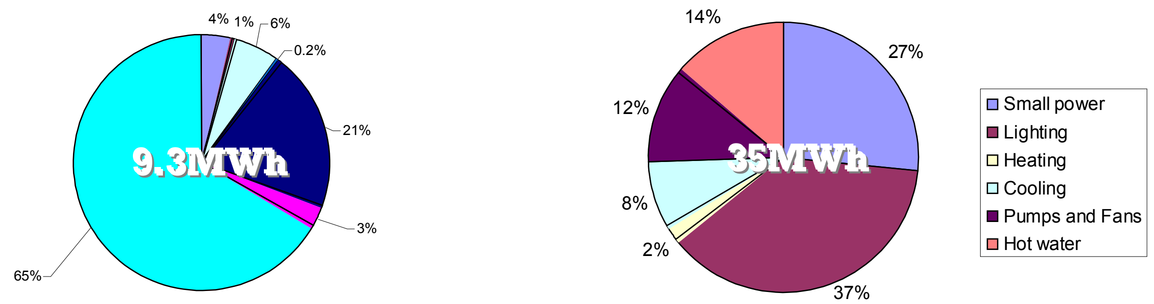
⇒ Mechanical ventilation heat recovery (MVHR)

⇒ Reduction in internal gains (see "Small Power and Lighting")

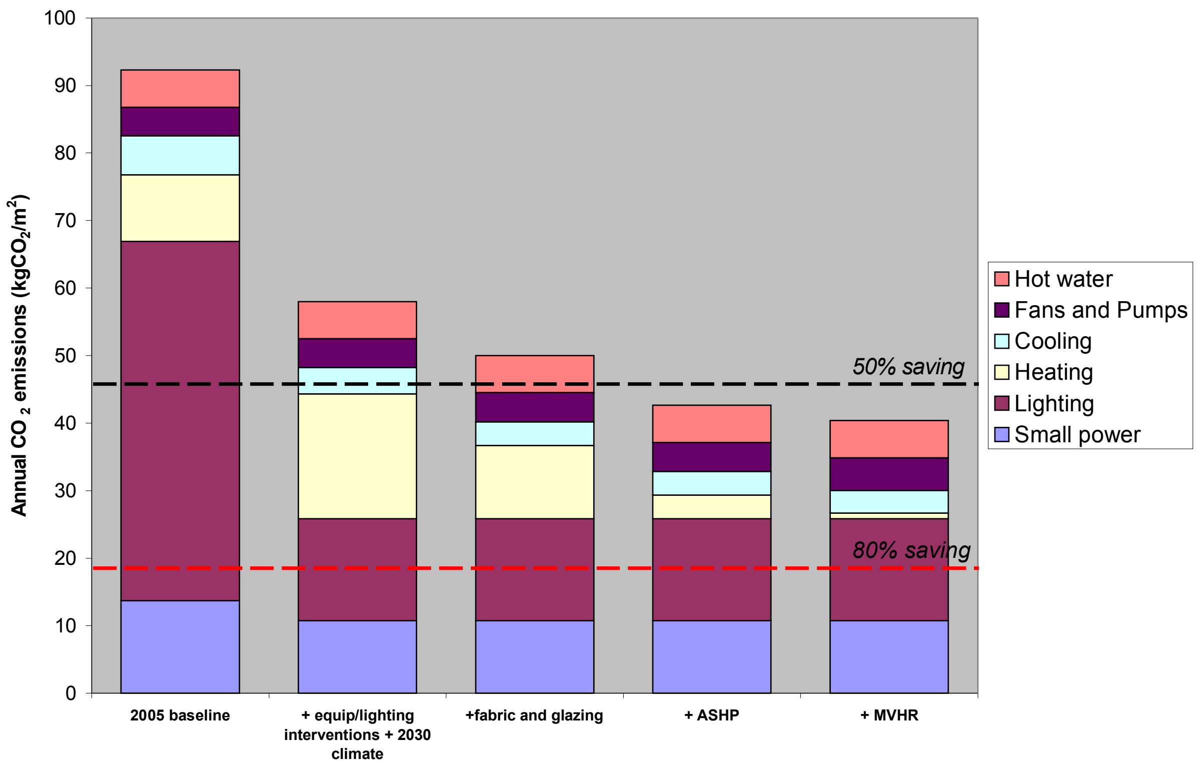
2005 small power and total energy consump-



2030 small power and total energy consumption

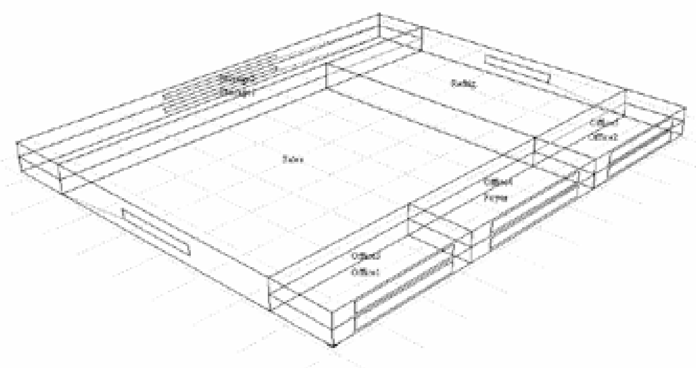


Final CO_2 savings



Non-Domestic building CO2 savings:

Retail variant VR4



Dimensions

Width: 82.5m

Length: 100m

Height: 1 x 6m (and 2 x 3m)

Total floor area: 10950m²

Age: Post 1990

Description

Large supermarket, situated in Manchester, with up to 128 staff and 550 customers present at any one time (varying hourly occupant profile applied throughout week). Building includes 2700m² storage area (split floor), 2214m² office area (split floor) and 6036m² sales area (of which 30% is refrigerated aisles). Uses 46kW of remote chiller cabinets and 52kW of freezer units (and six 7kW chilled storage "rooms"). Operating hours are seven days a week, 24 hours.

Construction

Brickwork/concrete building, with wall, floor and roof U-values of 0.60W/m²K, 0.46W/m²K and 0.45W/m²K respectively. Double-glazed, tinted windows (with 33m² on West and East walls, 300m² on South wall and 60m² on North) with U-value of 2.75W/m²K. Infiltration rate of 1.0ach.

HVAC systems

2 x 151kW non-condensing boilers for heating, with 2 x 119kW chiller units for air-conditioning, both with associated fans and pumps. Mechanical ventilation is used to provide 10l/s/person.

Internal gains

Peak gains (averaged over all areas) are: Occupant 9.6W/m²; Lighting 19.0W/m²; Small power 7.1W/m² (not including refrigeration, where heat is rejected outside the building)

Carbon-saving interventions

- **Small Power, Refrigeration and Lighting**

⇒ IT and "office" type energy management (see office variants)

⇒ LED lighting (150lm/W) replaces low pressure mercury discharge lighting in sales area (88lm/W) and T12 fluorescent tubes (70lm/W) elsewhere

⇒ Covers applied to all refrigeration and freezer units (with increase in refrigerated aisle temperature of, on average, 2°C, as well as reduced electrical load)

- **Fabric**

⇒ Cavity insulation of expanded polystyrene (EPS) added to walls

⇒ EPS also added to floor and roof, replacing mineral wool

⇒ Triple-glazed argon windows (U-value 0.78W/m²K), with low-e coating, replacing existing double-glazing

⇒ Infiltration reduced from 1ach to 0.5ach

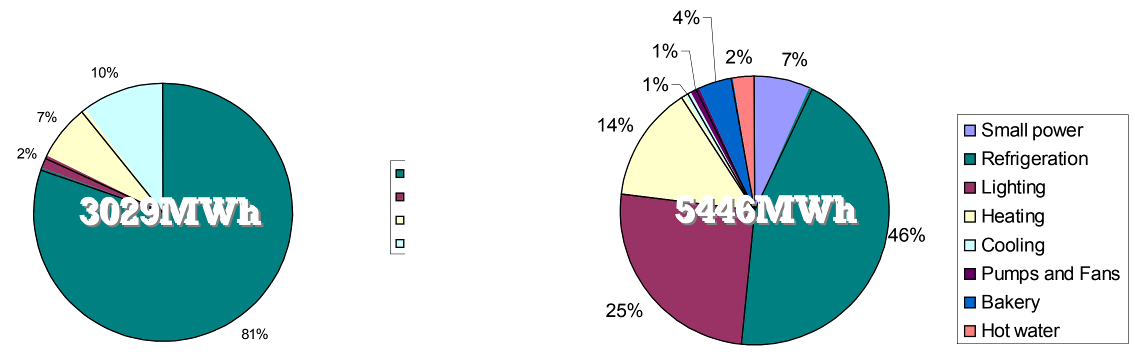
- **HVAC**

⇒ Condensing boiler replaces non-condensing boiler

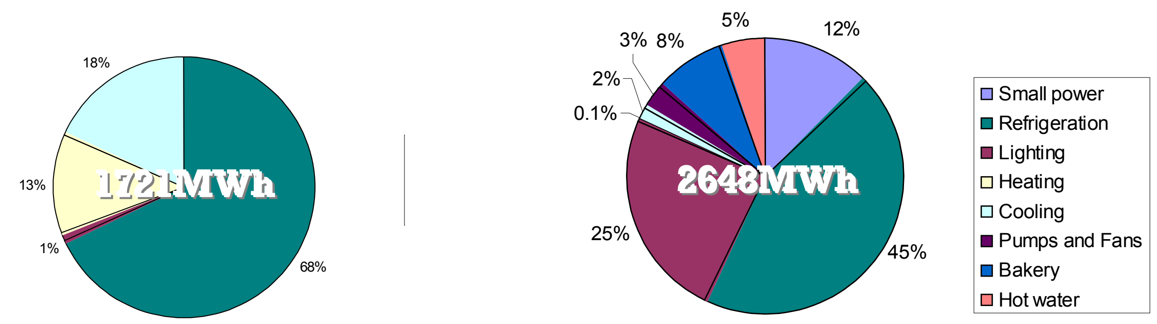
⇒ Heat recovery used with heat rejected from refrigeration units

⇒ Reduction in internal gains and reduced indirect cooling from refrigeration (see "Small Power, Refrigeration and Lighting")

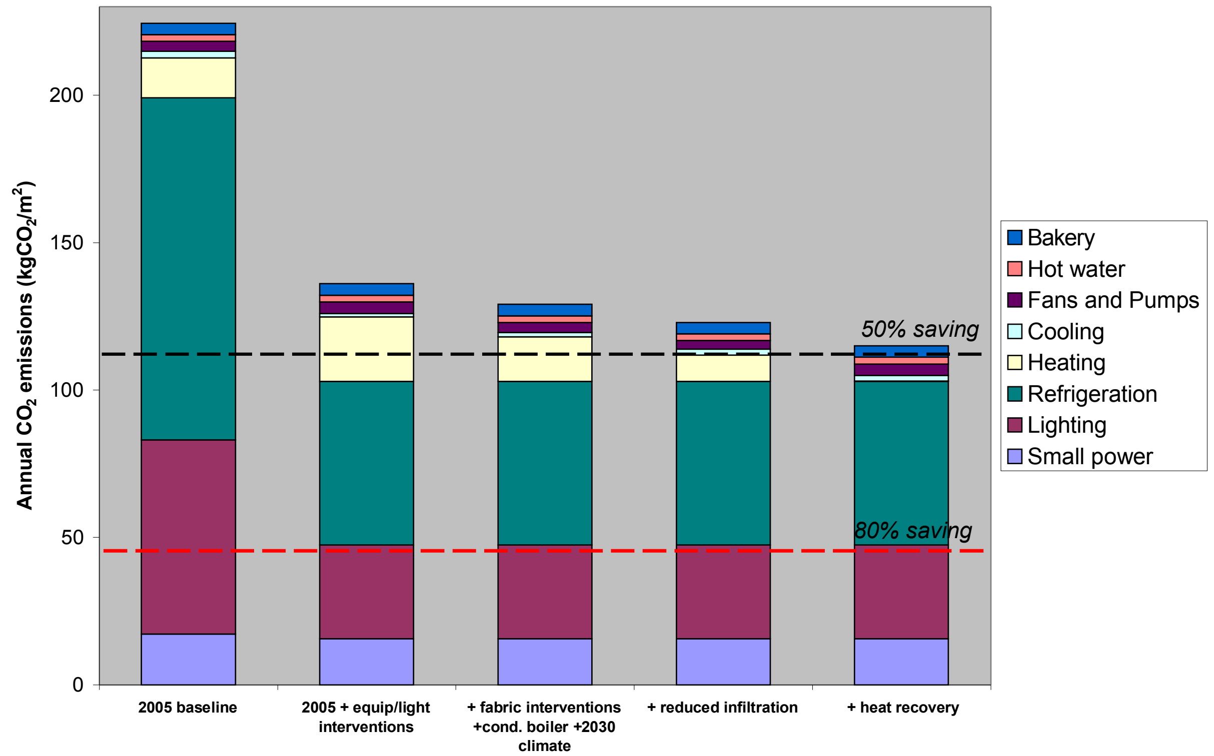
2005 small power and total energy consumption



2030 small power and total energy cons



Final CO_2 savings



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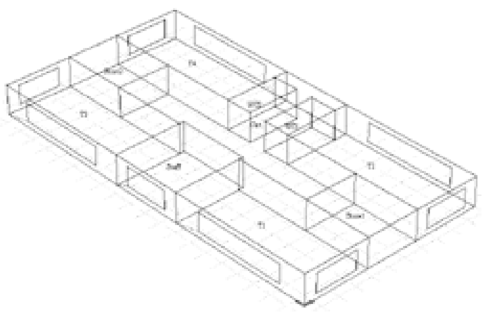
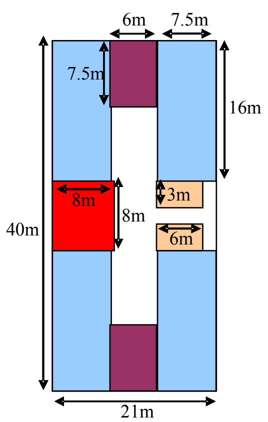
tarbase
technologies for carbon reduction in existing buildings

Non-Domestic building CO2 savings:

School variant VS1





Total floor area: 840m²

Teaching: 480m ²

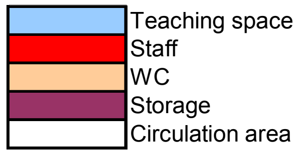
Storage: 90m²

Staff/admin: 64m²

Toilets: 36m²

Circulation: 170m²

Age: 2000 construction



Description

Single storey primary school, situated in Cardiff, with 150 pupils and 7 full-time staff. Operating hours are Mon-Fri, 9am to 4pm.

Construction

Brickwork/blockwork building with wall, floor and roof U-values of 0.56W/m²K, 0.25W/m²K and 0.22W/m²K respectively. Standard double glazing (40% of external wall area) of 2.75W/m ²K. Infiltration rate of 0.3ach

HVAC systems

2 x 46kW non-condensing boilers for heating. No mechanical ventilation or cooling. Assumed that 10l/s/person ventilation can be achieved passively through vents and windows.

Internal gains

Peak gains (averaged over all areas) are: Occupant 11.3W/m ²; Lighting 8.1W/m²; Small power 6.0W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT and "office" type energy management (see office variants but with below exception)

⇒ One low-power (15W) laptop per child (for increased IT usage while reducing energy usage) replacing all desktop machines

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ External insulation of expanded polystyrene (EPS) with concrete render added to walls

⇒ EPS also added to roof, replacing mineral wool

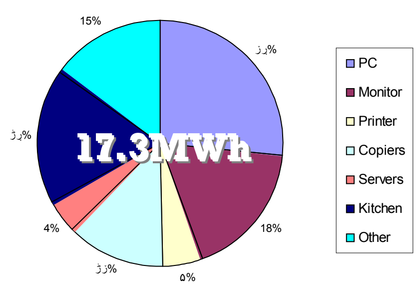
⇒ No change to glazing

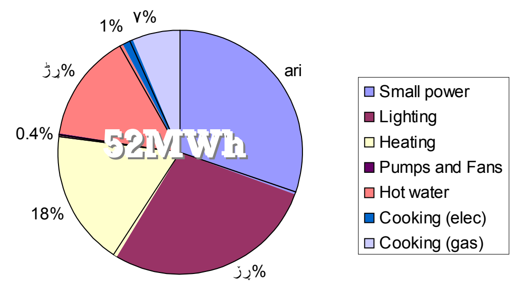
- **HVAC**

⇒ Condensing boiler replaces non-condensing boiler

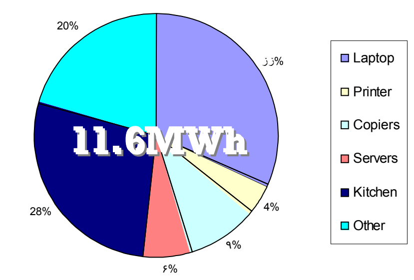
⇒ Reduction in internal gains (see "Small Power and Lighting")

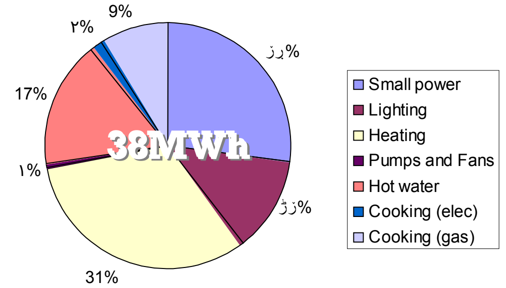
2005 small power and total energy consumption



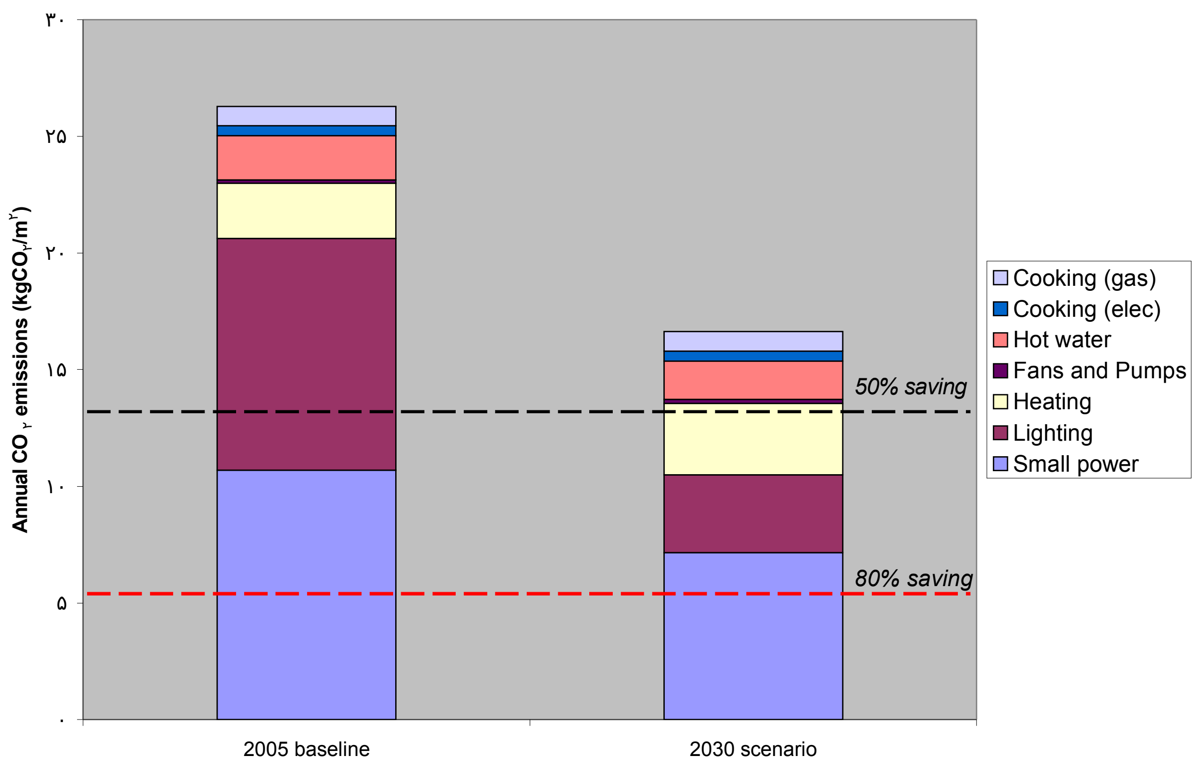


٢٠٣٠ small power and total energy consumption



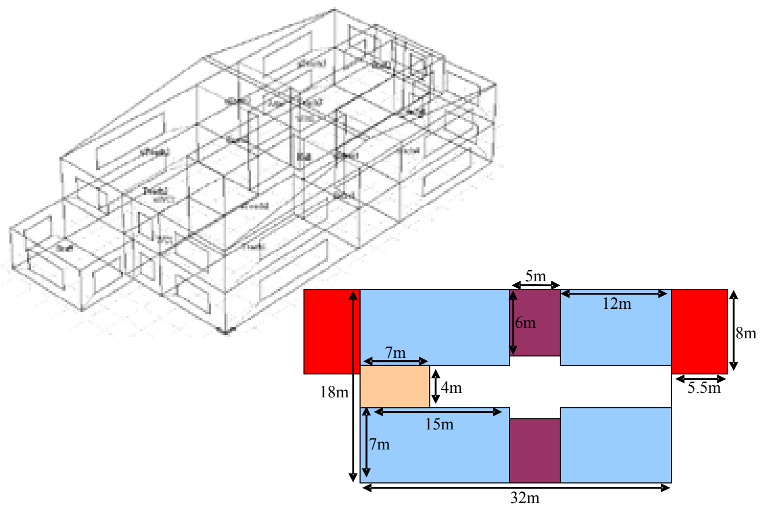


Final CO_2 savings



Non-Domestic building CO2 savings:

School variant VS2



Total floor area: 1240m²

Teaching: 756m²

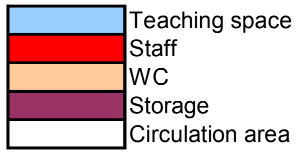
Storage: 120m²

Staff/admin: 88m²

Toilets: 56m²

Circulation: 220m²

Age: Pre-1900 construction



Description

Two-storey primary school, situated in Edinburgh, with 250 pupils and 11 full-time staff. Operating hours are Mon-Fri, 9am to 4pm.

Construction

Solid wall sandstone building with wall, floor and roof U-values of 2.71W/m²K, 0.34W/m²K and 0.76W/m²K respectively. Standard double glazing (40% of external wall area) of 2.75W/m²K. Infiltration rate of 0.3ach

HVAC systems

2 x 97kW non-condensing boilers for heating. No mechanical ventilation or cooling. Assumed that 10l/s/person ventilation can be achieved passively through vents and windows.

Internal gains

Peak gains (averaged over all areas) are: Occupant 12.8W/m²; Lighting 8.3W/m²; Small power 7.5W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT and "office" type energy management (see office variants but with below exception)

⇒ One low-power (15W) laptop per child (for increased IT usage while reducing energy usage) replacing all desktop machines

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ Internal insulation of expanded polystyrene (EPS) added to walls

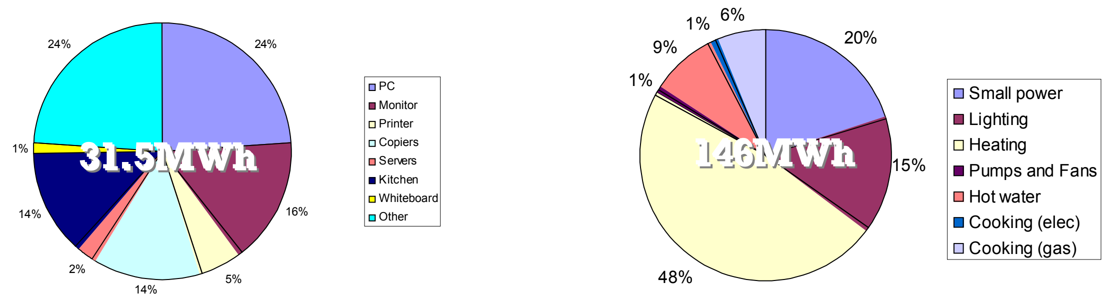
⇒ EPS also added to roof (200mm—replacing existing insulation) and floor (100mm)

- **HVAC**

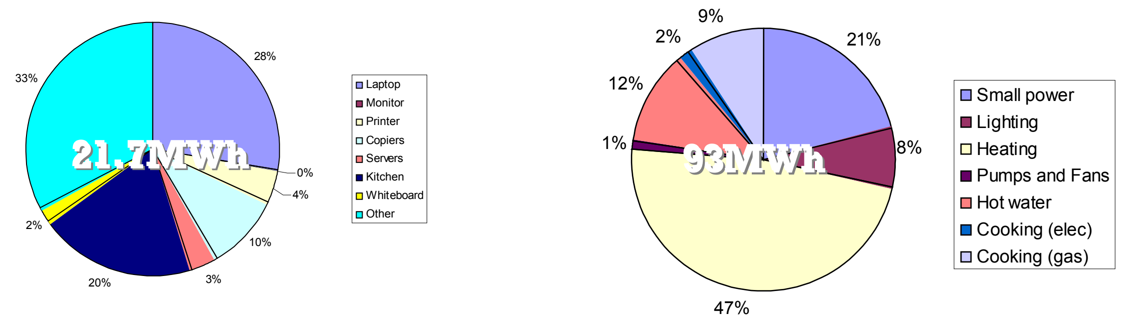
⇒ Condensing boiler replaces non-condensing boiler

⇒ Reduction in internal gains (see "Small Power and Lighting")

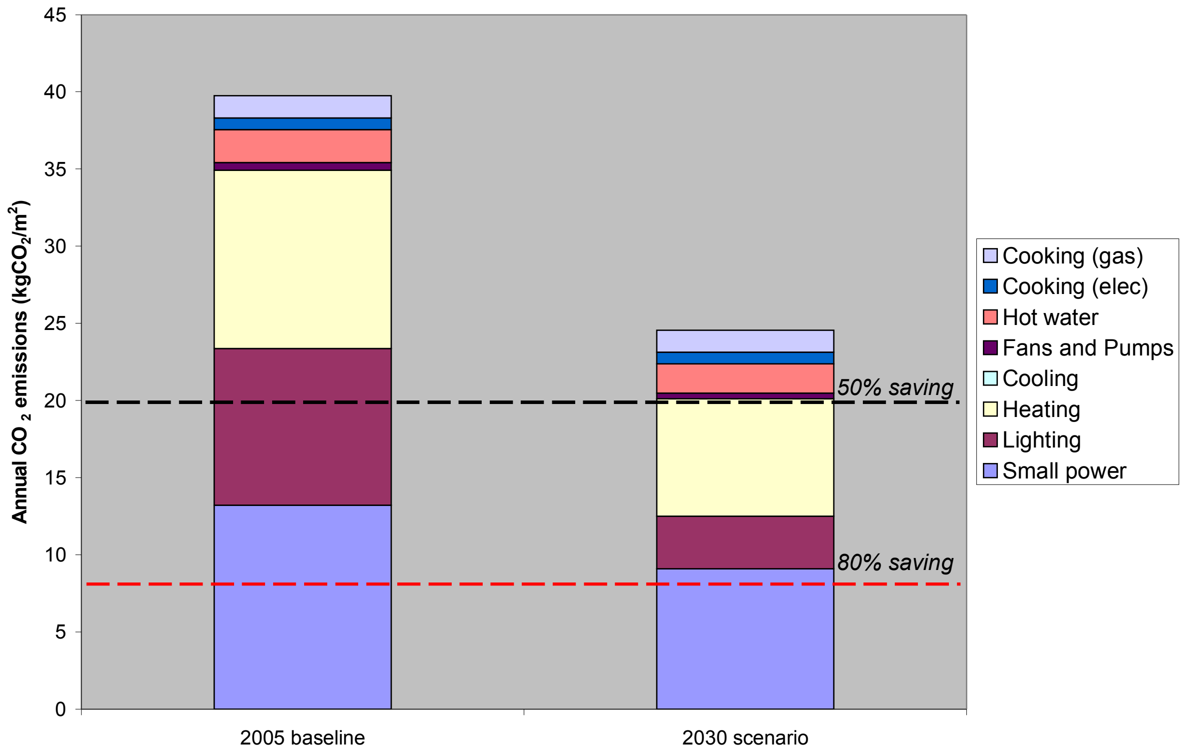
2005 small power and total energy consumption



2030 small power and total energy consumption

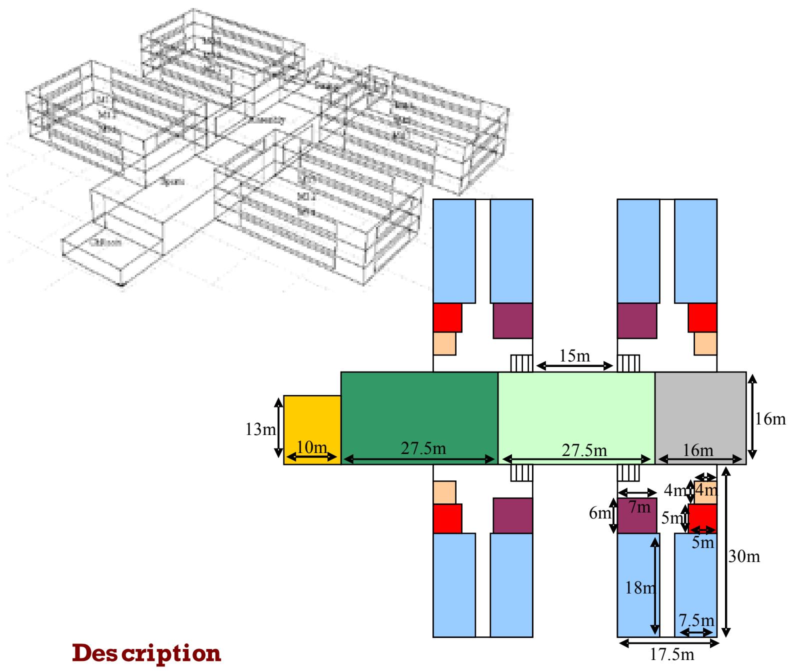


Final CO_2 savings



Non-Domestic building CO2 savings:

School variant VS3



Total floor area: 7566m²

Teaching: 3240m²

Storage: 504m²

Staff/admin: 300m²

Sports hall: 440m²

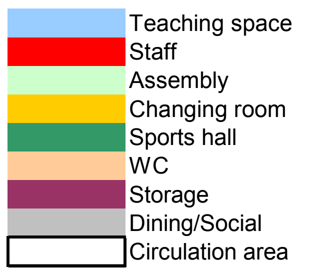
Changing rooms: 130m²

Assembly hall: 440m²

Toilets: 192m²

Circulation: 2064m²

Age: 2000 construction



Description

Three-storey secondary school, situated in London, with 900 pupils and 55 full-time staff. Operating hours are Mon-Fri, 9am to 4pm.

Construction

Brickwork/blockwork building with wall, floor and roof U-values of 0.56W/m²K, 0.25W/m²K and 0.22W/m²K respectively. Standard double glazing (40% of external wall area) of 2.75W/m²K. Infiltration rate of 0.3ach

HVAC systems

2 x 323kW non-condensing boilers for heating. No mechanical ventilation or cooling. Assumed that 10l/s/person ventilation can be achieved passively through vents and windows.

Internal gains

Peak gains (averaged over all areas) are: Occupant 7.7W/m²; Lighting 8.2W/m²; Small power 4.9W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT and "office" type energy management (see office variants but with below exception)

⇒ One low-power (15W) laptop per child (for increased IT usage while reducing energy usage) replacing all desktop machines

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ External insulation of expanded polystyrene (150mm) with concrete render added to walls

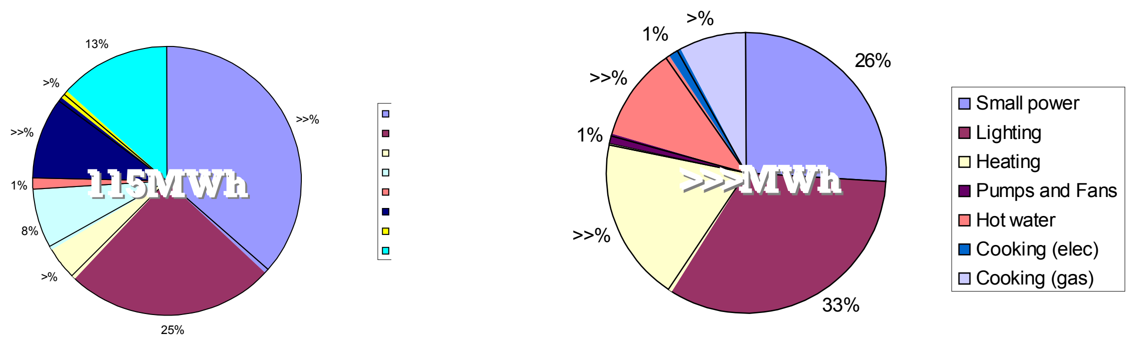
⇒ EPS also added to roof, replacing existing mineral wool

- **HVAC**

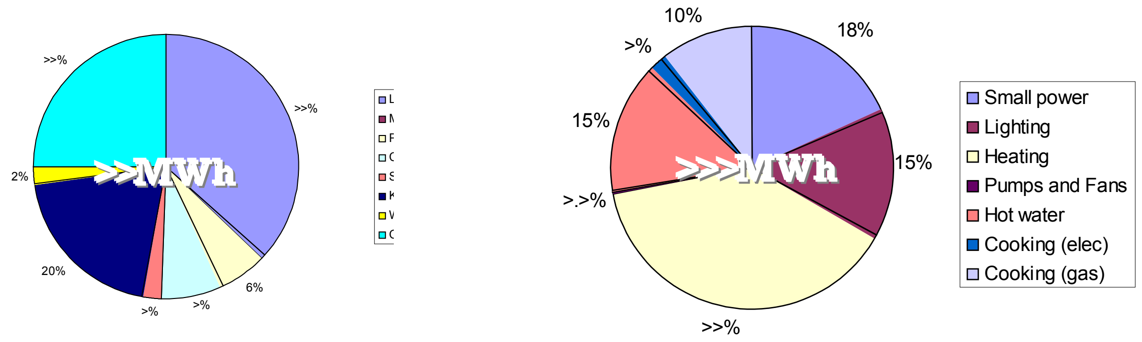
⇒ Condensing boiler replaces non-condensing boiler

⇒ Reduction in internal gains (see "Small Power and Lighting")

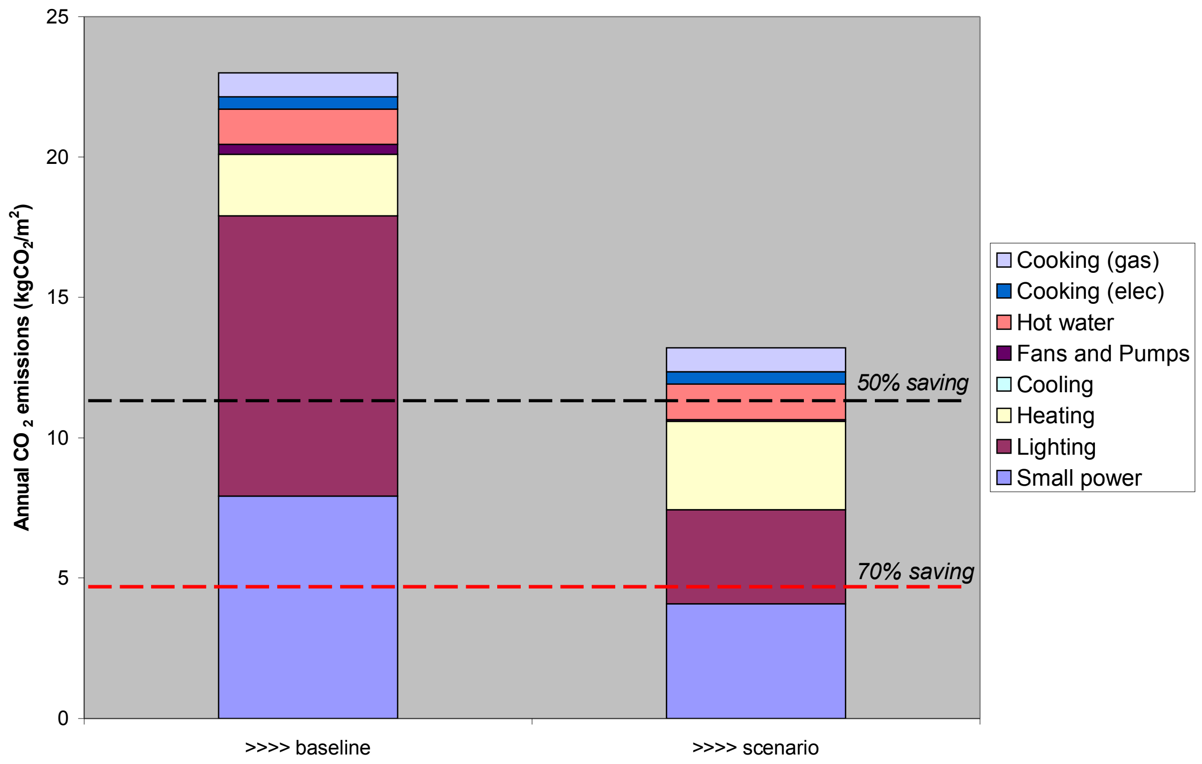
2005 small power and total energy cons



>>>> small power and total energy cons

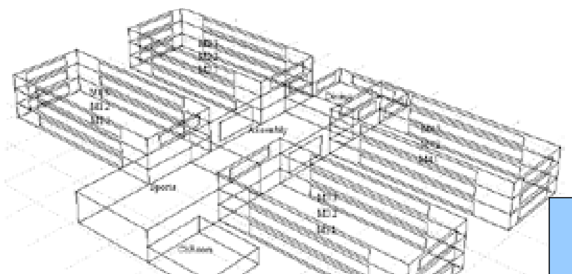


Final CO_2 savings



Non-Domestic building CO2 savings:

School variant VS4



Total floor area: 9198m²

Teaching: 4368m²

Storage: 648m²

Staff/admin: 432m²

Sports hall: 504m²

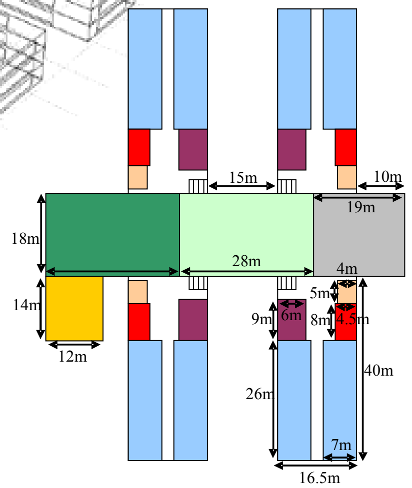
Changing rooms: 168m²

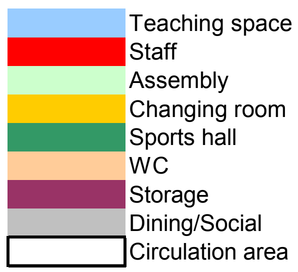
Assembly hall: 504m²

Toilets: 240m²

Circulation: 1992m²

Age: 2000 construction





Description

Three-storey secondary school, situated in Birmingham, with 1250 pupils and 76 full-time staff. Operating hours are Mon-Fri, 9am to 4pm.

Construction

Brickwork/blockwork building with wall, floor and roof U-values of 0.51W/m²K, 0.25W/m²K and 0.22W/m²K respectively. Standard double glazing (40% of external wall area) of 2.75W/m²K. Infiltration rate of 0.3ach

HVAC systems

2 x 413kW non-condensing boilers for heating. No mechanical ventilation or cooling. Assumed that 10l/s/person ventilation can be achieved passively through vents and windows.

Internal gains

Peak gains (averaged over all areas) are: Occupant 8.8W/m²; Lighting 8.5W/m²; Small power 4.9W/m²

Carbon-saving interventions

- **Small Power and Lighting**

⇒ IT and "office" type energy management (see office variants but with below exception)

⇒ One low-power (15W) laptop per child (for increased IT usage while reducing energy usage) replacing all desktop machines

⇒ LED lighting (150lm/W) replaces T12 fluorescent tubes (70lm/W)

- **Fabric**

⇒ External insulation of expanded polystyrene (EPS) with concrete render added to walls

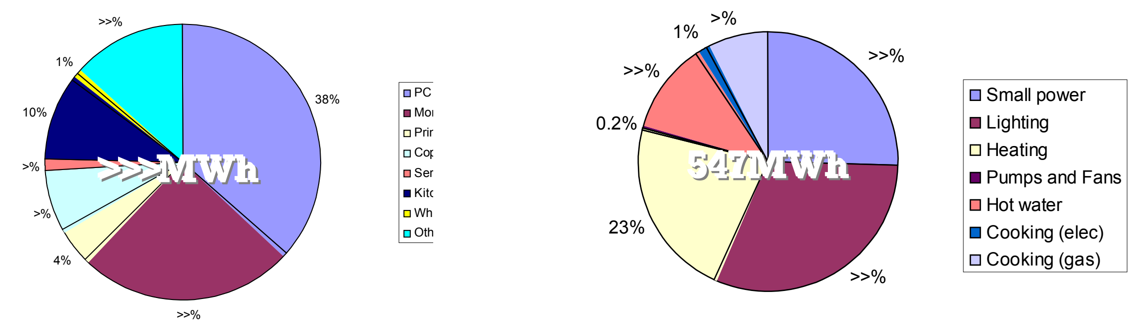
⇒ EPS also added to roof, replacing existing mineral wool

- **HVAC**

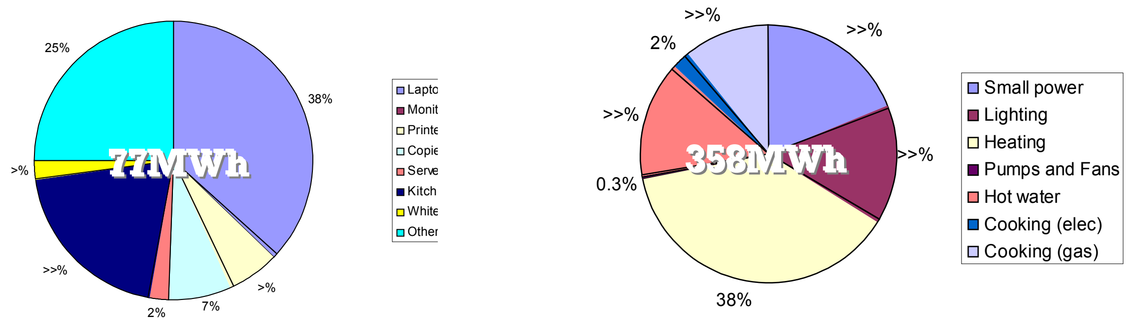
⇒ Condensing boiler replaces non-condensing boiler

⇒ Reduction in internal gains (see "Small Power and Lighting")

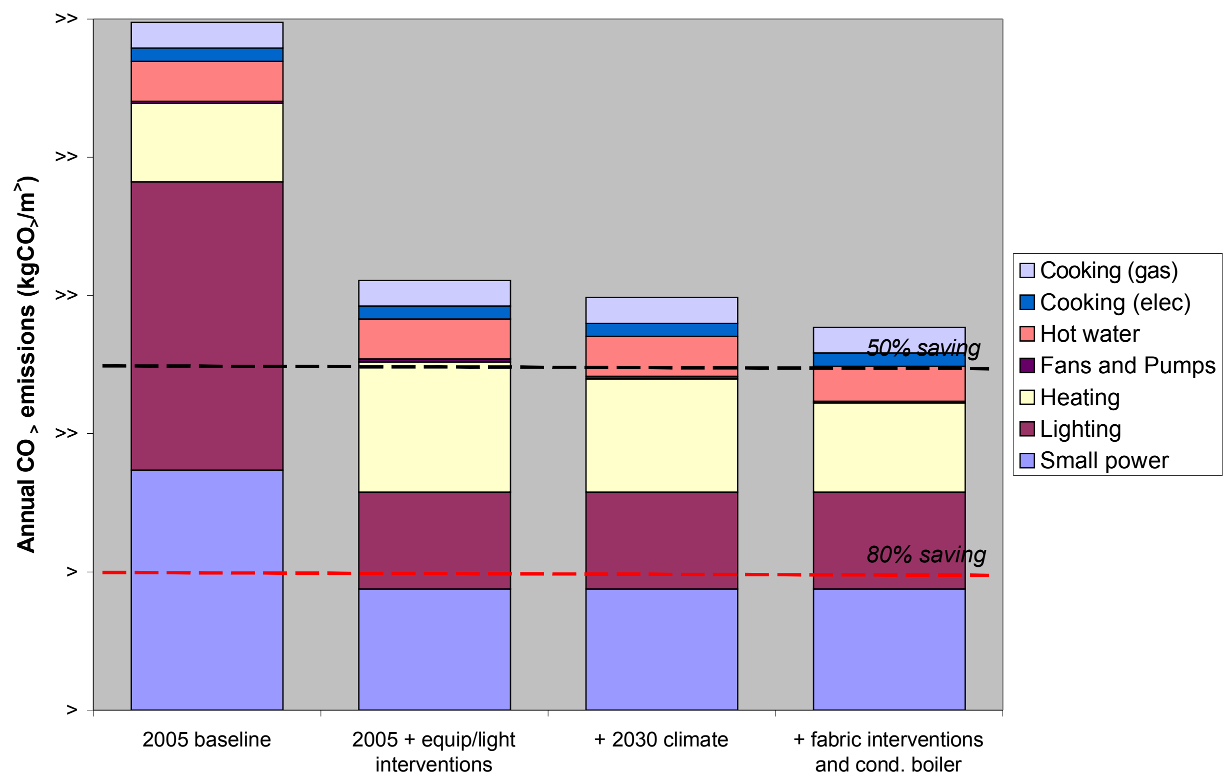
2005 small power and total energy consumption



2030 small power and total energy consumption

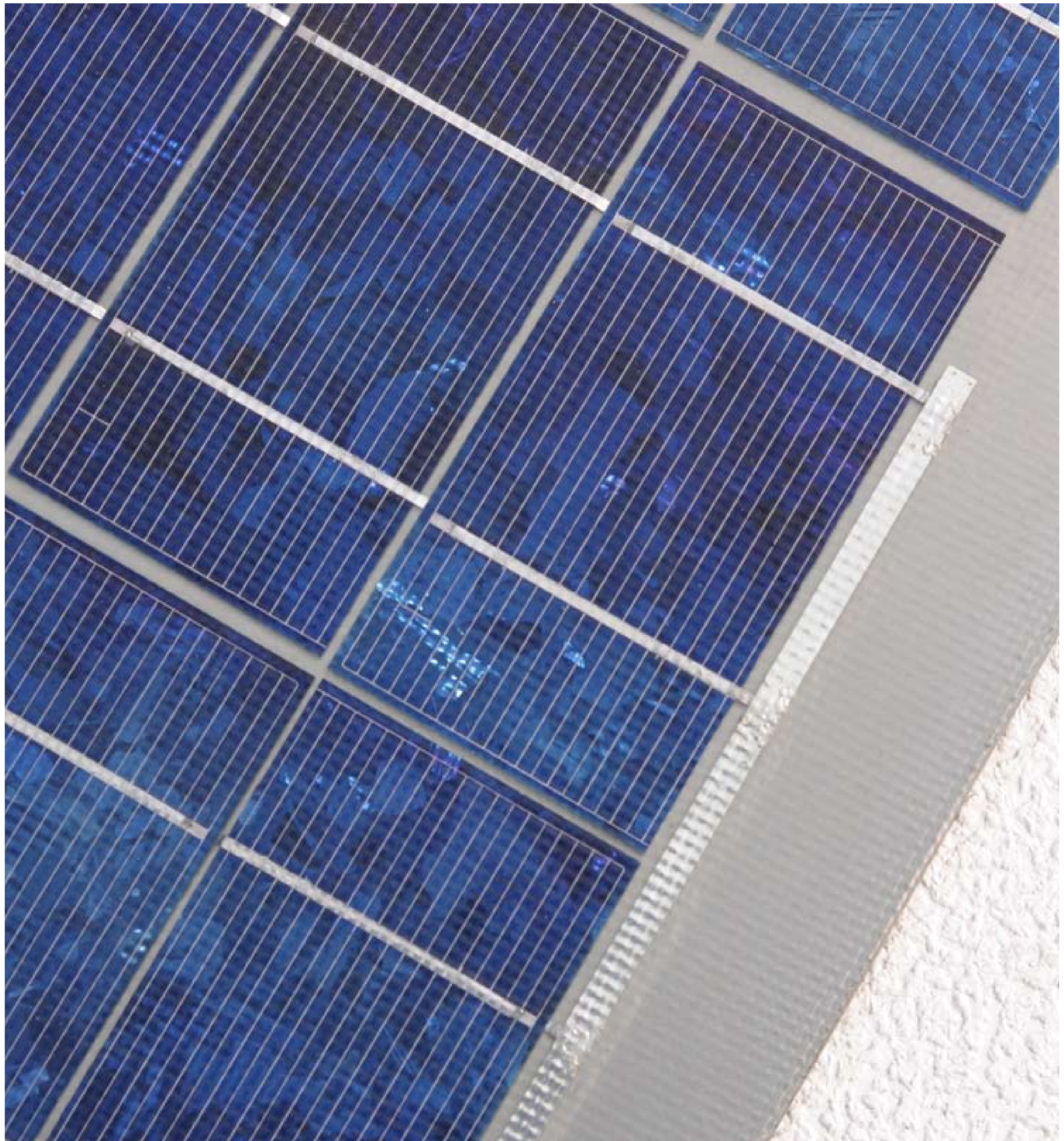


Final CO_2 savings



SECTION C

Effect of onsite generation on electrical and gas based carbon emissions



FOREWORD

The following figures provide estimates for the carbon savings of the different intervention packages across all building variants. A grid electricity CO_2 intensity of 0.52kgCO_2/kWh is used, with 0.19kgCO_2/kWh being the equivalent for gas. The inclusion of onsite generation measures enables a comparison to be made between the savings potential of demand-side measures with that of supply-side refurbishments. The figures support the hypothesis that demand reduction is likely to have far greater gains, in terms of carbon-savings, than large onsite generation installations.

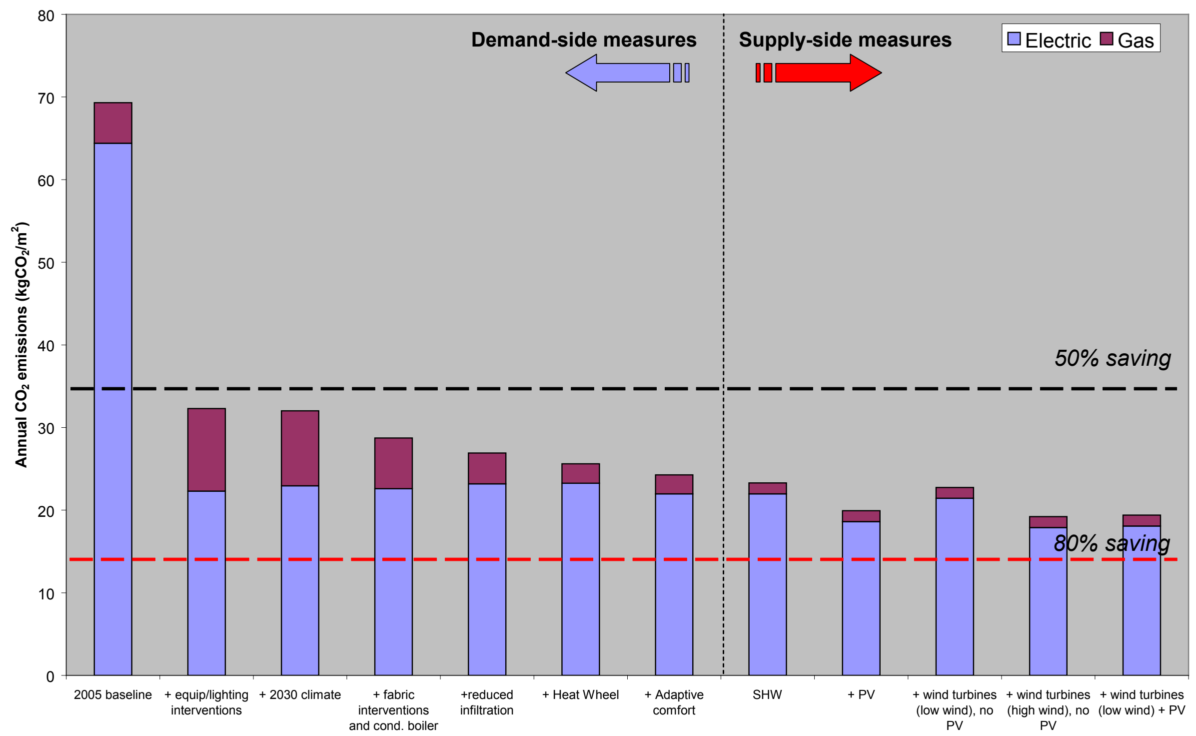


Figure 20 *– Electrical and gas based CO2 emissions of 4-storey office variant (VO1)*

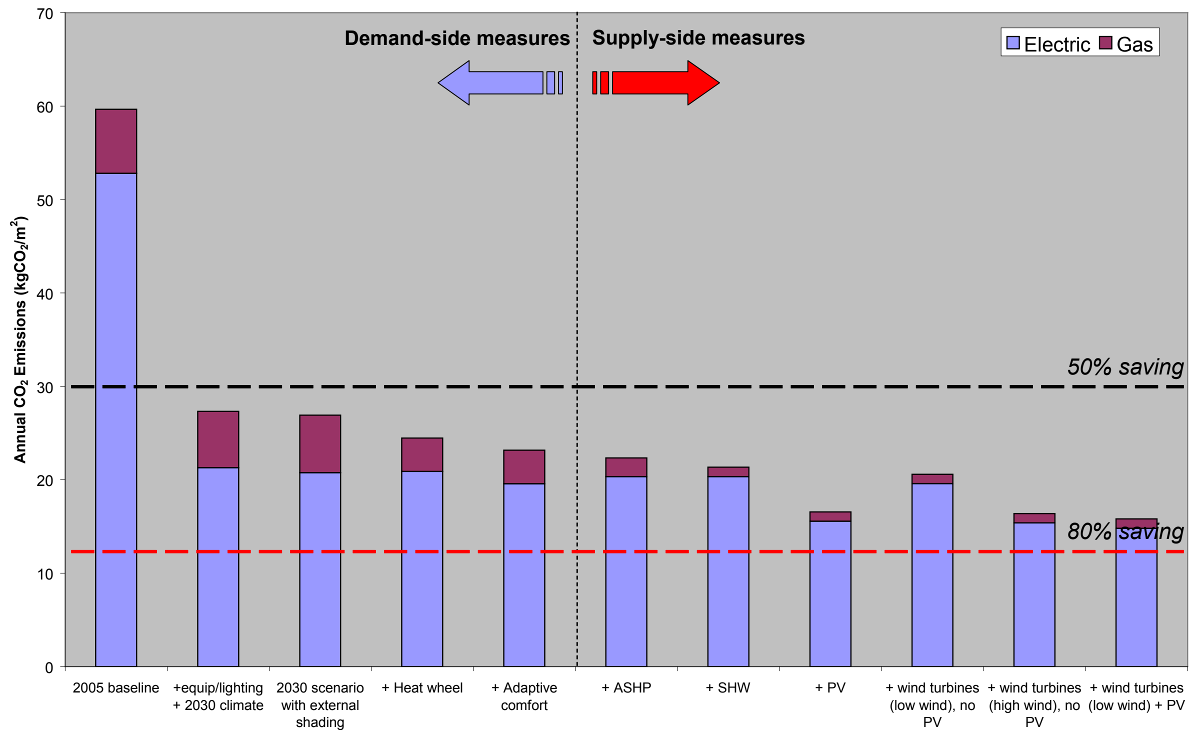


Figure 21 *– Electrical and gas based CO_2 emissions of 5-storey office variant (VO2)*

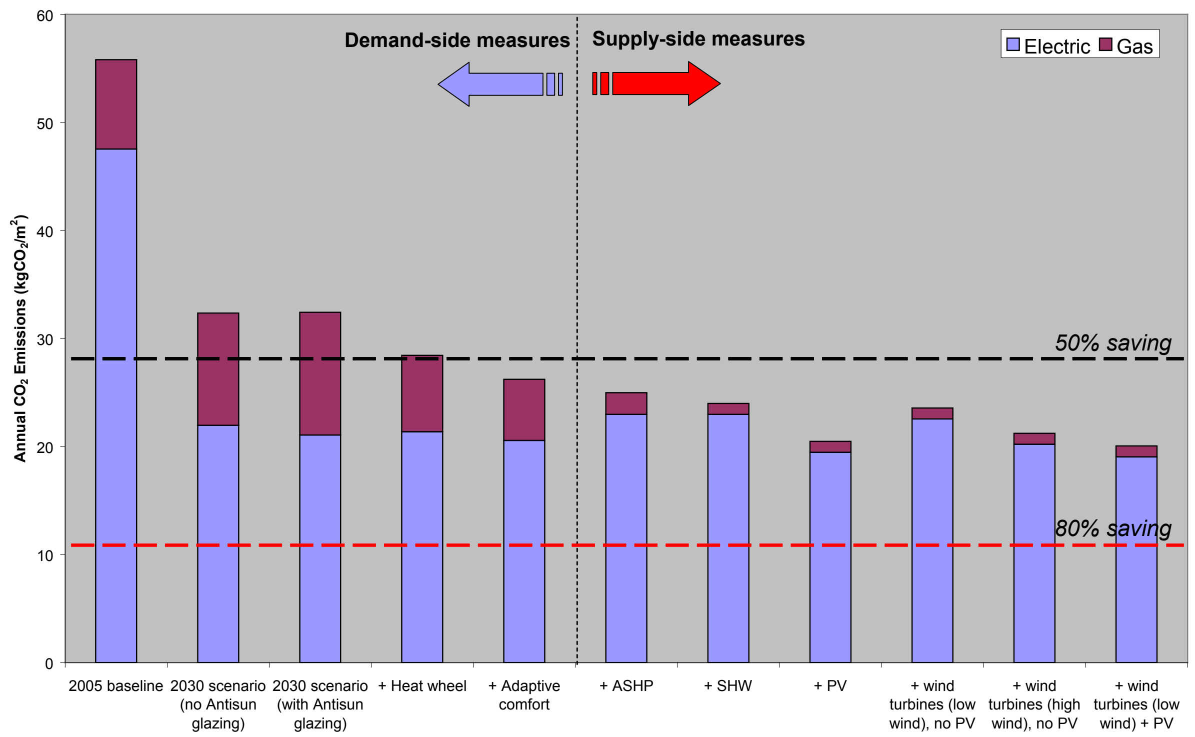


Figure 22 *– Electrical and gas based CO_2 emissions of 6-storey deep-plan office variant (VO3)*

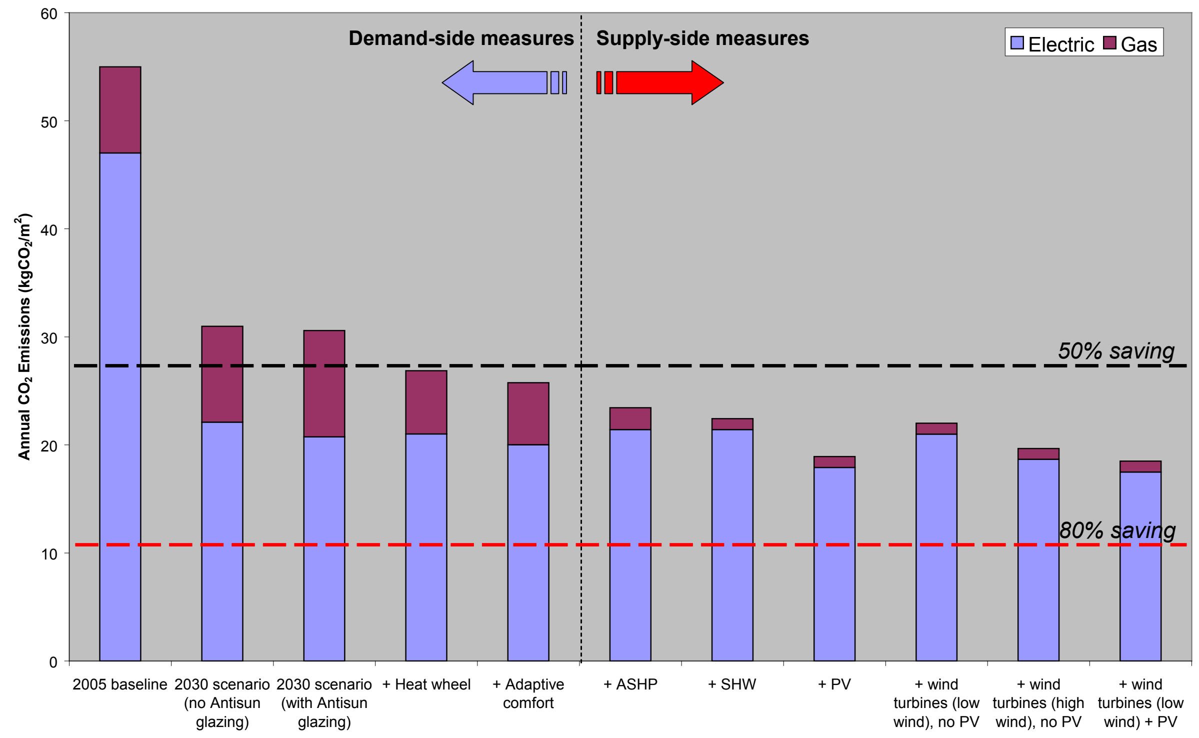


Figure 23 *– Electrical and gas based CO_2 emissions of 6-storey shallow-plan office variant (VO4)*

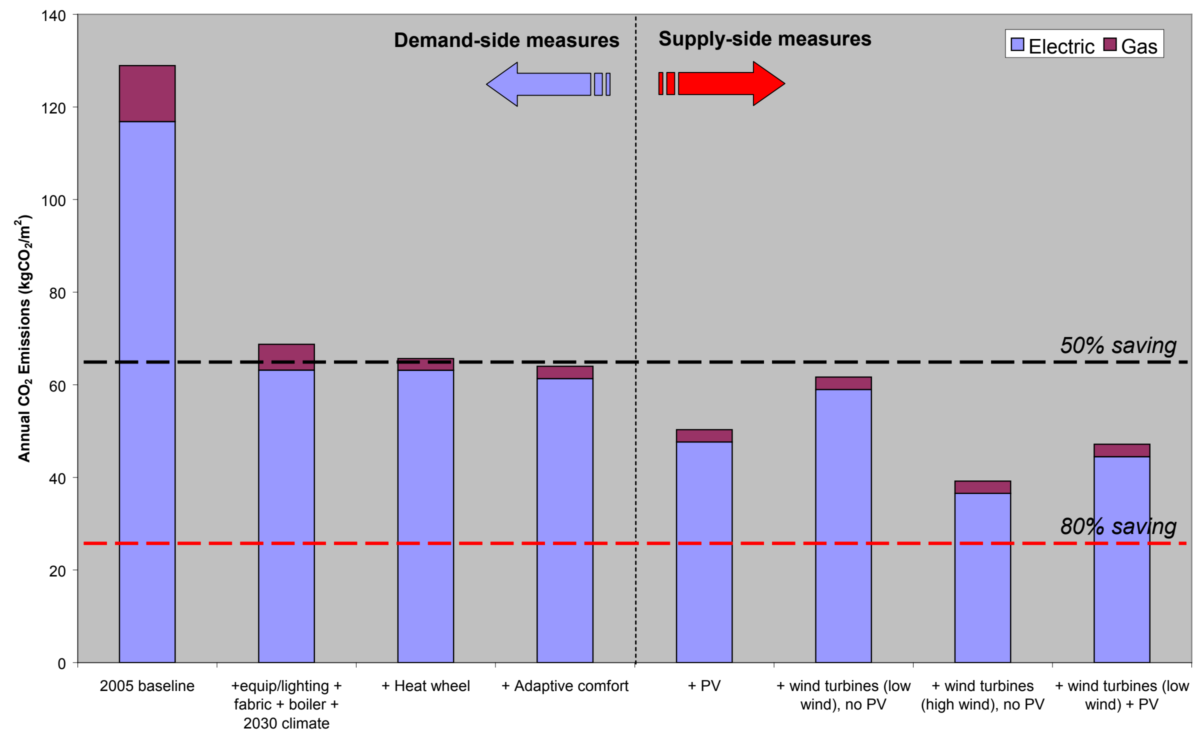


Figure 24 *– Electrical and gas based CO_2 emissions of small high-street office variant (VO5)*

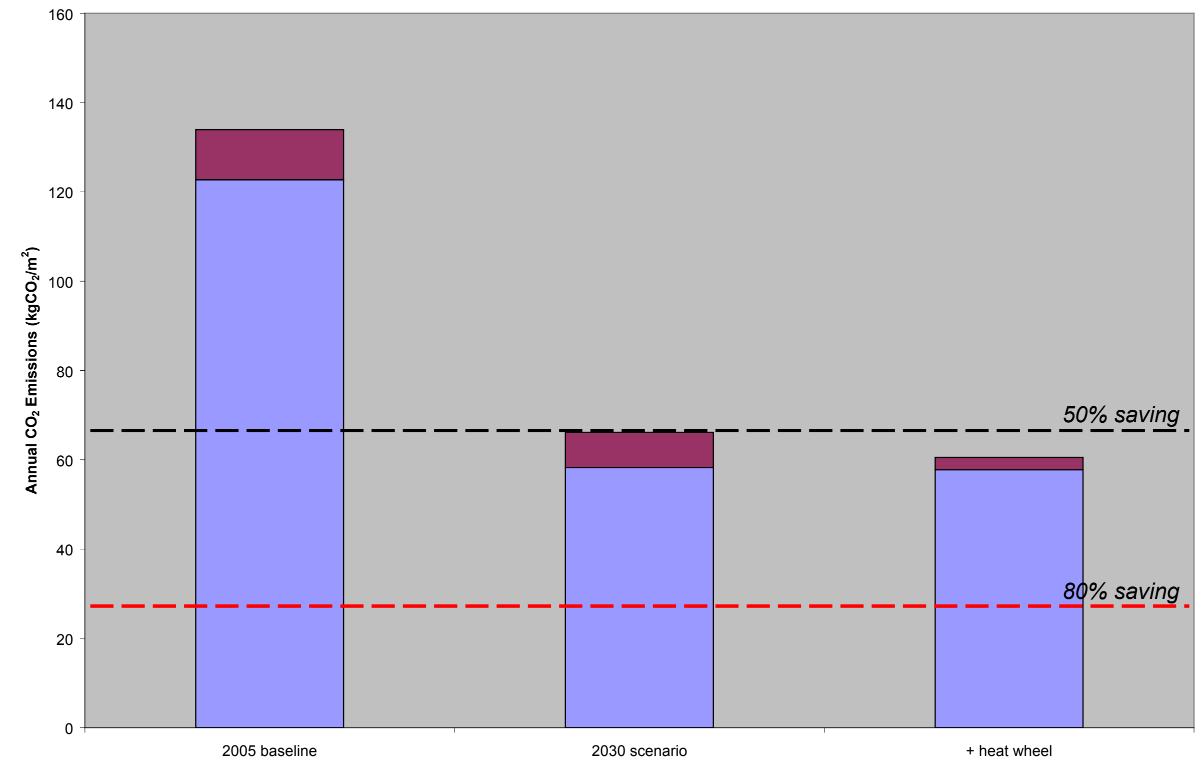


Figure 25 *– Electrical and gas based CO_2 emissions of estate agent variant (VR1)*

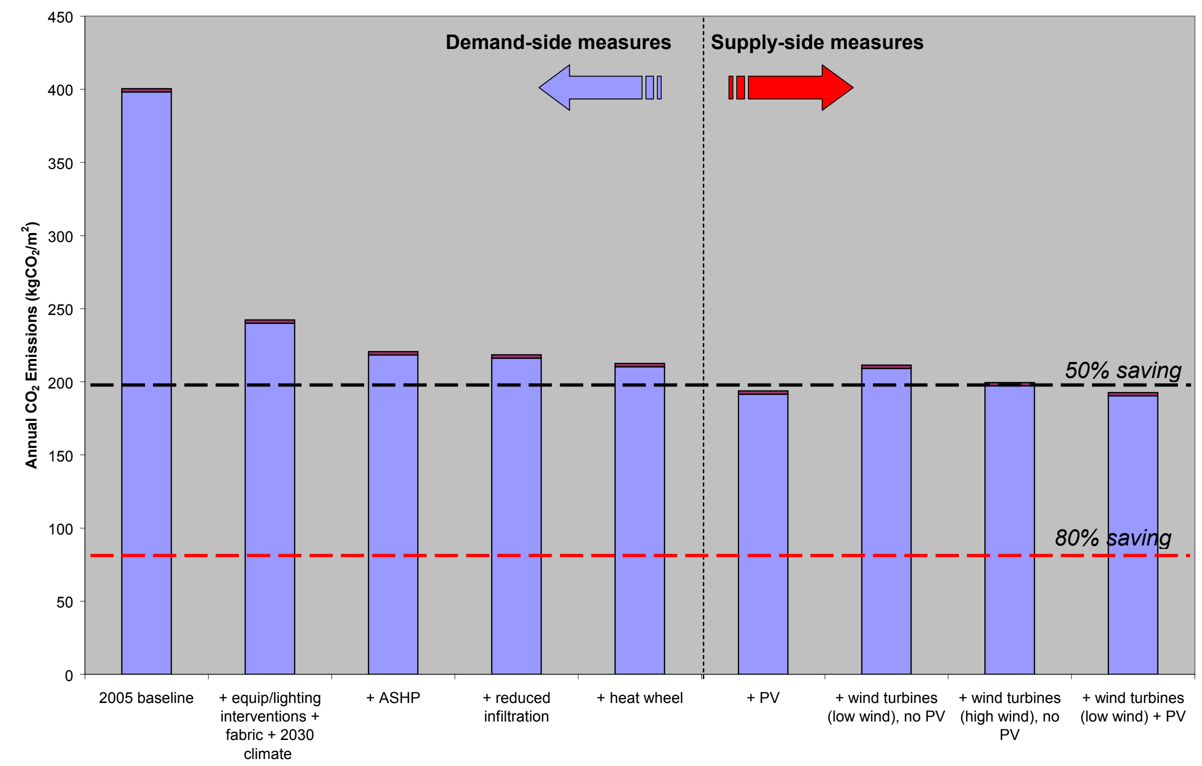


Figure 26 *– Electrical and gas based CO_2 emissions of convenience store variant (VR2)*

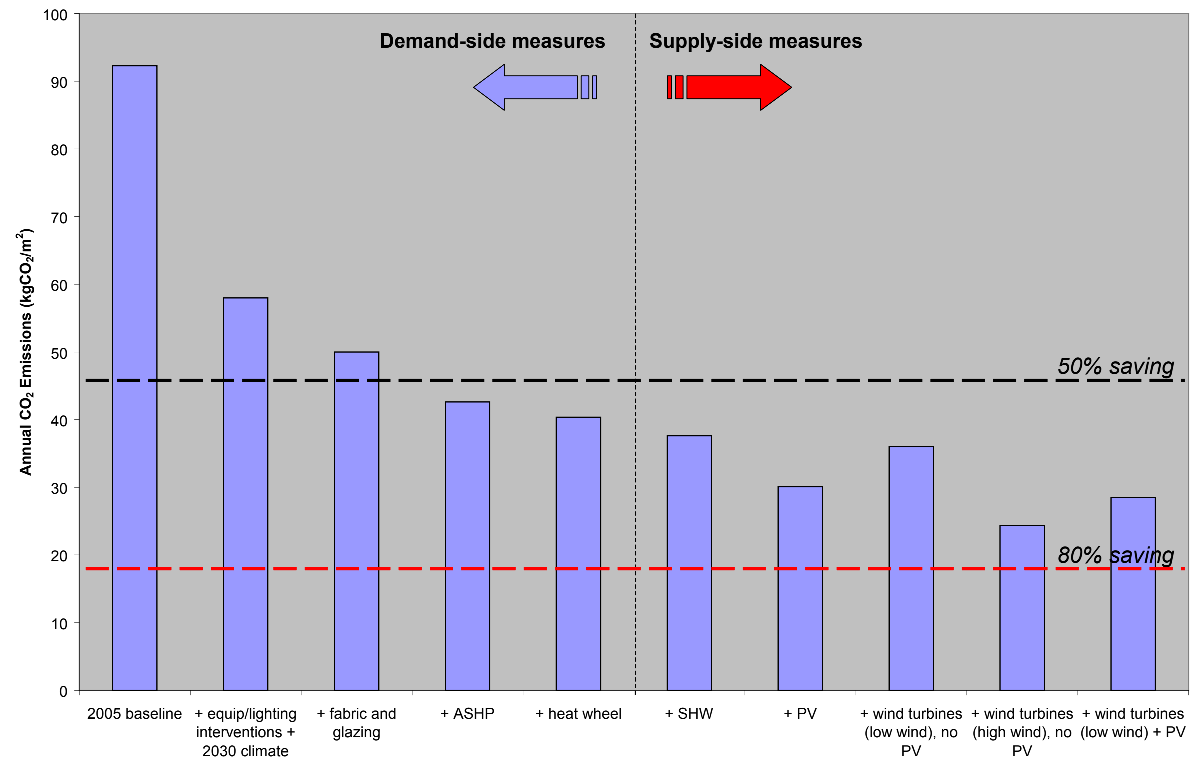


Figure 27 *– Electrical CO_2 emissions of clothes shop variant (VR3) [NB – no gas systems exist for this variant]*

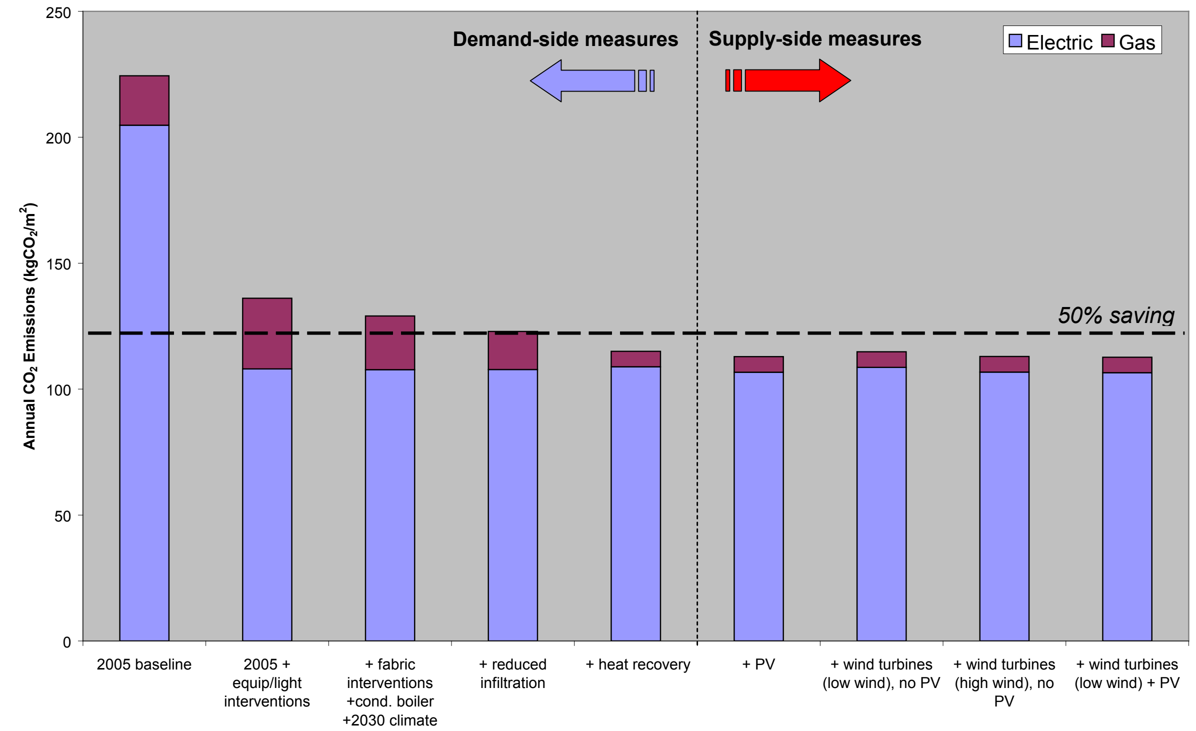


Figure 28 *– Electrical and gas based CO_2 emissions of supermarket variant (VR4)*

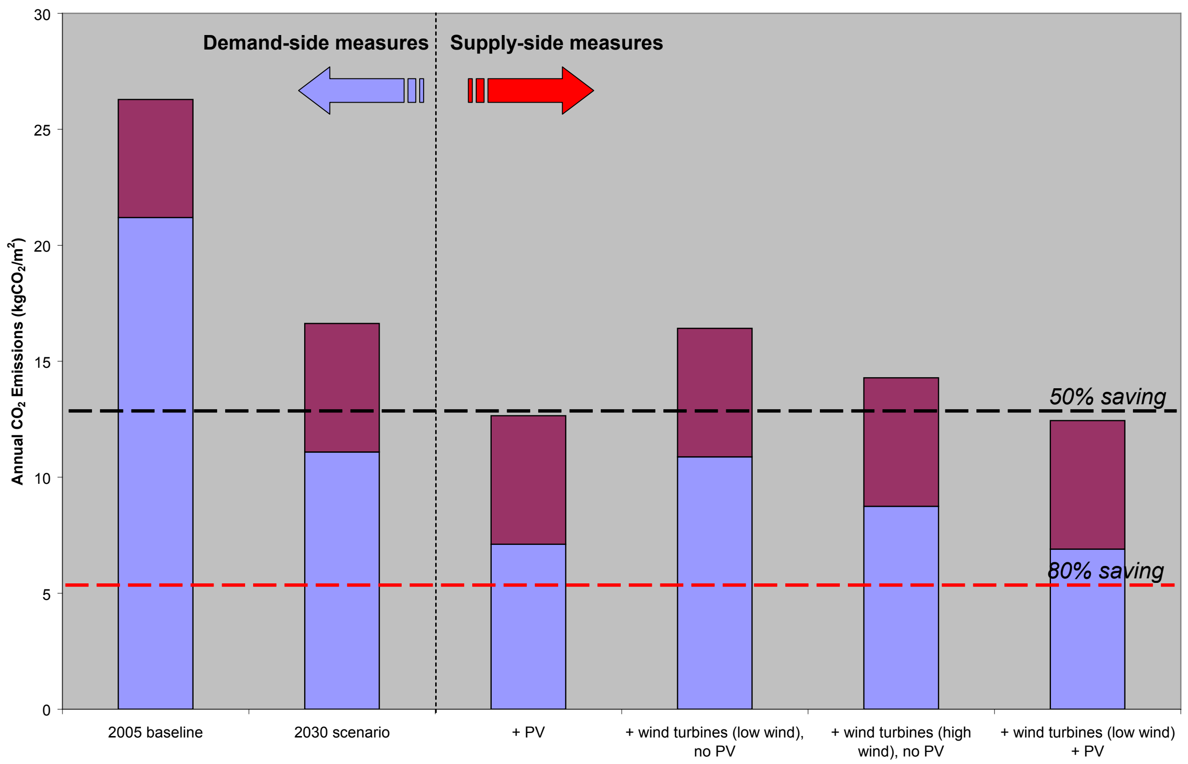


***Figure 29** – Electrical and gas based CO_2 emissions of small primary school (VS1)*

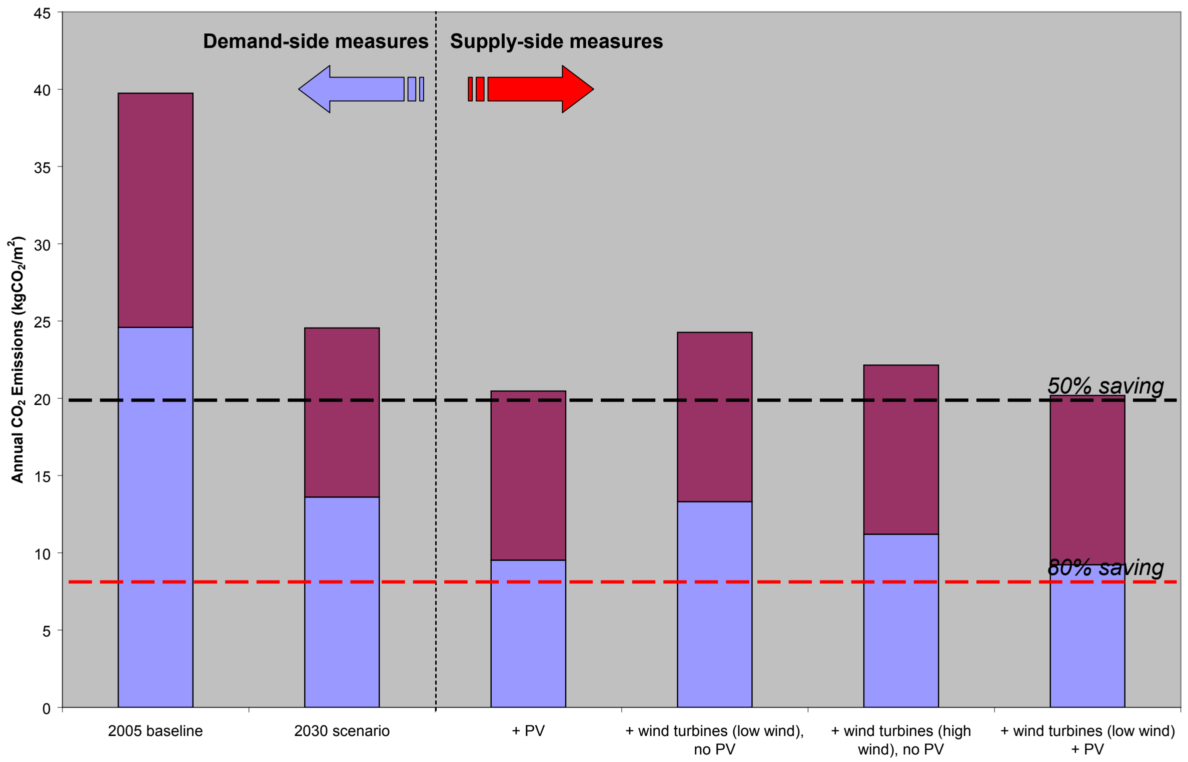


***Figure 30** – Electrical and gas based CO_2 emissions of medium primary school (VS2)*

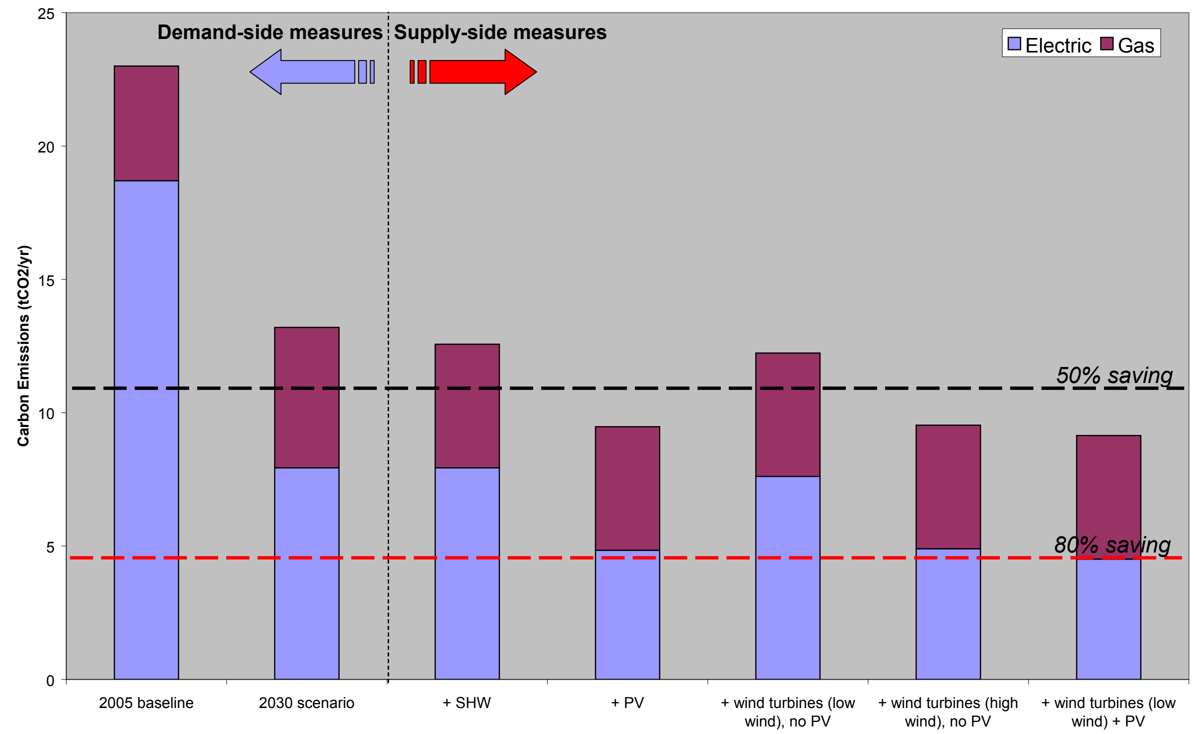


***Figure 31** – Electrical and gas based CO_2 emissions of medium secondary school (VS3)*

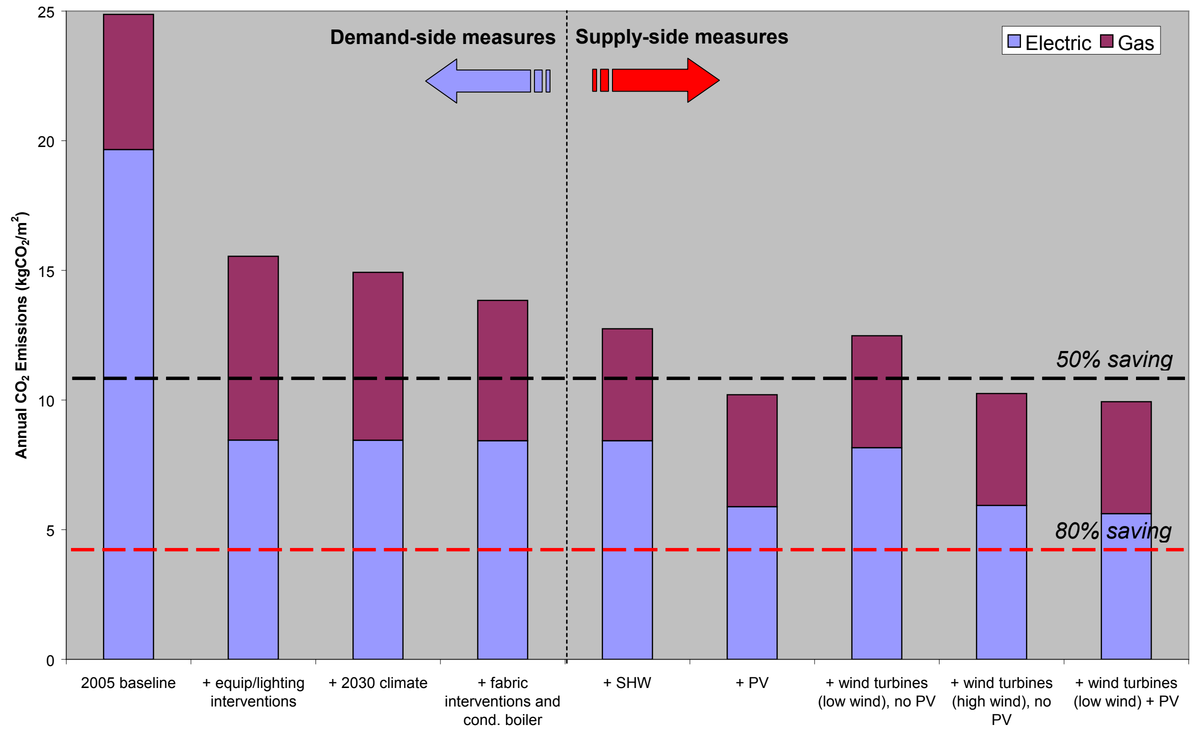


***Figure 32** – Electrical and gas based CO_2 emissions of large secondary school (VS4)*

SECTION D

Economic analysis of carbon-saving refurbishments of non-domestic buildings

Courtesy of Vicky Ingram, Urban Energy Research Group

D ECONOMIC ANALYSIS OF CARBON-SAVING REFURBISHMENTS OF NON-DOMESTIC BUILDINGS

To carry out a full quantity surveying exercise on the described intervention sets, Thomson Bethune were invited to provide estimations of capital and whole life cycle costs for a range of carbon-saving interventions, using the building variants already described in this report. The work was carried out by Gary McLaren and Ross Buchan of Thomson Bethune, using in-house software and methodologies. Assumptions on capital costs were based on manufacturers' estimations, though these are subject to uncertainties due to variations in specifications. Furthermore, some technologies relate to markets that are have not yet reached maturity; the assumptions used to deal with these technologies (such LED lighting) are discussed in the report.

As with the carbon-saving analysis, the cost figures for the various building variants are not presented as stock averages. They are used as indicative estimates for buildings of the type described. However, the overall results of the work does provide guidance as to the scale of cost that might be imagined for the non-domestic stock at large, particularly for the sub-sectors of offices, schools and retail.

A list of manufacturers who contributed to these cost estimates is given at the end of this section.

D1 CAPITAL COST OF REFURBISHMENTS

D1.1 INTRODUCTION

The capital cost section of this work involved gathering cost information for a wide range of interventions. This information was then applied to the different variants depending on quantities and performances as discussed in sections A to C of this report. Cost information was sought from a variety of different sources. This included suppliers, manufacturers, industry professionals and internal cost data from similar projects undertaken by Thomson Bethune. Costs received were verified by checking against several other sources. While conducting this part of the study it was found that there are several key uncertainties which will affect the cost and suitability of individual interventions. These uncertainties are described in further detail below.

Due to the theoretical nature of the work, it is difficult to provide an accurate cost and specification for each measure. Local factors such as location and access to the site, together with the absence of detailed specification have resulted in a number of assumptions being made with regards to this. These constraints also made it difficult for suppliers to provide an accurate cost for preliminaries. For this reason Thomson Bethune developed a schedule of preliminaries to ensure that these costs remained consistent. Further details of this are noted below.

Assumptions with regard to the variants have been made in-line with the date bands and general building types set out in the variant information provided by previous research within the Tarbase project. Also, VAT has been excluded from all costs involved in this report and no provisional sums or contingencies have been included. Costs have been based on the most foreseeable outcome, but there are still some unknown risks which could impact on the final cost of the intervention.

D1.2 PRELIMINARY COSTS

The term "preliminary costs" refers to the associated cost of installing a specific measure (or measures) which is additional to, and so does not include, the capital cost of the technology. This can include:

- Site Accommodation and Welfare Facilities
- Supervision
- Transport
- Plant and Equipment
- Access Requirements (including scaffolding)

As well as being significant for many technologies, preliminary costs will also vary depending on whether refurbishments are installed at different times or if they are installed in a combined project (e.g. external wall cladding installed at the same time as the glazing being changed). The latter scenario means that any duplication of equipment required for more than one intervention was removed, and items such as scaffolding and site accommodation could be utilised in a more cost effective manner. The effect of this cost-saving will be demonstrated in the estimations provided.

D1.2.1 WORKED EXAMPLE OF PRELIMINARY COST CALCULATION

To demonstrate the different factors behind the preliminary cost estimations, the four-storey office variant (VO1) will be used as an example of the calculation procedure. Section D1.2.2 will then overview the equivalent costs for the other non-domestic building variants.

The preliminaries are broken down into three options: Individual work packages; Joint work packages; Single Project. The first option assumes the various measures are installed separately, with separately calculated preliminaries.

The second option groups "similar" measures together (such as wall insulation and glazing measures) and optimises possible savings in scaffolding etc. The final option assumes all the refurbishments are carried out as a single project, providing maximum savings across the preliminary works. Clearly, this scenario is an optimum situation and might not be appropriate for some buildings due to disruption to business and very high capital cost, as opposed to work and costs spread out over a longer time period.

Tables 7 to 9 give the preliminary costs for refurbishing building VO1 through individual work packages, joint work packages or a single project respectively.

Table 7 *– Detail of preliminaries for four-storey office variant (VO1) for measures installed as individual work packages (NB MEWP = Mobile Elevated Work Platform)*

Individual work packages		Duration (weeks)	Rate (£/week)	Amount (£)	Total (£)
Lighting	Transportation	7	175	1225	
	Trades Supervision	7	480	3360	
	Temporary Lighting	7	125	875	
	Tools	7	75	525	
	Skips	7	150	1050	
			Sum	7035	7035
Boiler	Transportation	0.4	175	70	
	Trades Supervision	0.4	480	192	
	Tools	0.4	75	30	
	Lifting Equipment	0.4	200	80	
			Sum	372	372
Heat recovery	Transportation	2	175	350	
	Trades Supervision	2	480	960	
	Tools	2	75	150	
			Sum	1460	1460
Draft Stripping	Transportation	0.4	175	70	
	Trades Supervision	0.4	480	192	
	Tools	0.4	75	30	
			Sum	292	292
Glazing	Transportation	2	175	350	
	Trades Supervision	2	480	960	
	Tools	2	75	150	
	Lifting Equipment	2	200	400	
	Scaffolding (Erection)			4616	
	Scaffolding (Rental)	2	1,154.00	2308	
	Scaffolding (Dismantle)			2308	
	Welfare (toilet, canteen & office)	2	600	1200	
	Skips	2	150	300	
			Sum	12592	12592
Wall insulation	Transportation	6	175	1050	
	Trades Supervision	6	480	2880	
	Scaffolding (Erection)			4616	
	Scaffolding (Rental)	6	1,154.00	6924	
	Scaffolding (Dismantle)			2308	
	Welfare (toilet, canteen & office)	6	600	3600	
	Skips	6	150	900	
			Sum	22278	22278
Floor insulation	Transportation	8	175	1400	
	Trades Supervision	8	480	3840	
	Welfare (toilet, canteen & office)	8	600	4800	
	Skips	8	150	1200	
	Plant	8	400	3200	
			Sum	14440	14440
Roof insulation	Transportation	2	175	350	
	Trades Supervision	2	480	960	
	Tools	2	75	150	
	Rubbish Skips	2	75	150	
	Scaffolding (Erection)		Not required		
	Scaffolding (Rental)		Not required		
	Scaffolding (Dismantle)		Not required		
	Welfare	2	600	1200	
	Skips	2	150	300	
			Sum	3110	3110
PV system	Transportation	1	175	175	
	Tools	1	75	75	
	MEWP	1	400	400	
	Roof edge protection	1	200	200	
			Sum	850	850
Wind turbine	Transportation	2	175	350	
	Tools	2	75	150	
	MEWP	2	400	800	
	Roof edge protection	1	200	200	
			Sum	1500	1500
Solar thermal system	Transportation	2	175	350	
	Tools	2	75	150	
	MEWP	2	400	800	
	Roof edge protection	1	200	200	
			Sum	1500	1500
				Final total	**65429**

Table 8 *- Detail of preliminaries for four-storey office variant (VO1) for measures installed as joint work packages for appropriate groupings*

Joint work packages		Duration (weeks)	Rate (£/week)	Amount (£)	Total (£)
Lighting, boiler and heat recovery	Transportation	7	175	1225	
	Trades Supervision	7	480	3360	
	Temporary Lighting	7	125	875	
	Tools	7	75	525	
	Lifting Equipment	0.4	100	40	
			Sum	6025	6025
Insulation, draft stripping and glazing	Transportation	8	175	1400	
	Trades Supervision	8	480	3840	
	Scaffolding (Erection)			4616	
	Scaffolding (Rental)	8	1,154	9232	
	Scaffolding (Dismantle)			2308	
	Welfare	8	600	4800	
	Tools	8	75	600	
	Skips	8	150	1200	
	Plant	8	400	3200	
			Sum	31196	31196
Energy generation	Transportation	2	175	350	
	Tools	2	75	150	
	MEWP	2	400	800	
	Roof edge protection	2	200	400	
				1700	1700
				Final total	**38921**

Table 9 *- Detail of preliminaries for four-storey office variant (VO1) for measures installed as single project*

Single project		Duration (weeks)	Rate (£/week)	Amount (£)	Total (£)
All interventions	Transportation	8	175	1400	
	Trades Supervision	8	480	3840	
	Scaffolding (Erection)			4616	
	Scaffolding (Rental)	8	1,154	9232	
	Scaffolding (Dismantle)			9232	
	Welfare	8	600	4800	
	Tools	8	75	600	
	Skips	8	150	1200	
	Temporary Lighting	8	125	1000	
	L Equipment	8	100	800	
	Plant	8	400	3200	
			Sum	39920	39920
				Final total	**39920**

D1.2.2 OVERVIEW OF PRELIMINARIES FOR ALL VARIANTS

Using the approach detailed in section D1.2.1, Tables 10 to 12 display the results for all the non-domestic building variants. Figure 33 illustrates the comparison across all scenarios. It is clear that substantial cost savings are possible if measures are installed at the same time within a large project. The clothes shop variant (VR3) shows a 61% reduction in preliminary costs if all refurbishments are carried out as one single project.

Conversely, the convenience store (VR2) and smaller secondary school (VS3) buck this trend slightly – for these two cases there does not appear to be a saving from carrying refurbishments together. This might be due to the economy of scale for scaffolding and other equipment not transferring to certain sizes of projects – carrying out refurbishments as a larger project for these buildings might result in some of this equipment being surplus to requirements for long periods of time (representing poor use of resources and cost).

Table 10 *– Overview of preliminary costs for all non-domestic variants when installed by individual work packages*

Variant	Lighting	Boiler	Heat recovery	Wall insulation	Floor insulation	Roof insulation	Draught stripping	Glazing	PV system	Wind turbines	Solar thermal	Refrigeration	Total
Offices													
VO1	£7,035	£372	£1,460	£22,278	£14,440	£3,110	£292	£12,592	£850	£1,500	£1,500	N/A	£65,430
VO2	£7,035	£372	£1,460	£9,835	£10,830	£3,110	N/A	£18,464	£850	£1,700	£1,500	N/A	£55,160
VO3	£8,040	£372	£1,460	£9,835	£10,830	£3,110	N/A	£13,316	£850	£1,500	£1,500	N/A	£50,820
VO4	£8,040	£372	£1,460	£9,835	£10,830	£3,110	N/A	£15,980	£850	£1,500	£1,500	N/A	£53,480
VO5	£1,005	£186	£730	£2,810	N/A	£311	N/A	£1,834	£850	£850	£850	N/A	£9,430
Schools													
VS1	£5,025	£332	N/A	£4,215	N/A	£1,480	N/A	N/A	£850	£850	£1,700	N/A	£14,460
VS2	£6,030	£372	N/A	£5,620	£10,360	£1,480	N/A	N/A	£850	£850	£1,700	N/A	£27,270
VS3	£8,040	£492	N/A	£36,770	N/A	£4,440	N/A	N/A	£850	£3,075	£1,700	N/A	£55,370
VS4	£9,045	£372	N/A	£51,390	N/A	£4,665	N/A	N/A	£850	£2,425	£1,500	N/A	£70,250
Retail													
VR1	£1,005	£186	£730	£1,405	£4,215	N/A	N/A	£1,596	N/A	N/A	N/A	N/A	£9,140
VR2	£1,005	£930	£1,460	£2,810	£5,415	£622	£146	£1,680	£850	£850	N/A	£100	£15,870
VR3	£2,010	£930	£1,460	£5,916	£7,220	£1,555	N/A	£4,872	£850	£850	£850	N/A	£26,520
VR4	£10,050	£372	£1,460	£2,728	£21,660	£6,220	£730	£12,348	£1,700	£3,725	£850	£500	£62,350

Table 11 *– Overview of preliminary costs for all non-domestic variants when installed as joint work packages*

Variant	Lighting, boiler and heat recovery	Insulation, draft stripping and glazing	Energy generation	Refrigeration	Total
Offices					
VO1	£6,025	£31,196	£1,700	N/A	£38,930
VO2	£6,025	£37,704	£1,500	N/A	£45,230
VO3	£6,880	£37,704	£1,700	N/A	£46,290
VO4	£6,880	£32,005	£1,700	N/A	£40,590
VO5	£895	£3,536	£850	N/A	£5,290
Schools					
VS1	£4,775	£4,440	£1,500	N/A	£10,720
VS2	£5,730	£10,360	£1,500	N/A	£17,590
VS3	£7,640	£37,070	£4,650	N/A	£49,360
VS4	£7,735	£51,840	£4,150	N/A	£63,730
Retail					
VR1	£895	£4,782	N/A	N/A	£5,680
VR2	£955	£20,925	£100	£100	£22,080
VR3	£1,910	£9,810	£850	N/A	£12,570
VR4	£9,550	£27,162	£4,650	£500	£41,870

***Table 12** – Overview of preliminary costs for all non-domestic variants when installed as joint work packages*

Variant	All measures	Total (rounded)
Offices		
VO1	£32,996	£33,000
VO2	£39,279	£39,280
VO3	£42,872	£42,880
VO4	£36,950	£36,950
VO5	£3,986	£3,990
Schools		
VS1	£8,525	£8,530
VS2	£11,935	£11,940
VS3	£59,350	£59,350
VS4	£54,190	£54,190
Retail		
VR1	£6,377	£6,380
VR2	£21,300	£21,300
VR3	£10,310	£10,310
VR4	£30,762	£30,770

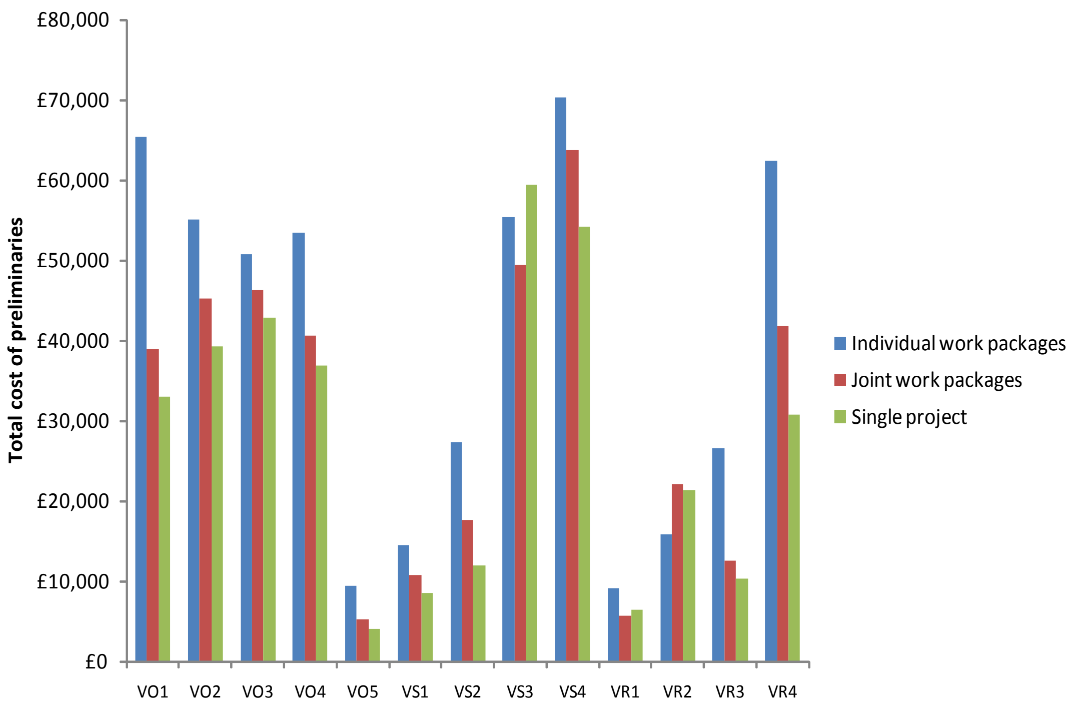


***Figure 33** – Comparison of preliminary costs for all non-domestic variants with three installation options*

D1.3 KEY UNCERTAINTIES

Several Key Uncertainties were noted against each intervention. These uncertainties are issues which could impact on the capital cost of specific interventions. The uncertainties identified can be classified into three main categories.

- Product-specific uncertainties which have been identified in conjunction with cost suppliers and also research into the specific interventions.
- Future cost trends identified by the predicted improvements in technology and manufacturing processes.
- Economic uncertainties in relation to the current economic climate.

The following discussion of the key uncertainties deals with the main issues that were encountered during the analysis, but should not be seen as exhaustive.

D1.3.1 LIGHTING INSTALLATION

As discussed in section A, future LED technologies are likely to significantly out-perform the current market options. Current-market luminaires might produce in the region of 60lm/W, whereas future predictions exceed 150lm/W. With a high degree of confidence with regard to product performance, the point at which this product will enter the market for general non-domestic lighting will ultimately be the cost per lumen, particularly when compared to the best current lighting (e.g. T5 fluorescent lighting). Bridging the gap between current LED cost and current T5 fluorescent costs is likely to be achieved through gradual increase in production, as LED technologies become more cost-effective for more applications (beyond the current applications of spotlight and decorative lighting). Organic LEDs (OLEDs), although not considered in this report explicitly, may provide more cost effective options in the future, when that technology achieves a similar performance and efficacy to conventional LEDs.

It is expected that as LED technology becomes more advanced it will become more commonly used in commercial and domestic situations. This will lead to a reduction in the cost of the full installation. At the moment using this system in areas which need a high luminescence is not feasible due to the high cost of each fitting and the large number required. As the fittings become more advanced, fewer fittings will be needed per square metre and once they are more commonly used the price will drop due to the economies of scale associated with large scale production. The detailed costs given in this section are based on current LED costs; however, Appendix IV gives alternative estimated costs that assume that the cost of installing a low energy LED lighting fixture in 2030 (i.e. in line with the Tarbase scenario) will be similar to the cost of installing modern T5 fluorescent lighting.

D1.3.2 CONDENSING BOILERS

The costs for boilers are inclusive of supply, delivery, installation, testing and commissioning. In addition to this, Thomson Bethune have made an allowance for removing and disposing of the existing system as well as any additional connections required to integrate the new boiler into the existing distribution system. Product development improvements in the efficiency of gas boilers are likely to be incremental, with current efficiencies for condensing boilers generally very high. Condensing boilers are a relatively mature technology and therefore it is expected that there will be only slight increases in the performance and efficiency of these systems in the near future. However, the use of boiler technology in non-domestic buildings is likely to be affected by competitive technologies, particularly heat pumps. Also, with improved building standards enforcing lower demands, it is feasible that smaller systems will be chosen – particularly with a warming climate over the next 25 years. This will have a clear implication on capital cost, though one that is difficult to quantify at present.

A further uncertainty in terms of cost relates to the problems associated with installing a new boiler within an existing distribution system. The condition of the existing distribution system may have a bearing on the overall costs, as will the layout of this system. An allowance has been made for any additional connections required for combining these systems, but the costs associated with repairing or replacing the distribution system have not been included.

D1.3.3 AIR-SOURCE HEAT PUMPS

The costs for this installation are based on two sized systems from a current manufacturer. These costs include the supply and installation of the full system and also all associated builders work, preliminaries, testing and commissioning. Subsequent improvements to refrigerants, with increased efficiency, may reduce capital cost. Conversely, restrictions made to refrigerant type, such as those seen with CFCs and HCFCs, can be detrimental to capital cost in the short-term, with more expensive refrigerants chosen (that are not currently mass produced on the same scale). However, this effect will then be reversed as the new refrigerant achieves wider adoption.

The fact that this is an emerging market makes it difficult to predict future cost trends, though costs would be expected to fall. This will be as a result of increased demand, greater competition and the advantages of larger scale production.

D1.3.4 HEAT RECOVERY

The capital costs of this intervention were supplied by a quotation from an established supplier with Thomson Bethune adding on an allowance for installation, builders work and preliminaries. The main form of mechanical ventilation heat recovery mechanisms are heat/enthalpy wheels (mostly used in this study) and cross-flow heat exchangers. Large heat wheels, as appropriate for most non-domestic buildings, are likely to see an improvement in efficiency over the next 25 years, which will improve the life-cycle cost performance. Further development of these systems might involve improved integration with existing ventilation and heating systems/controls, particularly important for retrofit options.

Accurate costing of this intervention would require full investigation into the ventilation systems in place, which is obviously not possible in this situation as the building is simulated not real. In order for this system to work it requires the extract vent to be located adjacent to the inlet vent. If this is not the case in the existing building then the ductwork layout would need to be altered to suit. The cost of this alteration has not been included in the capital costs as it is assumed that this is not the case. It is also assumed that no additional air filtration will be required.

D1.3.5 EXPANDED POLYSTYRENE (EPS) INSULATION

All costs received for this intervention were based on supplying and fitting silver bead expanded polystyrene insulation. The contractors contacted were asked to price for the new installation only. The costs of builders work and associated preliminaries were calculated by Thomson Bethune. In addition to the above sources, merchants were contacted in order to give prices for the supply of materials only. This was used to cross check to ensure the costs received were realistic.

EPS insulation is a well established product in the construction industry. It has been well developed and is not expected to improve greatly in the near future. The insulation industry's main focus seems to be on developing other types of insulation. It is likely that thin profile materials will be adopted where space restrictions apply, assuming such technology becomes economically competitive. More advanced insulation solutions, such as vacuum insulation panels and phase-change materials, will also need to overcome this barrier, as well as resolving certain issues with retrofit installation. It is therefore suggested that EPS insulation, and similarly applied materials, will have a large market in the near future, until more advanced materials become more cost-effective.

D1.3.6 GLAZING INSTALLATION

The costs of the various glazing systems, including triple-glazing, thin profile double glazing and anti-sun reflective films, were received from several companies and included supply and installation. An allowance was then added for preliminaries on the figure received, including the removal of the existing windows.

Double and triple glazing systems are mature technologies and only marginal development of the performance and efficiency of these products is expected in the near future. The main issue will be cost-effectiveness of the more advanced, and high-performing, glazing such as vacuum and gas-filled triple-glazing. This is perceived to be the main barrier to consumers choosing between medium performance (such as double-glazing) and very high performance (vacuum/gas filled triple-glazing).

D1.3.7 PHOTOVOLTAIC (PV) SYSTEMS

The capital costs of this intervention were supplied by a current manufacturer for supply and installation, with Thomson Bethune adding allowance for builders work and preliminaries.

PV systems are currently being developed to improve their cost-efficiency ratio. This development is expected to make this technology more commonly used in domestic and commercial situations. While current efficiencies are expected to improve significantly, the technology will achieve greater market penetration with an improvement in efficiency per unit cost, rather than high efficiencies at high cost. This could be achieved through the cost effectiveness of thin film technology. Furthermore, like other semi-conductor based products (such as LEDs, see section D1.3.1), organic materials might provide a more cost-effective product in the future, though this technology is not mature enough to provide a cost and performance prediction for 2030.

On a domestic scale, the market for PV is likely to increase as a result of feed-in tariffs in the UK, where a similar scheme in Germany was relatively successful in increasing the number of domestic installations. It is perceived that this will result in increased production and lower capital costs which will affect other markets for PV, such as non-domestic building installations. However, it should be emphasised that for a large non-domestic building to have an appreciable proportion of its electrical demand satisfied by PV, a very large system would be required. There is considerable uncertainty over the size of this end of the market.

D1.3.8 SOLAR THERMAL SYSTEMS

A solar thermal panel manufacturer provided supply and installation costs for the full solar thermal system. An allowance has been made by Thomson Bethune for additional builders work and preliminaries.

Efficiencies are likely to improve in the next 25 years, possibly through the use of integrated solar collectors (though such technologies are not yet market-ready). As the products achieve wider market penetration, it is imagined that installation and maintenance will become less of an issue, with measured performance likely to reach performance predictions (whereas currently there are issues with sub-optimal installation due to unfamiliarity with the product and poor integration with existing water heating systems). As with solar PV, efficiency per unit cost is the main metric governing the likely uptake of this technology.

It might be expected that there will be short term cost fluctuations in the cost of solar thermal systems. As these systems become more advanced, it is expected that their application will become more widespread, therefore increasing competition in the market. This will help level out any short term cost fluctuations which relate to improved product development.

D1.3.9 ONSITE WIND TURBINES

The quotations for this intervention were received from two sources, one for rooftop turbines and the other for larger, stand-alone devices. Thomson Bethune have made an allowance for preliminaries, builders work and installation of the smaller systems, added to the capital costs received from the manufacturers.

Building-integrated wind turbines are not likely to achieve large market penetration without a significant change in design, and reduction in the cut-in speed (i.e. the wind speed at which the turbine begins to produce electricity, typically 2.5-3m/s). With regards to this, there is some optimism in the area of vertical-axis wind turbines. However, unless independently verified performances improve, the use of small-scale wind is likely to be "near site" (e.g. school playing fields, in the region of 15kW and above) rather than building-integrated (such as 1.5kW rooftop systems). The issue of cost improvements are therefore somewhat secondary – the first barrier to widespread use of this technology is to improve the capacity factor in typical urban and suburban locations; otherwise it is likely to remain an expensive niche technology.

Therefore, demand for wind turbines is relatively low due the expensive nature of the product and the relatively low performance. If this technology is not improved greatly then it is expected that the cost of these systems will remain constant, but high. If the technology used in these systems were improved to a level which would make their widespread use more viable, then it is expected that the costs would be significantly reduced in the long term. This would occur as a result of increased demand, greater competition and the possibility of greater economies of scale in production.

D1.4 METHOD STATEMENTS

To be able to fully cost a measure, it is necessary to provide a certain level of detail for the installation of that particular technology. "Method statements" are used to provide a very general list of steps that would have to be carried out before and during the installation procedure. The technology-specific method statements are listed below, and relate to the refurbishment options used across all the variants in this report. The steps documented in these lists are also useful for highlighting installation requirements that are common across different measures, so that preliminaries could be reduced if measures were installed several at a time. This information emphasises that ease and cost of installation are major factors when assessing the feasibility of low-carbon refurbishment measures.

D1.4.1 REPLACING FLUORESCENT LIGHTING WITH LED LIGHTING

1. Isolate power to all lighting circuits
2. Remove existing light fittings and associated final circuits
3. Repair openings in plasterboard ceilings; fill openings and paint to match existing
4. Create openings in plasterboard ceiling for recessed LED down lighters
5. Install new lighting system in accordance with the manufacturers recommendations
6. Re-connect power to lighting circuits
7. Testing and Commissioning

D1.4.2 UPGRADING EXISTING BOILER HEATING SYSTEM

1. Disconnect water and gas supplies to existing boiler and drain system
2. Remove existing boiler(s), retaining distribution pipework and all other equipment
3. Fit new boiler(s), including any additional connections required to fit into existing distribution system
4. Re-connect gas and water system
5. Testing and Commissioning

D1.4.3 REPLACING EXISTING BOILER HEATING SYSTEM WITH AIR-SOURCE HEAT PUMP (ASHP)

1. Isolate power to existing electrical heating system
2. Remove heating system and all associated cabling etc
3. Form openings in external wall for all pipe work and cabling required
4. Install heat pump and compressor and all associated pipe work and outlets; and connect to electrical system
5. Testing and commissioning

D1.4.4 DRAUGHT-PROOFING OPENINGS

1. Fix draft-proofing strips to all openings in the external wall using adhesives/screw fixings etc. to suit the background material
2. Draught test all openings to ensure the rate of air change has been reduced to desired infiltration rate

D1.4.5 REPLACING EXISTING WINDOWS

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Remove and dispose of window unit, making good all surfaces disturbed
3. Elevate new window to the installation height and fit into existing opening

D1.4.6 APPLYING EXTERNAL CLADDING WITH INSULATION TO FACADE OF BUILDING

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Remove any existing finish applied to the external wall (e.g. render) and all rainwater downpipes etc
3. Perform 'Pull Test' to determine the strength of the wall and the number and type of fittings required
4. Attach base rails and surface profiles to walls
5. Place sheets of insulation on base rail and fix to wall. Work along the length of the base rail and then upwards, ensuring all joints are staggered
6. Apply a thin skim coat of cement to the insulation followed by reinforcing mesh
7. Fix all movement joints and corner/stop beads
8. Apply finishing coat of render

D1.4.7 APPLYING INTERNAL INSULATION TO WALLS OF BUILDING

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Remove existing plasterboard lining and any existing insulation.
3. Frame out walls with softwood timber framing to suit additional depth of insulation
4. Fix sheets of insulation to the walls, working around any existing services (e.g. pipework, cables etc.)
5. Apply plasterboard linings to timber framing, including the reveals and soffits of all windows
6. Replace window sills, if required, to suit new depth of the wall lining
7. Skim coat of plaster to new linings, followed by 3nr coats of emulsion

D1.4.8 INSTALLATION OF CAVITY-WALL INSULATION WHERE APPLICABLE

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Drill holes in mortar joints between brick courses at roughly one metre centres
3. Fill cavity by using compressed air to blow EPS bead through the drilled holes
4. Once the cavity is fully insulated, fill holes with mortar to match existing

D1.4.9 INSTALLATION OF ROOF INSULATION

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Remove and dispose of existing insulation from roof space (if applicable)
3. Cut insulation boards (such as expanded polystyrene) to fit between roof trusses, working around all existing services (e.g. light fittings, wiring, pipework etc.)

D1.4.10 INSTALLATION OF INSULATION BELOW GROUND FLOOR SLABS

1. Remove all fittings, furniture, partitions from the ground floor of the building
2. Lift existing floor finish and put aside for re-use
3. Breakout existing ground floor slab, disposing of all materials
4. Ensure ground is flat and free of and materials which could damage the insulation
5. Lay sheets of EPS board on flat ground surface
6. Cast new reinforced concrete slab
7. Once slab has cured, reinstate all partitions, floor finishes, furniture etc

D1.4.11 INSTALLATION OF SOLAR PHOTOVOLTAIC SYSTEM

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Attach mounting fixings through the supporting roof members by drilling through the roof covering and members from roof level, sealing around the fixing minimise moisture penetration
3. Drill all holes in roof – and upper floors if required – and feed cables through, sealing all openings to minimise moisture penetration
4. Connect metal frame to these mountings and elevate to required pitch
5. Assemble the Solar panel (if not pre-assembled) and hoist to roof level
6. Fix panel to frame
7. Connect the solar panel to the inverter and then into the existing distribution system
8. Testing and Commissioning

D1.4.12 INSTALLATION OF ROOFTOP WIND TURBINE(S)

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Attach mounting fixings through the supporting roof members by drilling through the roof covering and members from roof level, sealing around the fixing to minimise moisture penetration
3. Hoist wind turbine to roof level and bolt onto mountings
4. Connect turbine to inverter and wire into existing distribution system

D1.4.13 INSTALLATION OF STAND-ALONE SMALL WIND TURBINE

1. Contactor to provide suitable crane for lifting the turbine into place, excavator (if required) and all fencing required to isolate the trenches during excavation
2. Excavate trenches for reinforced concrete foundations and for any underground cables required
3. Lay cable ducts into trench, feed cables through the ducts and backfill with excavated material
4. Place mesh reinforcement and bolt cage into the foundation trench and pour the concrete
5. Once the concrete is cured, hoist the Tower into position with the crane, connecting all cables to those in the underground ducts
6. Bolt the tower into position and grout at the base
7. Connect the turbine and blades together and hoist into place
8. Connect the underground cabling to the inverter and wire into the existing distribution system

D1.4.14 INSTALLATION OF SOLAR THERMAL SYSTEM

1. Contractor to provide adequate working platform (Scaffolding, Mobile Elevated Working Platform, ladders etc. depending on specific variant requirements)
2. Attach mounting fixings through the supporting roof members by drilling through the roof covering and members from roof level, sealing around the fixing minimise moisture penetration
3. Drill all holes in roof - and upper floors if required – and feed supply and return pipework through, sealing around opening to minimise moisture penetration
4. Connect metal frame to the mountings and elevate to required pitch
5. Assemble the Solar panel (if not pre-assembled) and hoist to roof level
6. Fix panel to frame
7. Connect all pipework the existing hot water system
8. Testing and Commissioning

D1.4.15 INSTALLATION OF REFRIGERATION BLINDS (FOR SUPERMARKET)

1. Fix the back plate at the head of the cabinet with strong adhesive
2. Attach the blinds to the blind rail and slot into the back plate.
3. Fit capping piece over the blind rail to secure it in place.

D1.5 FINAL CAPITAL COSTS

With the above information and preliminary costs, the total capital costs can be estimated for each building variant. For clarity, as with section D1.2, the costs for a single variant (four-storey office variant) are given in detail followed by an overview of equivalent costs for all the non-domestic building variants considered.

The lighting refurbishment uses current LED costs, and so will appear substantial. Appendix IV provides an alternative cost based on the assumption that the lighting installation costs will, by 2030, be similar to current T5 fluorescent lighting installations.

D1.5.1 WORKED EXAMPLE OF TOTAL COST CALCULATION

The capital costs for refurbishing the four-storey office are given in Table 13, and assume that the measures are being installed individually (i.e. "individual work packages"). As quantified in section 1.2, the preliminary costs are subject to variation depending on the approach taken to refurbishing the building (see also section D1.5.2).

***Table 13** – Overview of total costs for refurbishing four-storey office (VO1) when measures are installed by individual work packages*

Description		Unit	Quantity	Rate (£ per unit)	Amount (£)	Running Total (£)
Lighting Replacing existing fluorescent lighting with LED installation	100 lux	m²	460	49	22,540	
	150 lux	m²	120	63	7,560	
	500 lux	m²	3,420	216	738,720	
	Builders work					
	Preliminaries	sum	1	7,035	7,035	
		TOTAL				775,855
Fabric and Boiler Replace existing boiler with condensing boiler (2Nr 147kW boilers)	Cost of Installation	nr	2	5,504	11,008	
	Builders work	nr	2	200	400	
	Preliminaries	sum	1	372	372	
		TOTAL				11,780
Draught strip all openings (reduce infiltration rate from 1ac/h to 0.5ac/h)	Cost of Installation	m²	4,000	1	4,400	
	Builders work					
	Preliminaries	sum	1	292	292	
		TOTAL				4,692
Replace double glazing with argon-filled triple glazing	Cost of Installation	m²	760	460	349,600	
	Builders work	m²	760	50	38,000	
	Preliminaries	sum	1	12,592	12,592	
		TOTAL				400,192
150mm EPS insulation to external face of wall with 13mm concrete render	Cost of Installation	m²	1,154	80	92,320	
	Builders work	m²	1,154		inc.	
	Preliminaries	sum	1	22,278	22,278	
		TOTAL				114,598
Replace mineral wool insulation in floor with 100mm EPS	Cost of Installation	m²	1,000	5	5,000	
	Builders work	m²	1,000	90	90,000	
	Preliminaries	sum	1	14,440	14,440	
		TOTAL				109,440
Replace mineral wool insulation in fat roof with 200mm EPS	Cost of Installation	m²	1,000	10	10,000	
	Builders work	m²	1,000	2	2,000	
	Preliminaries	sum	1	3,110	3,110	
		TOTAL				15,110
Heat recovery*	Cost of Installation	item	1	3,350	3,350	
	Builders work	item	1	1,500	1,500	
	Preliminaries	sum	1	1,400	1,460	
		TOTAL				6,310
Solar photo voltaic system	Cost of Installation	item	1	115,000	115,000	
	Builders work	item	1	1,500	1,500	
	Preliminaries	sum	1	850	850	
		TOTAL				117,350
Wind turbines	Cost of Installation	nr	10	6,500	65,000	
	Builders work	nr	10		inc.	
	Preliminaries	sum	1	1,500	1,500	
		TOTAL				66,500
Solar thermal panels	Cost of Installation	item	1	69,000	69,000	
	Builders work	item	1	2,000	2,000	
	Preliminaries	sum	1	1,500	1,500	
		TOTAL				72,500
					FINAL TOTAL (£)	**1,694,327**

**Mechanical ventilation heat recovery costs were found to be variable, with data difficult to obtain. The quoted value is a conservative estimate and subject to variation by building type.*

D1.5.2 OVERVIEW OF TOTAL COSTS FOR ALL VARIANTS

The final capital costs for all refurbishments across all variants are presented in Table 14 for measures installed as individual work packages. The two other installation options (using "joint work packages" and "single project" approach to reduce preliminary costs) are calculated in the same way and compared in Figure 34.

It is clear that the preliminary cost savings suggested in section D1.2 become less significant when seen compared to the capital cost of the entire refurbishment. In some cases, there might be economies of scale when sourcing materials from suppliers that are not included in this analysis but, generally, the overall cost of retro-fitting a wide range of technologies to a non-domestic building appears to be dominated by the capital cost of the technology itself.

Table 14 *– Overview of total costs for all non-domestic variants when installed by individual work packages*

Variant	Lighting	Fabric and boiler	Heat recovery	PV system	Wind turbines	Solar thermal	Refrigeration	Total
Offices								
VO1	£775,855	£655,812	£6,310	£117,350	£66,500	£72,500	N/A	£1,694,330
VO2	£644,250	£649,975	£6,310	£117,350	£52,000	£51,300	N/A	£1,521,190
VO3	£1,110,480	£269,044	£6,310	£177,850	£53,500	£104,500	N/A	£1,721,690
VO4	£1,110,480	£296,007	£6,310	£177,850	£53,500	£104,500	N/A	£1,748,650
VO5	£24,949	£52,367	£2,730	£20,350	£13,850	£5,500	N/A	£119,750
Schools								
VS1	£89,520	£44,035	N/A	£30,350	£13,850	£19,550	N/A	£197,310
VS2	£132,590	£120,792	N/A	£61,850	£13,850	£37,000	N/A	£366,090
VS3	£587,160	£348,186	N/A	£228,350	£79,575	£118,700	N/A	£1,361,980
VS4	£747,477	£414,350	N/A	£228,350	£78,925	£141,000	N/A	£1,610,110
Retail								
VR1	£13,415	£18,276	£2,730	N/A	N/A	N/A	N/A	£34,430
VR2	£45,325	£54,120	£4,260	£30,350	£13,850	N/A	£555	£148,460
VR3	£58,210	£118,448	£4,260	£30,350	£26,850	£13,650	N/A	£251,770
VR4	£2,587,506	£1,437,911	£10,760	£229,200	£80,225	N/A	£22,470	£4,368,080

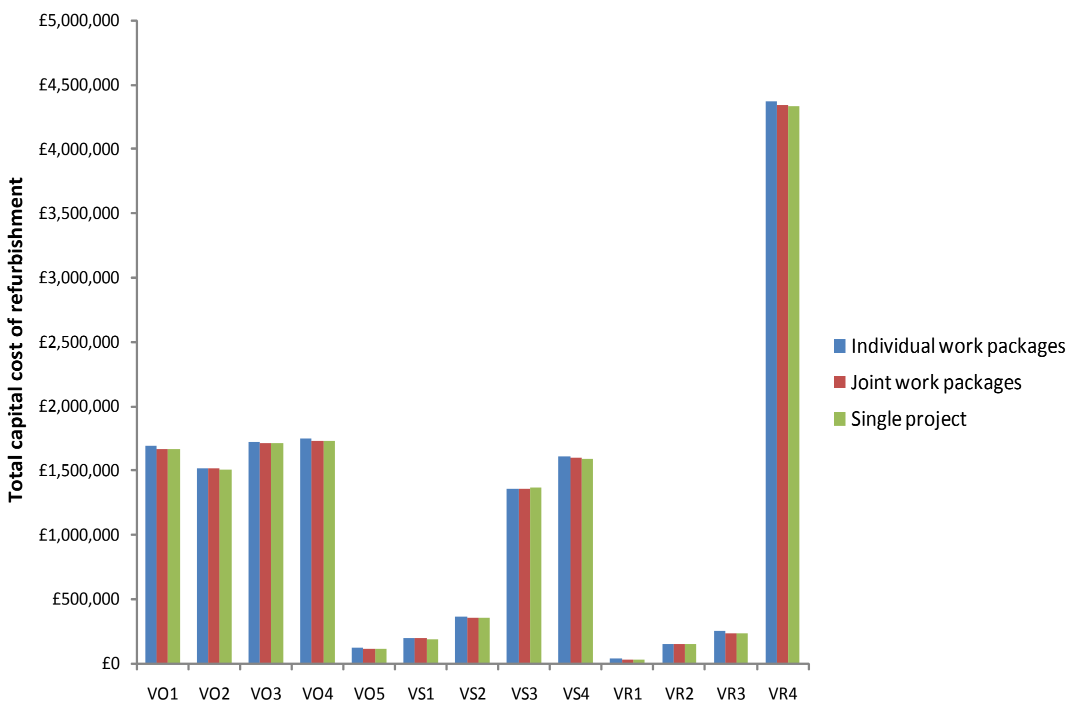


Figure 34 – Comparison of total costs for all non-domestic variants with three installation options

D2 WHOLE LIFE-CYCLE COSTING

Whole life-cycle (WLC) costing methodologies are used to ascertain the economic value of a technology over the course of its lifetime, and to investigate over what period of time these measures might become cost effective. WLC costs are calculated over a 30 year period, and include the cost of purchasing, installing, operating, maintaining and replacing all items associated with the interventions. These costs are offset against the benefits of reduced energy costs, relating to the energy consumption of different scenarios discussed throughout this report.

For illustrative purposes, the four-storey office (VO1) will be used to demonstrate the method used, though the same process could be used for any building.

D2.1 ASSUMPTIONS AND EXCLUSIONS

The following is a summary of the assumptions involved in the WLC calculations.

- All WLCC estimates are relative to the base case. The lifetime costs associated with this base case assume that carbon saving technologies have not been implemented. Within this scenario typical assumptions have been made concerning the condition of, and maintenance required for, the existing building
- Existing boilers will need to be replaced within 10 years of the project start. The cost of the new boiler installation is based on the boiler capital costs of the specific variant, less 20% reduction associated with installing a non condensing boiler
- Windows are to be replaced within 20 years of the project start. The cost of this installation has been calculated based on the glazing capital costs of the specific intervention less a 20% reduction associated with installing less thermal efficient windows
- Existing windows will be timber framed and will require re-painting regularly
- Boilers are to be serviced on an annually. This cost is expected to be greater than the cost of maintaining the new condensing boilers
- For the base case, it is assumed that the existing lighting system will be replaced with T5 fluorescent lighting within 20 years of the project start. The cost of this is based on the T5 lighting prices given in Appendix IV of this report, less a 20% learning rate. The lighting interventions for the refurbishment scenarios assume LED lighting costs, as described in section D1.5.
- It is assumed that fluorescent tubes and starters are replaced in every light fitting at 2 year intervals
- Energy costs have been fixed at current prices (dated April 2009)
- Discount rate (see section D2.2) is assumed at 3.5% per annum
- Inflation rate is assumed at an average of 2% per annum over a thirty year time period (in line with Bank of England targets, but subject to large uncertainties)
- Energy price volatility over time is not accounted for outside the above assumptions
- All costs are exclusive of VAT

D2.2 WORKED EXAMPLE OF WHOLE LIFE-CYCLE COSTING METHODOLOGY

The four-storey office variant (VO1) will now be used to demonstrate the methodology carried out for all building variants. The term "Net Present Value" (NPV) will be used to measure the performance of the various refurbishment packages and in this report it represents the whole life cost of the intervention cases and of the base cases (without intervention). WLC can be used for deciding, over a given lifetime, whether an action will be cost effective or not and can be calculated[41] by:

$$WLC = C_p + \sum_{t=0}^{n} \frac{C_t}{(1+d)^t}$$

(3)

where:

WLC = total cost implications of intervention set or base case expressed in net present value (NPV) terms.

C_p = initial capital cost. For each of the intervention sets, the cost of installation is estimated, making due allowance for additional costs associated with retrofitting to the existing variants.

n = number of years of the period of study. The TARBASE period of study is 25-30 years as previously described.

d = discount rate. A high discount rate favours technologies with low capital cost, short lifetime and high recurring cost, while a low discount rate will have the reverse effect[42]. Although Geller and Attali (2005)[43] report that studies evaluating energy efficiency technology usually use a discount rate of 4–8%, the Tarbase project adopts a discount rate of 3.5%, as this the figure recommended by HM Treasury (2003)[44] in the appraisal of any investment in the public sector.

C_t = sum of all relevant operational costs incurred over the 25-year period for each scenario. Energy costs – consumption of gas and electricity by the consumer – dominate this category. These are highest for the base case scenario where there is no energy reducing intervention. Costs in this category also include periodic and annual maintenance activities.

For each variant, the NPV is calculated for every refurbishment scenario, including the baseline. Table 15 shows the net present value for the baseline scenario for the four-storey office variant, which is the "value" in doing nothing to the building from an energy-saving perspective. Clearly there is no value for capital cost in this scenario as no technologies are being prescribed.

***Table 15** – Calculation of whole-life cycle costs for four-storey office variant (VO1) in baseline scenario*

	QTY	UNIT	RATE	COST	LIFE EXPECTANCY	2009	2010	2011	2012	2013	2014	...etc	2038
Initial Cost													
Capital Cost				£0		£0							
Operating Costs													
Gas	103319	KWh	£0.05	£5,166		£5,166	£5,269	£5,373	£5,476	£5,579	£5,683		£8,162
Electricity	495414	KWh	£0.10	£49,541		£49,541	£50,532	£51,523	£52,514	£53,505	£54,496		£78,275
Maintenance / Replacement													
Annual Maintenance													
Heating	1	sum	£900.00	£900		£900	£918	£936	£954	£972	£990		£1,422
Periodic Maintenance													
Lighting Install	997	Nr	£6.00	£5,983	2	£0	£6,103	£0	£6,342	£0	£6,582		£9,453
Glazing	760	m²	£7.50	£5,700	5	£0	£0	£0	£0	£6,156	£0		£9,006
Replacement													
Heating	1	sum	£9,424	£9,424	30	£0	£0	£0	£0	£0	£0		£14,890
Lighting Install	1	sum	£204,320	£204,320	20	£0	£0	£0	£0	£0	£0		£0
Glazing	1	sum	£320,154	£320,154	20	£0	£0	£0	£0	£0	£0		£0
One off Costs													
Replace existing boiler at end of lifespan	1	sum	£10,602	£10,602	10	£0	£0	£0	£0	£0	£0		£0
Revenue / Income													
Residual Value													
Grants / Subsidies													
Cash Flow						-£55,607	-£62,822	-£57,832	-£65,286	-£66,212	-£67,750		-£121,209
Cumulative Cash Flow						-£55,607	-£118,430	-£176,261	-£241,547	-£307,759	-£375,509		-£3,065,337
Discounted Cash Flow						-£53,727	-£58,645	-£52,161	-£56,893	-£55,749	-£55,114		-£43,184
Cumulative Discounted Cash Flow						-£53,727	-£112,372	-£164,533	-£221,426	-£277,175	-£332,289		-£1,738,046
Net Present Value				-£1,738,046									

The same calculation is then carried out for each refurbishment scenario. Table 16 gives an example of this in the first refurbishment scenario, which involves the installation of LED lighting. As already mentioned, this uses the higher capital cost of current LED lighting systems, though Appendix IV gives alternative costs based on LED lighting reaching the cost target of current best practice T5 fluorescent lights.

***Table 16** – Calculation of whole-life cycle costs for four-storey office variant (VO1) for refurbishment scenario 1 (installing LED lighting)*

	QTY	UNIT	RATE	COST	LIFE EXPECTANCY	2009	2010	2011	2012	2013	2014	...etc	2038
Initial Cost													
Capital Cost	1	sum	£775,855.00	£775,855		£775,855							
Operating Costs													
Gas	210322	KWh	£0.05	£10,516		£10,516	£10,726	£10,937	£11,147	£11,357	£11,568		£16,615
Electricity	171516	KWh	£0.10	£17,152		£17,152	£17,495	£17,838	£18,181	£18,524	£18,867		£27,100
Maintenance / Replacement													
Annual Maintenance													
Heating	1	sum	£900.00	£900		£900	£918	£936	£954	£972	£990		£1,422
Periodic Maintenance													
Lighting Install	1990	Nr	£98.00	£194,981	8	£0	£0	£0	£0	£0	£0		£0
Glazing	760	m²	£7.50	£5,700	5	£0	£0	£0	£0	£6,156	£0		£9,006
Replacement													
Heating	1	sum	£9,424	£9,424	30	£0	£0	£0	£0	£0	£0		£14,890
Lighting Install	1	sum	£620,684	£620,684	35	£0	£0	£0	£0	£0	£0		£0
Glazing	1	sum	£320,154	£320,154	20	£0	£0	£0	£0	£0	£0		£0
One off Costs													
Replace existi	1	sum	£9,424	£9,424	10	£0	£0	£0	£0	£0	£0		£0
Revenue / Income													
Residual Value													
Grants / Subsidies													
Cash Flow						-£804,423	-£29,139	-£29,710	-£30,282	-£37,009	-£31,425		-£69,033
Cumulative Cash Flow						-£804,423	-£833,562	-£863,272	-£893,554	-£930,563	-£961,988		-£3,153,463
Discounted Cash Flow						-£777,220	-£27,202	-£26,797	-£26,389	-£31,161	-£25,564		-£24,595
Cumulative Discounted Cash Flow						-£777,220	-£804,422	-£831,219	-£857,608	-£888,768	-£914,332		-£2,099,514
Net Present Value				-£2,099,514									

There is an additional complication in generating these figures. While recommending measures that would not otherwise be carried will have a clear capital cost, other carbon-saving measures in sections A and B are less straightforward. In particular, IT equipment changes are imagined to occur due to rapid turnover of computers and IT equipment in non-domestic buildings. Therefore, it could be argued that costing these interventions in a conventional way would be misleading – they are not energy efficiency measures they merely reflect the technology being updated. In the WLC estimates, these IT measures are essentially dealt with as an externality of a future scenario, in the same way as climate would be. The disadvantage of this approach is that the carbon-savings that come from these measures do not have a capital cost associated with them. This is a reiteration of the problem, mentioned in sections A and E, of defining "regulated" and "non-regulated" energy use; what energy use should be apportioned to the actual building, and therefore be of interest to a quantity surveyor approaching such a project?

Carrying out this process for all scenarios produces Figure 35. The refurbishment packages are numbered as follows (with specifics as detailed in Sections A and B):

- Base – this refers to the 2005 baseline without any energy-saving refurbishments applied
- Package 1 – Low-energy lighting refurbishment (including non-costed IT improvements)
- Package 2 – Fabric improvements and reduced infiltration
- Package 3 – Mechanical ventilation heat recovery
- Package 4 – Solar thermal hot water
- Package 5 – Solar photovoltaic panels
- Package 6 – Onsite wind turbine.

These numbered packages just relate to the four-storey office (VO1), with the choice of refurbishments being altered slightly for other variants (see section D2.3).

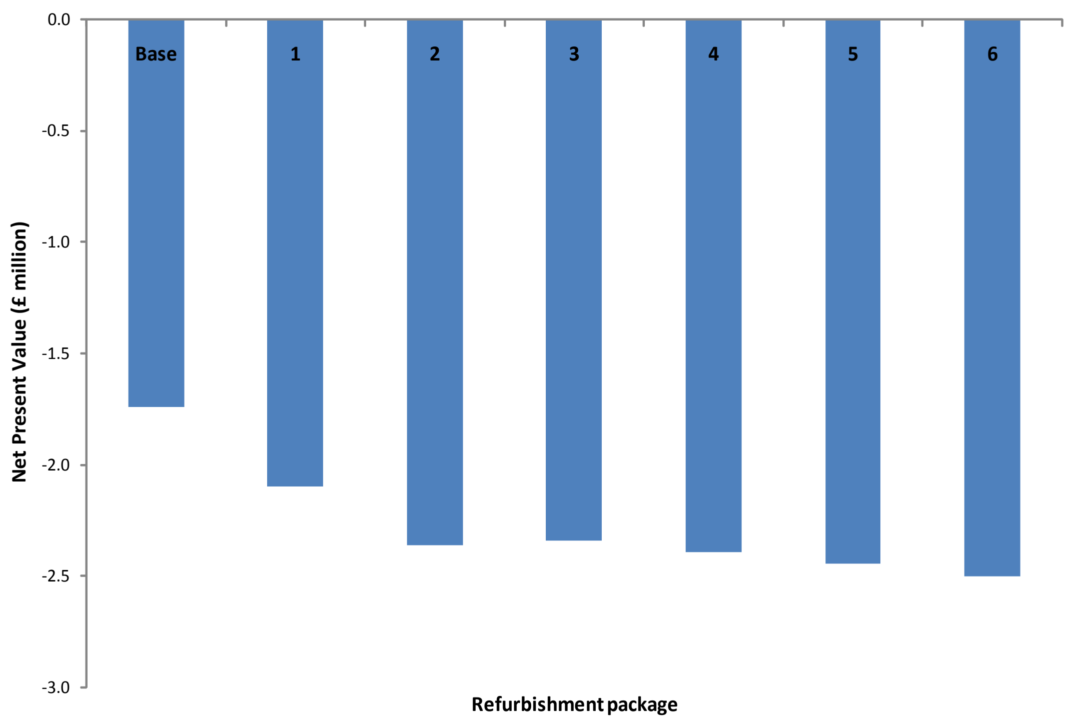


Figure 35 *– Net Present Value of cumulatively applied refurbishment packages for four story office variant (VO1)*

The results show that the economic justification for most of the packages is not strong, with all packages showing a negative net present value. Package 3 does show an improvement, implying that the addition of this measure (heat recovery) has resulted in a better long-term economic value than the previous scenario (package 2) where it was not applied. Also, this analysis does not include the added financial benefit that might emerge to the rental or purchase value of a property (as discussed in section D3).

Figure 36 interprets the effect of the refurbishment packages by comparing the energy saved (per year) with the additional total investment (compared with the baseline), which includes maintenance and operation costs. This curve shows a peak at the point where onsite generation is replacing energy efficiency measures; this confirms the supposition of demand-reduction measures being more cost effective than low-carbon building-integrated energy production in terms of energy saved per unit cost. As these measures are being applied cumulatively, the addition of onsite generation can be seen as causing a decline in this cost ratio.

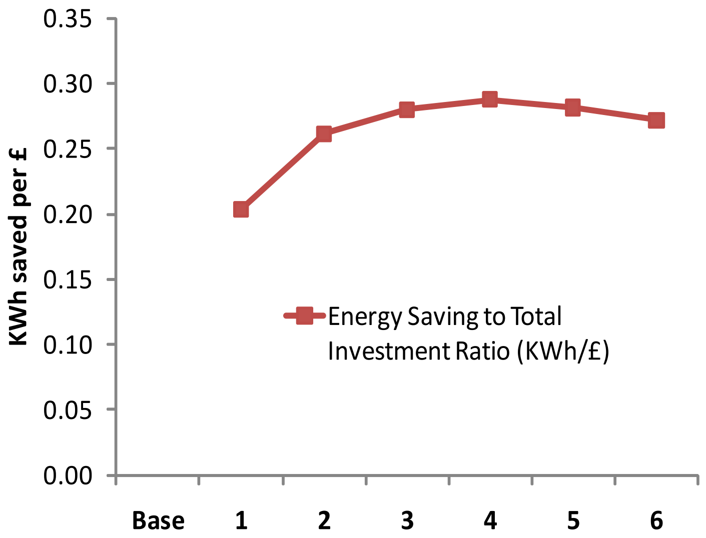


Figure 36 *– Energy saving per unit cost across all intervention packages for four-storey office variant (VO1)*

DATA ACQUISITION

Capital cost data was obtained from a variety of manufacturers, including the following, and their assistance is acknowledged:

- Alsecco
- Arthur McKay
- BCA group
- Bespoke Blinds Leeds
- CCF
- Commercial Blinds UK
- Dantherm
- eccleston & hart ltd.
- EJ Horrocks
- Energy Saving Trust
- Gazelle Wind Turbines
- Heat King
- Home Insulation Services
- Ideal Boilers (commercial)
- Nordan
- Philips
- Plum Centre
- Purlfrost
- Rationel
- Renewable Devices Swift Turbine
- Segen
- Sheerframe
- Slimlite
- Solartwin
- Swedish timber products
- Thorn Lighting
- Vencel
- Wetherby Building

D3 DRIVERS AND BARRIERS TO PURCHASING ENERGY EFFICIENT TECHNOLOGIES

In exploring the drivers and barriers for the uptake of energy efficiency in commercial buildings, we have focused on the office sector.

In the current economic crisis, it is plausible to think that businesses might have a limited availability of finances to spend on paying a premium for a rented building. Organisational slack, in terms of availability of funds and time of employees and managers, was found to be positively related to green innovations[45,46]; therefore in a time of diminished profits and shrinking organisations it is plausible to assume that this might hinder the progress towards more energy efficient buildings. This was also confirmed by two recent surveys: one found a limited availability of corporate property executives for paying a premium for sustainable rented space[47] and the other[48] found that the majority of small to medium enterprises (SMEs) surveyed don't have funds (62%) or time (61%) to invest in energy efficiency.

On the basis of the limited contribution of energy costs to overall business costs, it is certainly possible that companies might refrain from actively seeking an energy efficient building if the rental rates are higher than in more traditional buildings. Conversely, there might be an expectation of rapidly rising energy costs, which would rest on the evidence of a long term trend: between the year 1995 and the year 2008 the price of electricity rose approximately 84%[49]. On a shorter term, the increase between 2004 and 2008 was 97%. This expectation is reasonable and was confirmed by the Npower[48] survey of British SMEs and major energy users (MEUs) which reports that the majority of the sample, 300 British businesses surveyed, expected energy prices to increase. Businesses could therefore be more readily enticed into achieving energy savings because of this expected energy price increase. Nevertheless, the extent of this price increase is uncertain and energy forecasts have often been considered deficient[50,51], providing information of little use for a reliable WLC analysis. As a result of the combination of these pressures on businesses we could expect to see the effort to curb energy consumption resting mainly on low-cost strategies, such as behavioural change and optimisation of facilities. This seems to be confirmed by the Npower survey already cited[48].

Despite these general economic arguments appearing reasonable, other intangible benefits in choosing a sustainable office should not be underestimated, at least for large and visible businesses. In a survey carried out in 2007 for the Tarbase project[52] it was found that a further significant factor positively influencing companies' interest in sustainability was the reputational gain deriving from adopting sustainable business policies. This is not in itself surprising; the presence of increased business opportunities for those engaged in Corporate Social Responsibility (CSR) and Sustainability has been an object of research for many years[53]. Research has shown clear that not all companies are equally exposed to such benefits (and costs): retail companies[54,55] and larger businesses[56,57,58] that have a more direct relationship with their consumers can be particularly affected, positively or negatively, by reputational gains or losses.

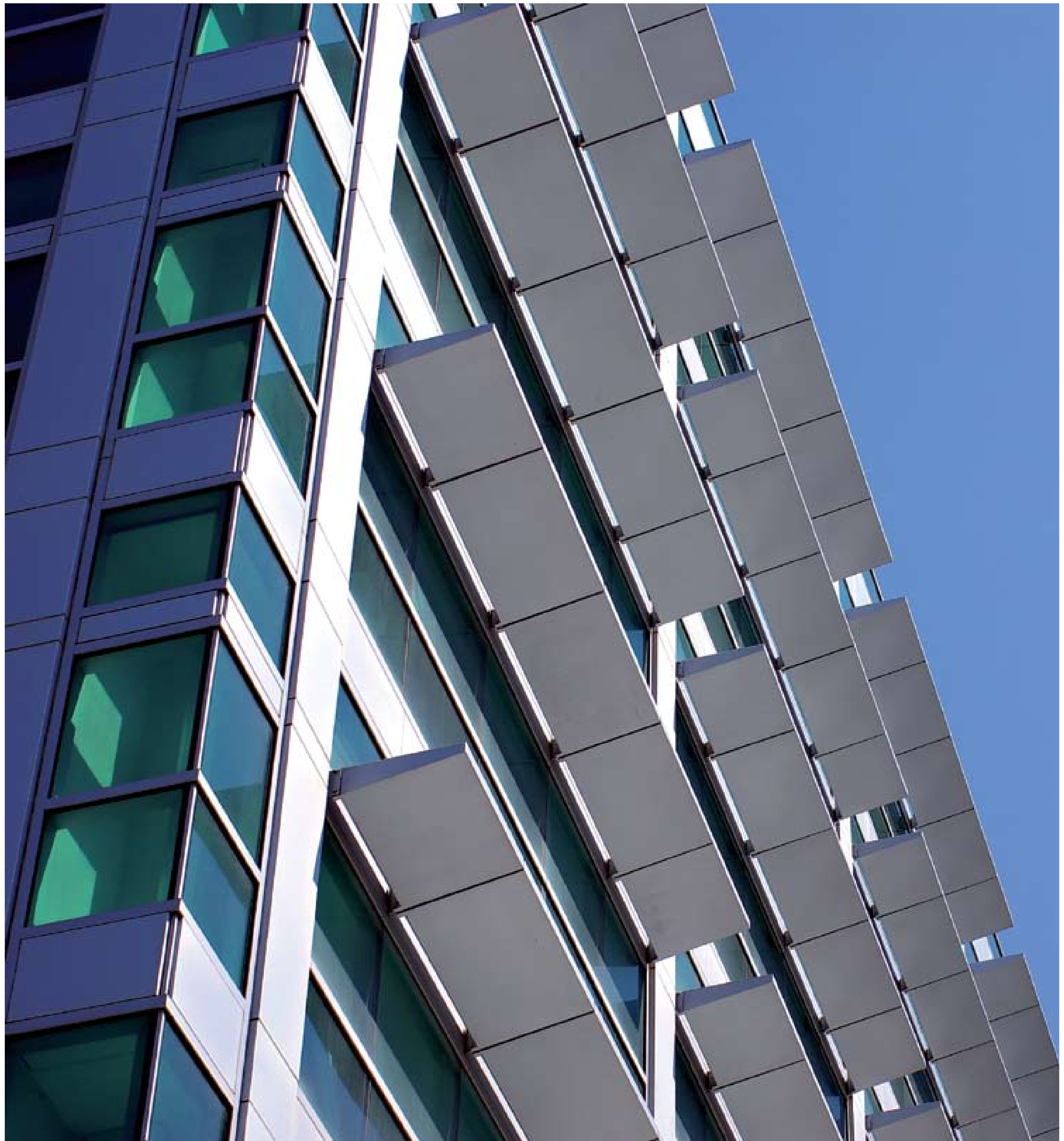
The Tarbase survey[52] of office market stakeholders presented an analysis of the factors influencing business decision-making with regard to the pursuit of energy efficient office space. In July 2007 twenty-one interviewees were surveyed through sixteen semi-structured interviews held in London, Glasgow and Edinburgh. The interviewees consisted of ten surveyors (eight based in London and two in Glasgow) and two technical consultants based in London (one the head of the facilities management department of an international consultancy firm). The remaining respondents were members of businesses and office occupiers based in Glasgow, with the exception of one respondent based in Edinburgh. Office occupier respondents were consisted of an operations and property manager, a CSR officer, two environmental officers, three facility managers and a facility manager assistant. The interviews were chiefly conducted with letting surveyors because of their privileged position in the market which mediates between the demand and the offer of office space.

While the full extent of the theoretical background and the findings of the survey are presented elsewhere[52] the main conclusions will be summarised here. Firstly, all the subjects surveyed showed an awareness and sensitivity to energy efficiency. There was also a broad consensus about the general awareness of market actors and a growing demand for energy efficiency was reported. Nevertheless interviewees reported a lack of willingness to pay more for energy efficient rented offices: this finding is consistent with the 2009 survey of Jones Lang LaSalle[46]. Despite this, interviewees pointed to the growing importance of reputational drivers which would be influencing investors and large occupiers towards an increased pursuit of energy efficient office space. Increased reputation would influence occupiers positively, attracting both customers and investors. Furthermore, it was found that employees in some cases had promoted their own energy saving behavioural initiatives. This is consistent with the widespread pro-environmental attitudes which surveys have repeatedly found within the British public[59,60]. This might be hinting at the reason why it has been found in research that "corporate greening" increases organisational commitment[61] and attractiveness of skilled jobseekers[62,63] an issue that was also reported by respondents in the Tarbase survey of office market stakeholders.

Tarbase survey respondents considered investors as being under pressure from their shareholders, who might request a CSR agenda for the investing institution and who also might see sustainable buildings as a better value investment in the long term: these issues also emerged in British[64,65] American[66] and Australian[67] surveys. Despite these combining forces on investors and occupiers conducive to increased energy efficient offices, the Tarbase survey found that occupiers lacked the willingness to spend more for sustainable offices, and this fact might have been even reinforced by the 2008-2009 economic crisis.

If this is indeed the case, it could be difficult for investors to give in to the pressure of shareholders and stakeholders. Nevertheless, recent research on the US building stock[68,69,70,71] has found that energy efficient offices return a rental premium in comparison with non-energy efficient buildings. It is difficult to say if the British market will follow, or is already following, the American trends. Certainly the scale of the investment required to abate emissions in office buildings might be regarded as significant for owner-occupiers who are dealing with the crisis. It is perhaps more likely that investor-owners will be the actors leading the change, possibly investing in energy efficient technology when they have to refurbish the buildings within their portfolios. The necessary refurbishment might be an opportunity to reduce the costs of installation and it might engender a total cost which is generated mainly by the difference between current conventional technologies, which during a refurbishment need to be installed anyway, and energy efficient solutions. This idea is supported by the estimations in section D2. If we take package 4, with all the technologies preceding it, the total refurbishment cost equates to £229/m^2 of total floor area (increasing to £293/m^2 for package 6). Renovations of buildings can take many forms, and so costs will naturally vary considerably. However Rawlinson and Wilkes[72] give figures of £300-825/m^2 (using gross, rather than total, internal floor area) for a minor refurbishment, with a "category A" major refurbishment costing £1,450-2,100/m^2. While such refurbishments include a range of improvements not considered in the Tarbase analysis (such as carpets/flooring, stairwell and other aesthetic improvements), these figures do provide an indication as to the expected cost of making a major change to a building. It also gives credence to the idea that carbon-saving refurbishments might be more successfully promoted if other, non-energy, benefits were highlighted for carrying out a major refurbishment; very large sums of money are already spent on building renovations that are not expected to pay back through improved "building performance", but rather have added value to the image and running of that particular organisation.

SECTION E
Conclusions of the non-domestic sector



The points below summarise the findings of the Tarbase study on non-domestic buildings:

- Non-domestic buildings are generally, across the stock, non-homogeneous and different solutions apply to different sectors.

- Even within each sector, particularly the retail sector, homogeneity does not really exist and so benchmarks of energy use can often be misleading. Likewise, solutions to carbon savings should be tailored to specific buildings.

- Internal activity is key to all non-domestic buildings, but particularly offices. The use of IT equipment and lighting directly causes substantial carbon emissions, but also causes internal heat gain profiles that are fundamental to understanding how to heat and cool the building effectively. In the temperate climate of the UK, excessive non-domestic cooling loads are mostly the result of internally generated heat. Altering these profiles, through energy management and technology selection, is vital to achieving large-scale carbon savings but such measures completely change the approach to choosing HVAC and building fabric refurbishments – for example, a cooling-dominated office will require a different strategy to a heating-dominated office. This problem is more difficult to define due to the distinction between "regulated" and "non-regulated" energy consumption. Such terms, the former involving building-related energy consumption such as HVAC and the latter describing activity-related consumption such as IT equipment, suggest that it is possible to dissociate the energy use of buildings from the energy use of people within the building. This, unfortunately, is not possible and it is crucial to understand this complexity.

- Improving small power and lighting efficiency in the non-domestic sector should be the first step (before HVAC and building fabric measures) to reducing carbon emissions. In addition to the previous point, it is far more economical and has a greater chance of success for all non-domestic buildings.

- A large proportion of the carbon emissions associated with small power and lighting are due to poor energy management (i.e. leaving equipment on overnight and the weekend). IT equipment should have software installed to enable automatic switch-off when idle, which can be achieved while allowing for regular software downloads as required by the IT management of the organisation.

- Future trends of energy use need to be managed within the school sector – if internal temperatures (and other internal environment factors) become unsuitable for teaching environments, then mechanical cooling and ventilation will become the norm for many schools, particularly in the south of the UK. This will have a noticeable carbon penalty – but it is a penalty that can be avoided (or substantially reduced) through intelligent building design and the correct choice and management of IT equipment and lighting.

- The outlook for lighting energy consumption in the non-domestic sector is generally positive, with fluorescent lighting improving and future LED technologies predicted to have very high efficacies with suitable colour rendering. However, technologies such as halogen lighting (used for aesthetically popular GU10-fixture spotlights) are becoming popular within the retail sector and should be discouraged. Halogen lights in particular are often advertised as "energy savers", but this is only true compared to poor-efficacy incandescent lights.

- Supermarket display refrigerators, with open fronts, are extremely inefficient (due to heat gain from the surrounding air) and are responsible for large carbon emissions in the food retail sector. They also substantially contribute to heating energy consumption due to indirect cooling.

- Non-domestic onsite energy generation will only achieve significant carbon savings (relative to the buildings they serve) if very large systems are installed. The current status of some of these technologies, particularly rooftop wind turbines, does not make them an effective and reliable carbon-saving measure (though, in the case of vertical-axis wind turbines, improvements in cut-in speeds and capacity factor may be possible). Most options are currently difficult (or impossible) to justify economically and will not produce carbon savings on the same scale as measures relating to small power, lighting and HVAC. The issue of onsite generation should be just one part of an integrated approach to low-carbon energy provision that involves consideration of offsite energy production and the implementation of onsite technologies with the existing network infrastructure (and should account for the often improved efficiency of near-site/district solutions as opposed to building-integrated). As with the domestic sector, the goal should be an overall reduction in the carbon intensity of delivered energy – identifying niche technologies for small markets will not help achieve the ambitious carbon savings targets that we are currently trying to meet.

- While energy management and some current market technologies have clear potential for reducing carbon emissions of non-domestic buildings, there does not appear to be a strong economic justification, in the short term, for installing some of the technologies required for larger scale carbon savings (particularly beyond 50%). The conclusion is based on both capital and whole-life cycle cost analyses which indicated that many of the refurbishments, when taken in combination with other measures, have high installation costs and negative net present values over their lifetime. This makes the funding and implementation of these measures particularly difficult – the attraction for stakeholders and managers of non-domestic buildings is not currently strong enough to imagine the suite of technologies described in this report being installed en masse throughout the country.

- Economic analyses of building-related technologies are subject to uncertainties, particularly when attempting to future-cast costs of emerging technologies that are not yet market-ready. Learning rates and capital cost reductions of these technologies needs to be considerable; such improvements are likely to require substantial extra funding in terms of research, development and, ultimately, actual installation. Such economic analyses are also clearly reliant on discount and inflation rates, which are assumed to be 3.5% and 2% respectively in this study, and are themselves subject to large uncertainties year-on-year. Further uncertainties about future energy prices should be remembered when putting such figures into context.

- The project identified some non-energy benefits that might encourage the adoption of some of the described measures. In some sectors, there is an indication that the added monetary and aesthetic value of a "green" building is significant from the point of view of the organisation occupying that building, be they owner occupiers or tenants. These factors need to be further exploited as, for many buildings, modest energy bill savings are unlikely to be large enough drivers for stock-wide refurbishments in the private sector.

- Carbon dioxide reduction targets of greater than 50% are highly challenging for existing non-domestic buildings. This is particularly true when the proposed solutions are being imagined for a large percentage of the stock, not just a few exemplar buildings. Surpassing these targets and looking at the goal of "net-zero" carbon for existing non-domestic buildings is probably a distraction that misses a more fundamental problem – electrical energy use in non-domestic buildings has to be tackled from the demand-side before looking at any supply-side options. The majority of buildings will not, even by 2030, be able to satisfy their electrical energy use through PV, wind and CHP alone without firstly reducing that energy demand. Large carbon savings will not be achieved without dramatically changing the way buildings are used, particularly in relation to small power and lighting usage. The ambitious policy targets for non-domestic energy use are not currently commensurate with the actual empirical trends of this usage.

Appendix I

SMALL POWER EQUIPMENT LISTS

***Table A** – Summary of small power equipment used in baseline office variants*

	VO1		VO2		VO3		VO4			
	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)
PC	286	106480	214	79674	386	143711	386	143711	15	5585
Monitor	286	59661	214	44642	386	80522	386	80522	15	3129
Fax machine	15	1980	11	1452	20	2640	20	2640	1	132
Laser Printer	96	15840	72	11880	129	21285	129	21285	5	825
Scanner	15	573	11	420	20	764	20	764	1	39
Photocopier	15	16207	11	11885	20	21610	20	21610	1	1080
Servers/ network	n/a	8716	n/a	7683	n/a	8706	n/a	8706	n/a	1152
Phone lines	286	1704	214	1275	386	2299	386	2299	15	77
Vending machine	6	5028	3	2514	6	5028	6		2	1989
Coffee maker	5	4030	2	1612	6	4836	6	4836	1	806
Kettle	5	3898	4	3119	18	14034	18	14034	2	1559
Fridge-freezer	4	2593	2	1296	3	1945	3	1945	1	648
Dishwasher	3	526	2	350	3	526	3	526	-	-
Microwave	4	526	2	263	3	394	3	394	1	131
Water dispenser	8	2803	4	1402	6	2102	6	2102	1	350
Lift	1	1742	1	1742	1	1742	1	1742	-	-
Shredder	3	105	2	70	6	210	6	210	1	35
Security camera	2	1402	4	2803	6	4205	6	4205	1	701
Hand dryer	15	1971	8	1051	12	1577	12	1577	2	263
UPS	-	-	1	429	1	429	1	429	-	-
TOTAL (kWh/yr)		235785		175562		318565		313537		18501
TOTAL (kWh/m2)		58.9		58.5		59.0		58.1		123.3

***Table B** – Summary of small power equipment (including refrigeration) used in baseline retail variants*

	VR1		VR2		VR3		VR4	
	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)
Small Cash till	-	-	2	350	3	172	8	7008
Checkout till	-	-	-	-			26	54662
Credit Card Processor	-	-	-	-	3	43	26	1139
Illuminated sign	-	-	-	-	1	678	-	-
PC	5	1951	1	390	3	1224	50	20406
Monitor	5	1242	1	248	3	865	50	14419
Fax machine	1	132	-	-	1	132	7	924
Laser Printer	2	330	1	165	1	165	14	2357
Scanner	1	39	-	-	-	-	-	-
Photocopier	1	1080	-	-	1	1080	7	7563
Servers	n/a	767	-	-	n/a	18	n/a	3385
Shredder	1	35	-	-	-	-	-	-
Franking machine	1	55	-	-	-	-	-	-
Phone lines	2	12	4	6	3	18	25	149
UPS	-	-	-	-	-	-	1	429
Refrigeration	-	-	Multiple	50853	-	-	Multiple	1049558
Freezer units	-	-	Multiple	27353	-	-	Multiple	1025741
Chilled storage rooms	-	-	-	-	-	-	Multiple	367920
Kettle	1	780	1	333	1	780	8	6237
Water dispenser	1	350	-	-	1	350	4	1402
Microwave	-	-	1	131	1	131	4	526
Coffee maker	-	-	-	-	-	-	4	3224
Staff Fridge-freezer	-	-	-	-	1	648	-	-
Staff cooker	-	-	-	-	-	-	2	2184
Dishwasher	-	-	-	-	-	-	2	350
Security systems	1	701	1	876	2	1752	55	41347
Hand dryer	-	-	1	131	2	263	16	2102
Weighing Scales	-	-	7	58	-	-	10	1752
Radio/Hi-Fi	1	60	1	60	2	860	-	-
Iron	-	-	-	-	2	148	-	-
Meat Slicer	-	-	-	-	-	-	4	109
Decorative lighting	1	137	-	-	2	274	-	-
Hoover	1	63	-	-	1	76	2	1372
TV	-	-	-	-	1	19	20	10030
VCR	-	-	-	-	1	4	10	2278
Electric door	-	-	-	-	1	316	4	21854
Clock	-	-	-	-	3	105	5	131
Air curtain	-	-	-	-	-	-	2	151200
Amusement Ride	-	-	-	-	-	-	2	1475
Lift	-	-	-	-	1	1742	1	1742
Instore bakery	-	-	-	-	-	-	n/a	224398
TOTAL (kWh/yr)		7734		80954		11863		3029373
TOTAL (kWh/m2)		128.9		539.7		26.4		276.7

***Table C** – Summary of small power equipment (and cooking) used in baseline school variants*

	VR1		9408VR2		VR3		VR4	
	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)	Number of appliances	Total energy usage (kWh/yr)
PC	20	4625	33	7632	184	42553	255	58973
Monitor	20	3124	33	5155	184	28905	255	39837
Fax machine	1	132	2	264	3	396	4	528
Laser Printer	5	825	10	1650	30	4950	35	5775
Scanner	1	39	1	39	5	192	7	267
Photocopier	2	2161	4	4322	8	8644	10	10805
Servers/network	n/a	767	n/a	767	n/a	1568	n/a	1568
Phone lines	4	24	5	30	6	60	15	89
Vending machine	-	-	1	1840	4	4354	4	4354
Coffee maker	1	806	1	806	3	2418	4	3224
Kettle	1	780	2	780	5	3898	5	3898
Fridge-freezer	1	648	1	648	3	1945	4	2593
Dishwasher	1	175	1	175	2	350	2	350
Microwave	1	131	1	131	3	394	5	657
Water dispenser	2	701	3	1051	8	2803	12	4205
Shredder	1	35	1	35	2	70	3	105
Security camera	2	1402	2	1402	5	3504	6	4205
Hand dryer	4	526	6	788	12	1577	15	1971
Lift	-	-	1	1742	1	1742	2	3484
Electronic whiteboard	-	-	2	468	6	1404	9	2106
Extractor fans (kitchen)	n/a	375	n/a	956	n/a	3447	n/a	4573
TOTAL (kWh/yr)		17276		30681		115174		153567
TOTAL (kWh/m2)		20.6		24.7		15.2		16.7
School cooking (elec)*	n/a	693	n/a	1764	n/a	6363	n/a	8442
School cooking (gas)*	n/a	3696	n/a	9408	n/a	33936	n/a	45024

**Cooking within school kitchen estimated from design guide[32]*

Appendix II

EFFECT OF GRID CARBON INTENSITY ON CO_2 SAVINGS

The main carbon saving estimations of this work assume a grid carbon intensity of 0.52kgCO_2/kWh. The following graphs are the result of a simple sensitivity analysis on grid carbon intensity, showing how it can affect the target of 50% carbon savings. Green bars indicate the intervention strategy has achieved a 50% carbon saving target (compared to the blue baseline) while red indicates failure to achieve this. Details of the intervention packages are also given in Appendix III.

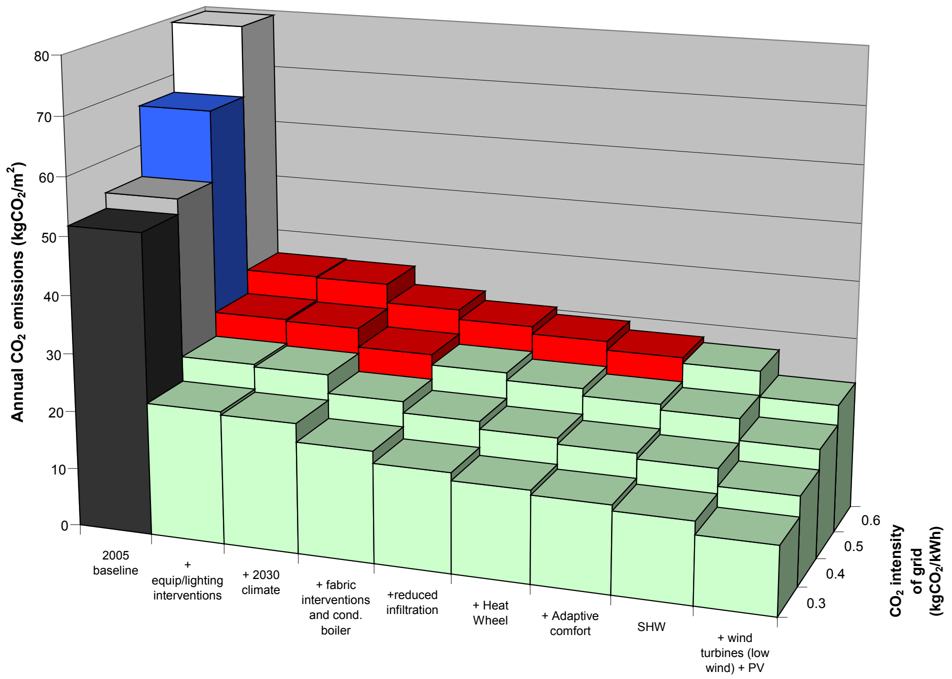


Figure A *– CO_2 emissions of 4-storey office variant (VO1) with grid carbon intensity*

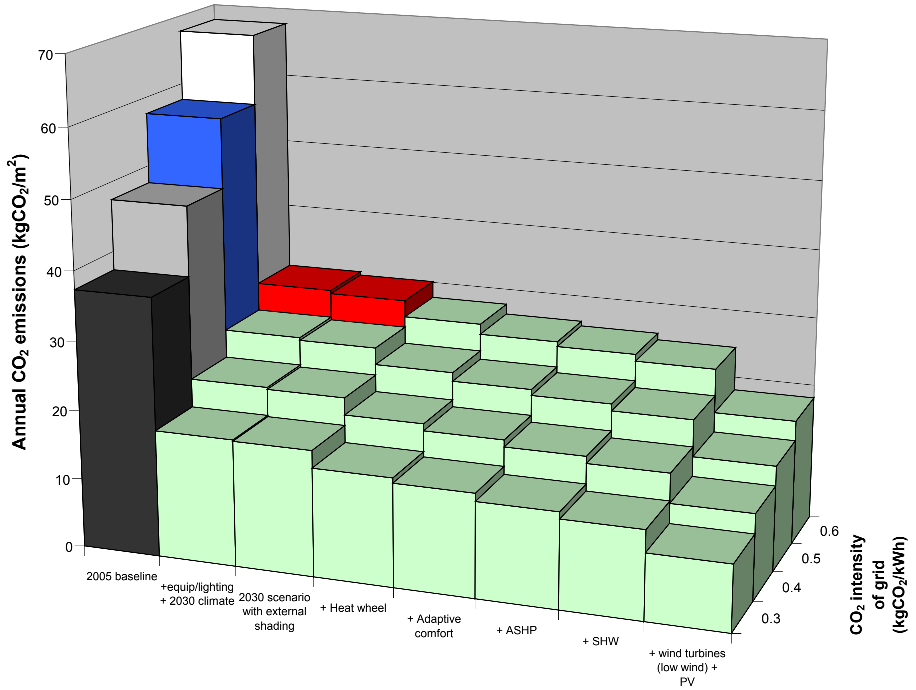


Figure B *– CO_2 emissions of 5-storey office variant (VO2) with grid carbon intensity*

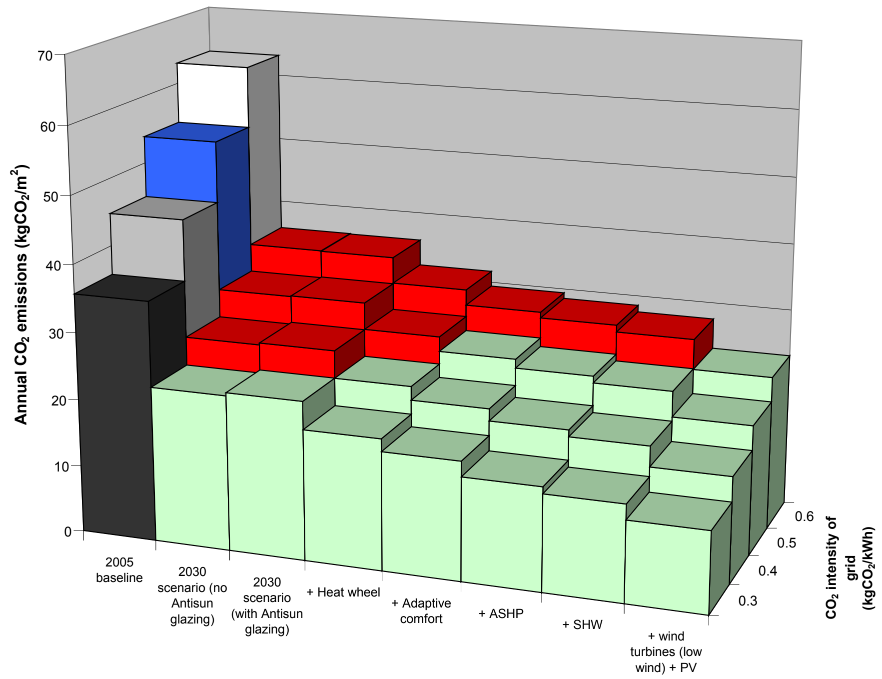


Figure C *– CO_2 emissions of 6-storey deep-plan office variant (VO3) with grid carbon intensity*

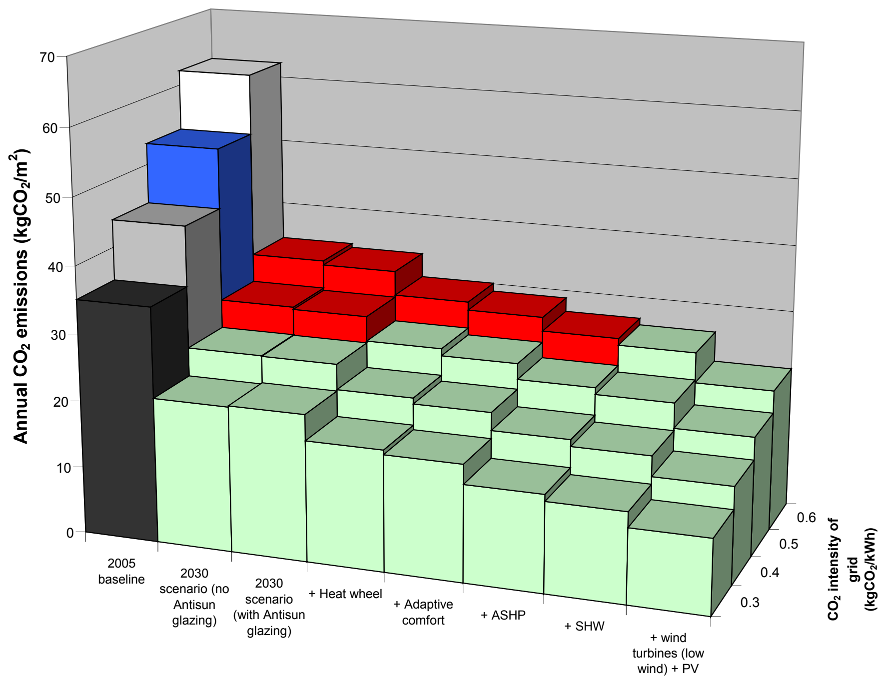


Figure D *– CO2 emissions of 6-storey shallow-plan office variant (VO4) with grid carbon intensity*

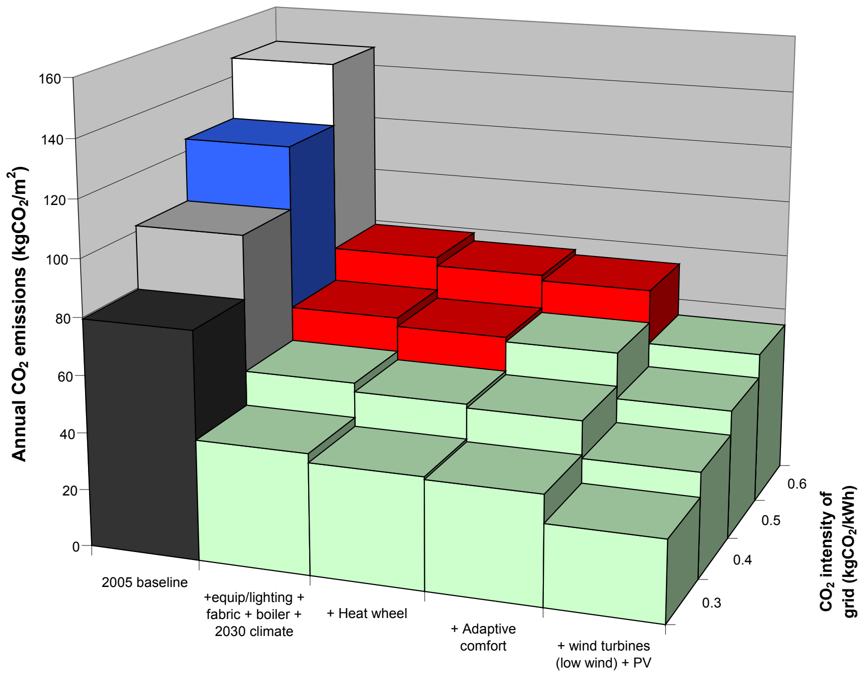


Figure E – CO_2 emissions of small high street office variant (VO5) with grid carbon intensity

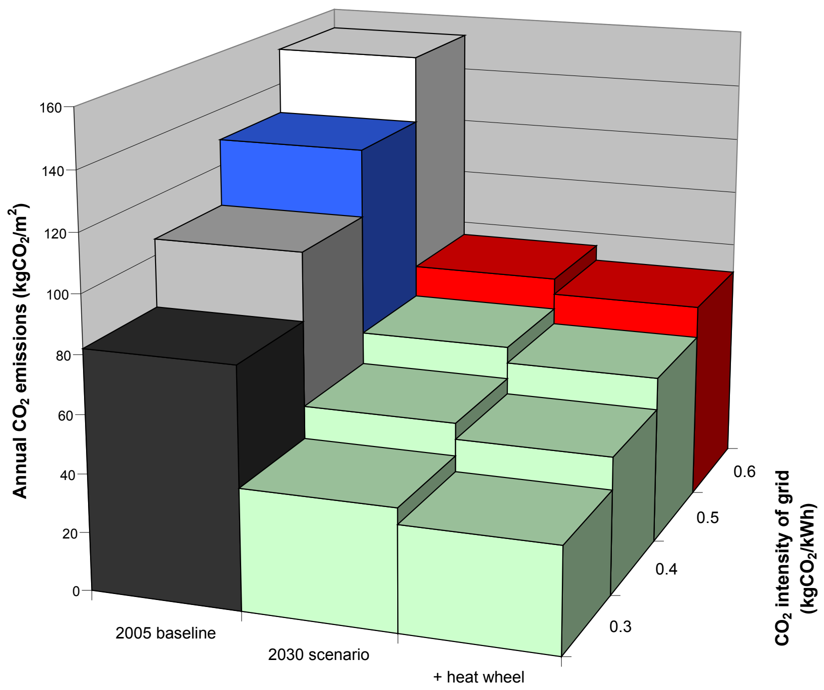


Figure F – CO_2 emissions of estate agent retail variant (VR1) with grid carbon intensity

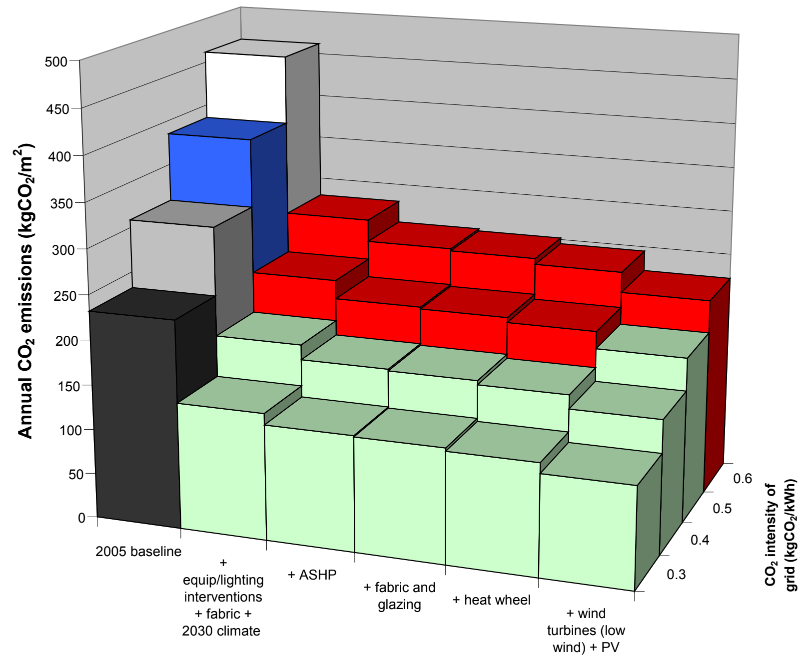


Figure G – CO_2 emissions of convenience store retail variant (VR2) with grid carbon intensity

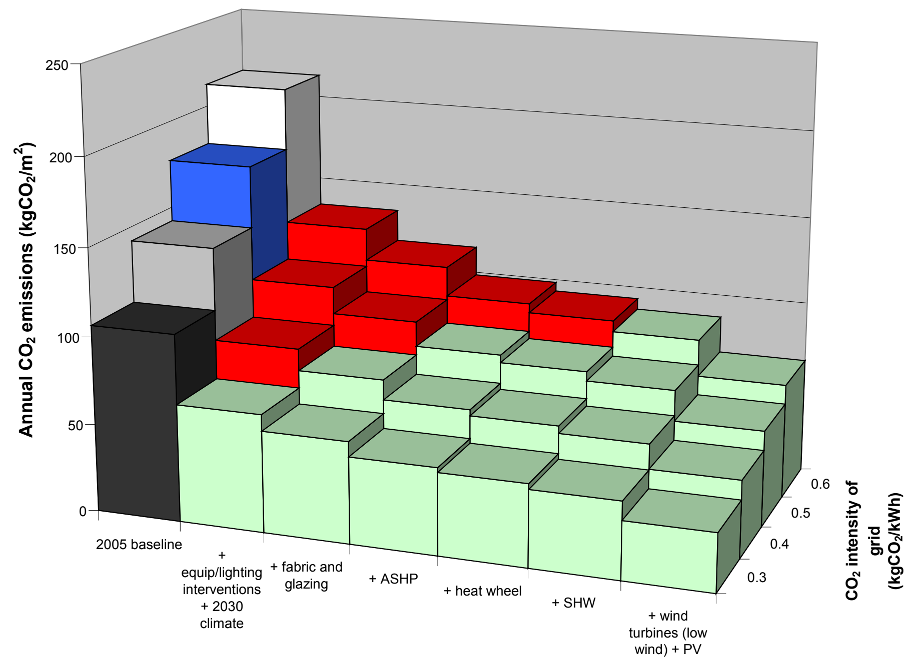


Figure H – CO_2 emissions of clothes shop retail variant (VR3) with grid carbon intensity

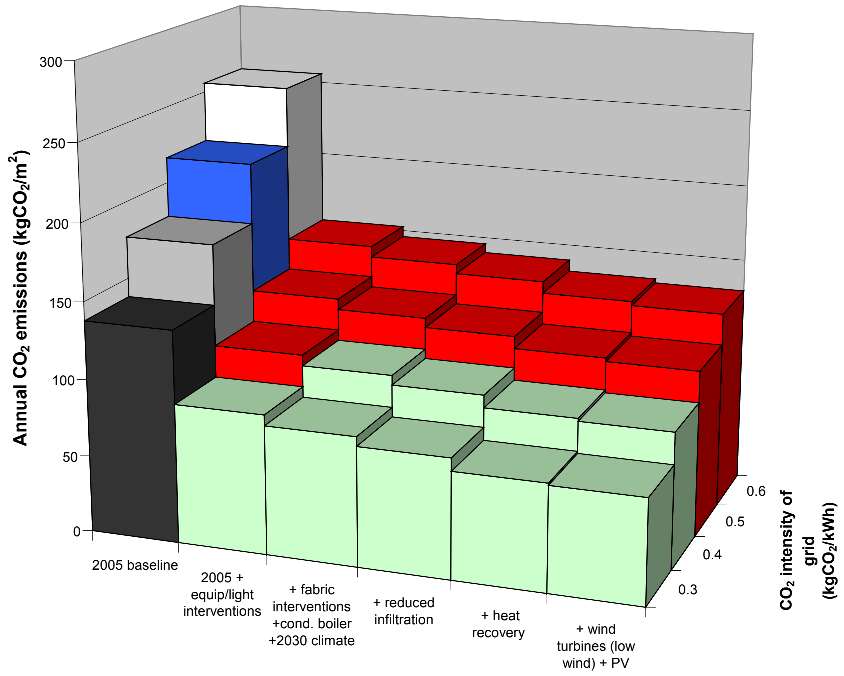


Figure I *– CO2 emissions of supermarket retail variant (VR4) with grid carbon intensity*

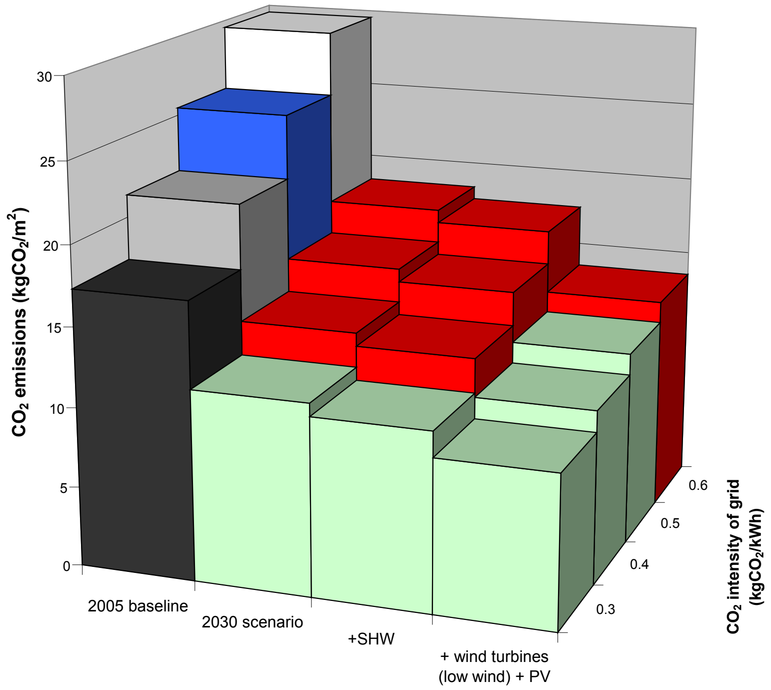


Figure J *– CO2 emissions of small primary school variant (VS1) with grid carbon intensity*

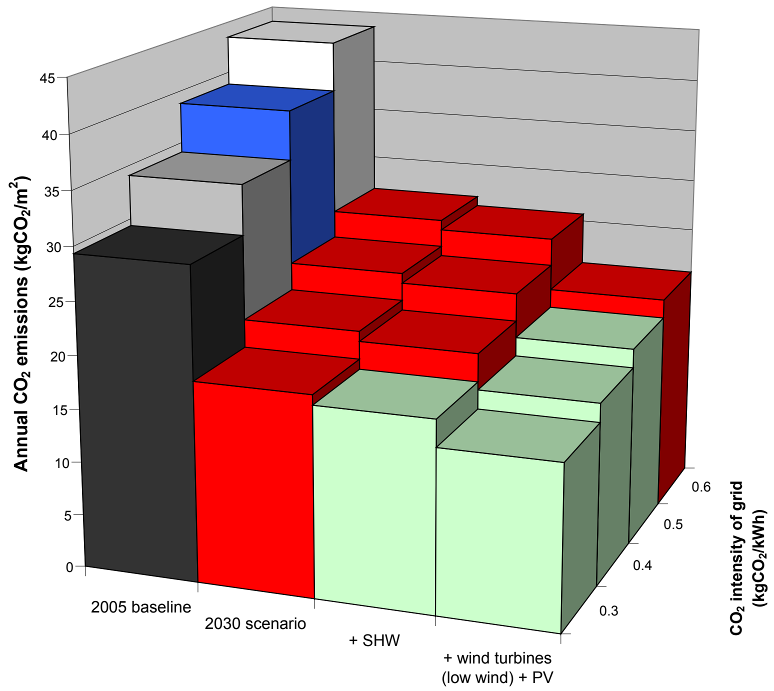


Figure K *– CO2 emissions of medium primary school variant (VS2) with grid carbon intensity*

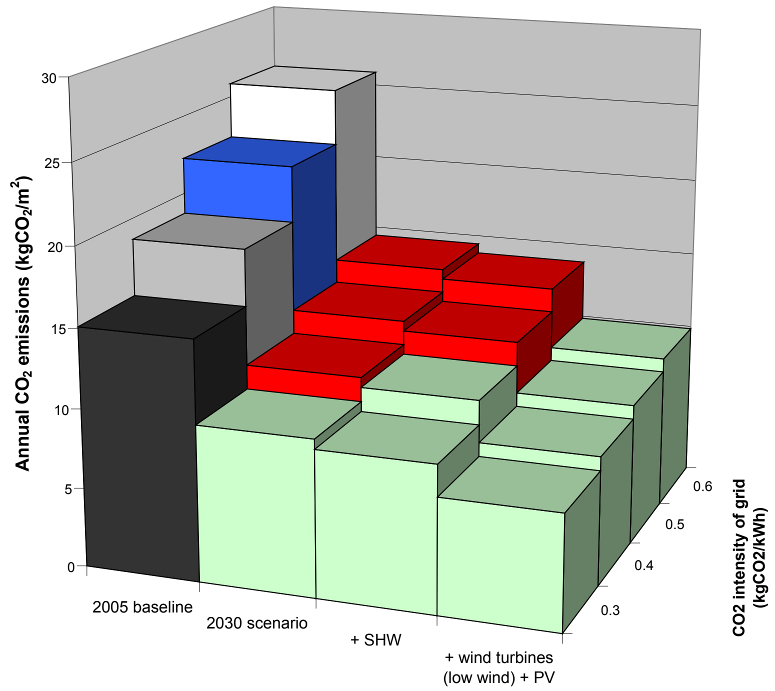


Figure L *– CO2 emissions of medium secondary school variant (VS3) with grid carbon intensity*

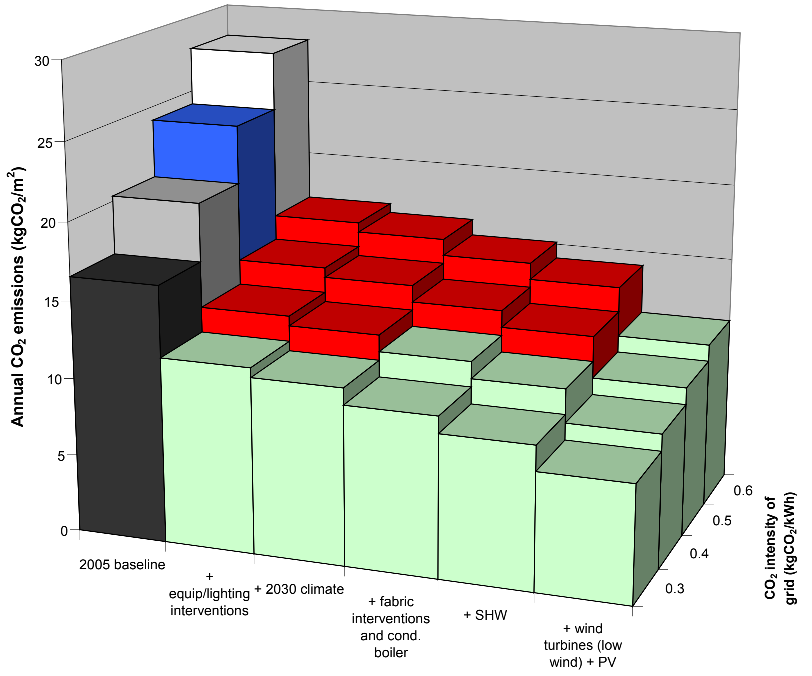


Figure M *– CO2 emissions of large secondary school variant (VS4) with grid carbon intensity*

Appendix III

OVERVIEW OF INTERVENTION SETS FOR ALL NON-DOMESTIC VARIANTS

Table D *– List of carbon-saving technologies used across all non-domestic building variants*

	Interventions applied to non-domestic buildings					
	Small power/end-use	**Lighting**	**Building fabric****	**Glazing**	**HVAC**	**Onsite generation*****
4-storey office (VO1)	See Table 1	LED lighting (150lm/W*) replacing combination of fluorescent technolgies (70-100lm/W)	External expanded polystyrene (150mm) with concrete render; Reduced infiltration rate (1.0ach to 0.5ach)	Triple-glazed argon windows, low-e coating	New gas condensing replacing non-condensing boilers; reduction in internal heat gains; mechanical ventilation heat recovery; adaptive comfort	200m^2 monocrystalline PV; 10 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
5-storey office (VO2)			Internally applied expanded polystyrene (100mm)	Single-glazing replaced with thin double glazing, low-e coating		200m^2 monocrystalline PV; 8 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Deep plan 6-storey office (VO3)				Anti-sun film applied to existing double-glazing		300m^2 monocrystalline PV; 8 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Shallow plan 6-storey office (VO4)						
Small office (VO5)						30m^2 monocrystalline PV; 2 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Estate agent (VR1)						No rooftop available
Convenience Store (VR2)	As above and covers applied to refrigeration		Internally applied expanded polystyrene (100mm); Reduced infiltration rate (1.0ach to 0.5ach)	Single-glazing replaced with thin double glazing, low-e coating	As above but air-source heat pump replacing existing electric radiant heaters	50m^2 monocrystalline PV; 2 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Clothes Shop (VR3)	Office IT improvements	LED lighting replacing combination of fluorescent and halogen lights	External expanded polystyrene (150mm) with concrete render	Triple-glazed argon windows, low-e coating		50m^2 monocrystalline PV; 4 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Supermarket (VR4)	As above and covers applied to refrigeration	LED lighting replacing mercury discharge lighting and fluorescents	Expanded polystyrene (80mm) or similar applied to internal cavity; Reduced infiltration rate (1.0ach to 0.5ach)		Condensing boiler installed and heat recovery from refrigeration units; reduce indirect cooling from refrigeration	400m^2 monocrystalline PV; 1 x 20kW wind turbines
Small primary school (VS1)	One low power laptop per child; no desktops; no increase in electronic whiteboards	LED lighting replacing combination of fluorescent technolgies (70-100lm/W)	External expanded polystyrene (150mm) with concrete render	No changes to existing double-glazing	New gas condensing replacing non-condensing boilers; reduction in internal heat gains	50m^2 monocrystalline PV; 2 x 1.5kW rooftop wind turbines; 50% of hot water met by solar thermal
Medium primary school (VS2)			Internally applied expanded polystyrene (100mm)			As above but 100m^2 of PV
Medium secondary school (VS3)			External expanded polystyrene (150mm) with concrete render			400m2 monocrystalline PV; 1 x 20kW wind turbine; 50% of hot water met by solar thermal
Large secondary school (VS3)						

**or lighting of similar efficacy*
***insulation also added to roof and floors*
****deliberately optimistic systems sized to allow for improved future yields*

Appendix IV

ALTERNATIVE COSTS USING T5 FLUORESCENT LIGHTING COSTS

Table E is a version of Table 14 but with LED lighting costs assumed to have reached parity with current T5 fluorescent lighting (i.e. one of the most efficient, commonly used lighting technologies in non-domestic buildings).

***Table E** – Overview of total costs for all non-domestic variants when installed by individual work packages with alternative lighting costs*

Variant	Lighting	Fabric and boiler	Heat recovery	PV system	Wind turbines	Solar thermal	Refrigeration	Total
Offices								
VO1	£255,400	£655,812	£6,310	£117,350	£66,500	£72,500	N/A	£1,173,880
VO2	£213,430	£649,975	£6,310	£117,350	£52,000	£51,300	N/A	£1,090,370
VO3	£364,620	£269,044	£6,310	£177,850	£53,500	£104,500	N/A	£975,830
VO4	£364,620	£296,007	£6,310	£177,850	£53,500	£104,500	N/A	£1,002,790
VO5	£8,750	£52,367	£2,730	£20,350	£13,850	£5,500	N/A	£103,550
Schools								
VS1	£53,190	£44,035	N/A	£30,350	£13,850	£19,550	N/A	£160,980
VS2	£78,470	£120,792	N/A	£61,850	£13,850	£37,000	N/A	£311,970
VS3	£341,520	£348,186	N/A	£228,350	£79,575	£118,700	N/A	£1,116,340
VS4	£433,750	£414,350	N/A	£228,350	£78,925	£141,000	N/A	£1,296,380
Retail								
VR1	£5,030	£18,276	£2,730	N/A	N/A	N/A	N/A	£26,040
VR2	£14,950	£54,120	£4,260	£30,350	£13,850	N/A	£555	£118,090
VR3	£19,860	£118,448	£4,260	£30,350	£26,850	£13,650	N/A	£213,420
VR4	£832,160	£1,437,911	£10,760	£229,200	£80,225	N/A	£22,470	£2,612,730

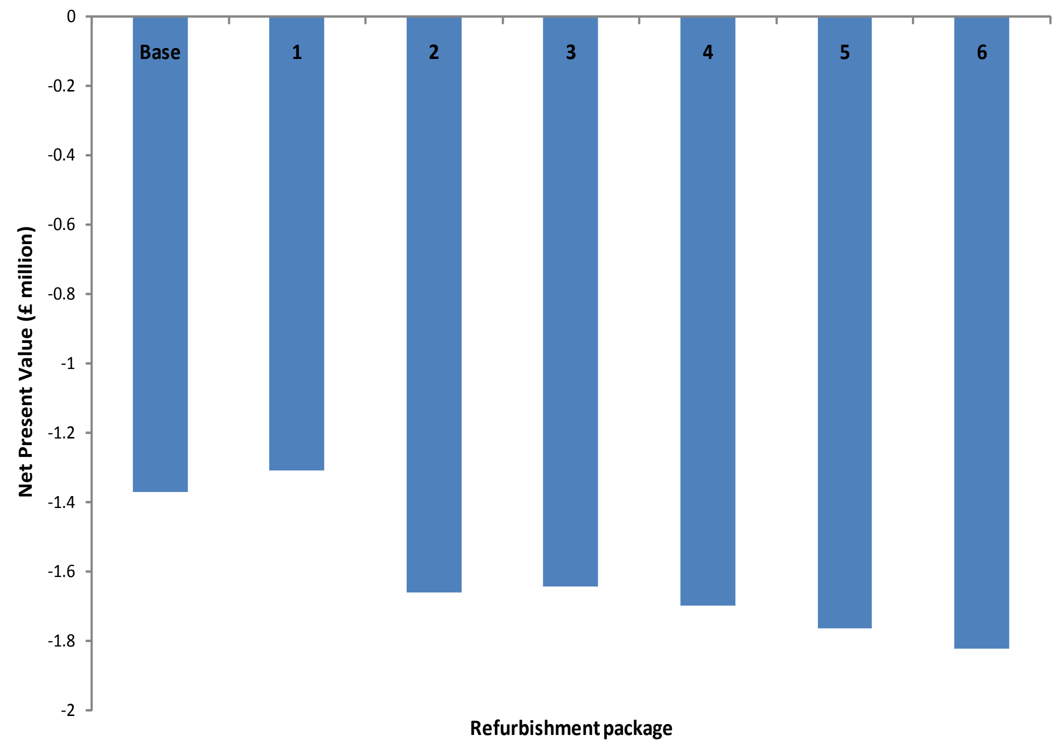


***Figure N** – Net Present Value of cumulatively applied refurbishment packages of four-storey office variant with alternative lighting costs*

Figure gives the NPV estimations with alternative lighting costs for the four-storey office variant. The most obvious change is the difference in NPV between the base case and scenario 1 (i.e. the lighting refurbishment scenario). Due to the reduced capital cost there is now a long-term economic justification, seen by an improved NPV, in installing low-energy lighting throughout the building.

As a lighting refurbishment is not a novel alteration to make to a building, it is possible to imagine future costs based on current costs, in this case imagining that LED lighting will be of a similar cost to fluorescent lighting at some point in the future. With more novel technologies, such as onsite generation, this extrapolation is more difficult as the data does not exist for any current equivalent (e.g. solar photovolatics are not installed en masse and so future costs for their installation are difficult to quantify).

This example does, however, show that future-casted capital costs are highly sensitive to economic analyses of technologies. It is suggested that the logical conclusion of such work would be to identify threshold conditions where, for a given refurbishment, the capital cost required to achieve an improved NPV is given. This would show at what point the measure becomes economic.

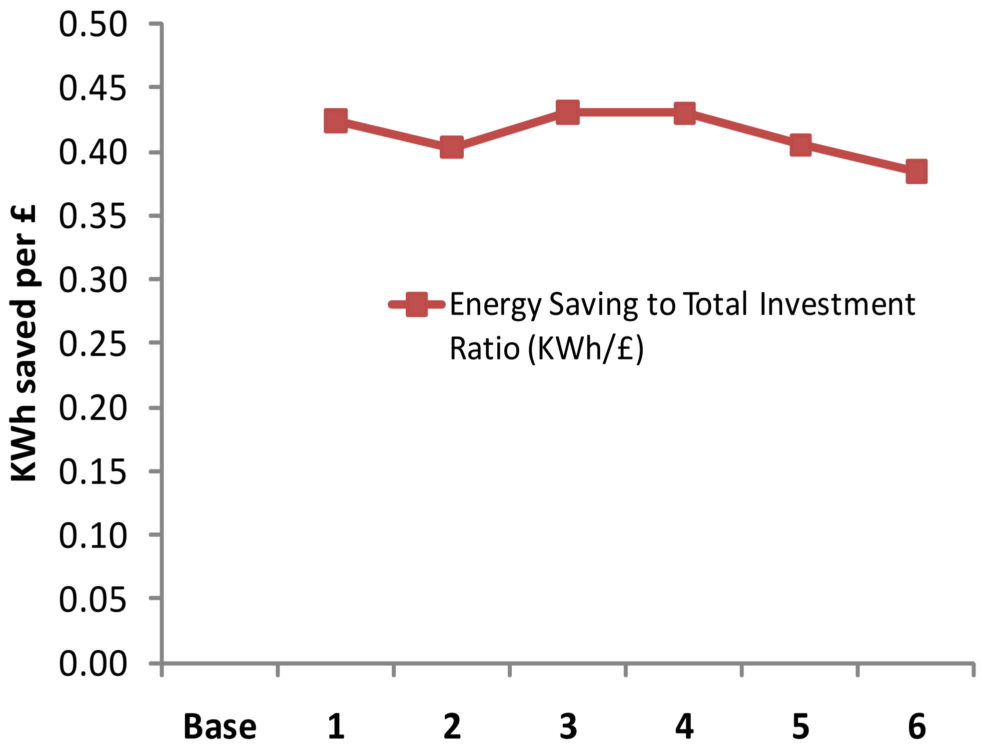


***Figure O** – Energy saving per unit cost across all intervention packages for four-storey office variant with alternative lighting costs*

Finally, Figure O gives an alternative to Figure 36. Again, this shows the improved cost performance of the LED lighting when costed equally with T5 fluorescent lighting. Refurbishment package 1 providing over 0.4kWh of energy saving per pound of total investment cost compared with 0.2kWh for the more expensive lighting used in Figure 36.

References

(ENDNOTES)

1 B.K. Schmidt, M.S. Lam and J.D. Northcutt, The interactive performance of SLIM: a stateless, thin-client architecture, Operating Systems Review, 34, 32-47, 1999

2 P. Chou, M. Gruteser, J. Lai, A. Levas, S. McFaddin, C. Pinhanez, M. Viveros, D. Wong and S. Yoshihama, IBM Research Report – Bluespace: Creating a Personalized and Context-Aware Workspace, RC22281 (WO112-044), December 11th 2001, *http://domino.research.ibm.com/library/cyberdig.nsf/papers/5D4286C1228AD04A85256BC3006C7191/$File/rc22281.pdf*

3 K.W. Roth, F. Goldstein and J. Kleinmann, Energy Consumption by Office and Telecommunications Equipment in Commercial Buildings, Arthur D Little, December 2004

4 Roberson et al, After-hours Power Status of Office Equipment and Inventory of Miscellaneous Plug-Load Equipment, Lawrence Berkeley National Laboratory, University of California, January 2004

5 W-S. Choi and M-K. Kim, Effect of small liquid crystal molecules on the driving voltage of cholesteric liquid crystal displays, Displays 25(5), 2004

6 D.P. Jenkins and M. Newborough, An approach for estimating the carbon emissions associated with office lighting with a daylight contribution, Applied Energy 84(6), 2007

7 D.R.G. Hunt, Availability of Daylight, Building Research Establishment (1979)

8 D.A. Steigerwald, J.C. Bhat, D. Collins, R.M. Fletcher, M.O. Holcomb, M.J. Ludowise, P.S. Martin and S.L. Rudaz, Illumination with Solid State Lighting Technology, IEEE Journal on Selected Topics in Quantum Electronics 8(2), 2002

9 S.C. Allen and A.J. Steckl, ELiXIR – Solid-state luminaire with enhanced light extraction by internal reflection, Journal of Display Technology, 3, 155-159, 2007

10 Chartered Institute of Building Services Engineers (CIBSE), Environmental Design, CIBSE Guide A, 2006

11 C. Wilkins and M. Hosni, Heat gain from office equipment, ASHRAE Journal 42(6), 2000

12 Chartered Institute of Building Services Engineers (CIBSE), Heating, CIBSE Guide B1 (2006)

13 J. Clarke, Energy Simulation in Building Design (2nd edition), Butterworth-Heinemann, 2001

14 American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Fundamentals Handbook, Service Water Heating, Ch. 49, 2001

15 UK Government Department for Communities and Local Government (DCLG)/UK Green Building Council (UKGBC), Report on carbon reductions in new non-domestic buildings, DCLG/UKGBC December 2007

16 D.P. Jenkins, The importance of office internal heat gains in reducing cooling loads in a changing climate, International Journal of Low-Carbon Technologies, 4, 134-140, 2009

17 D. Jenkins, Y. Liu and A.D. Peacock, Climatic and internal factors affecting future UK office heating and cooling energy consumptions, Energy and Buildings, 40, 874-881, 2007

18 D.P. Jenkins, H. Singh and P.C. Eames, Interventions for large-scale carbon emission reductions in future UK offices, Energy and Buildings, 41, 1374-1380, 2009

19 D.P. Jenkins, The importance of office internal heat gains in reducing cooling loads in a changing climate, International Journal of Low-Carbon Technologies, In Press 2009

20 D.P.Jenkins, A.D.Peacock and P.F.G.Banfill, Will future low-carbon schools in the UK have an overheating problem?, Building and Environment 44, 2008, 490-501

21 D.P.Jenkins, Using dynamic simulation to quantify the effect of carbon-saving measures for a UK supermarket, Journal of Building Performance Simulation 1, 2008, 275-288

22 F.Nicol and M.Humphreys, Maximum temperatures in European office buildings to avoid heat discomfort, Solar Energy 81, 2007, 295-304

23 H.B. Rijal, P. Tuohy, F. Nicol, M.A. Humphreys, A. Samuel, and J. Clarke, Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings, Journal of Building Performance Simulation, 1, 17-30, 2008

24 S.E. Belcher, J.N. Hacker and D.S. Powell, Constructing design weather data for future climates, Building Services Engineering Research and Technology 26(1), 2005

25 Chartered Institution of Building Services Engineers (CIBSE)/UK Meteorological Office (Met Office), Test Reference Year Hourly Weather Data, CIBSE/Met Office October 2005

26 Building Bulletin 87, Guidelines for Environmental Design in Schools, UK Government Department for Education and Skills 2003

27 T. Karimipanah, H.B. Awbi, A. Sandberg and C. Blomqvist, Investigation of air quality, comfort parameters and effectiveness for two floor-level air supply systems in classrooms, Building and Environment, 42, 647-655, 2007

28 R. Becker, I. Goldberger and M. Paciuk, Improving energy performance of school buildings while ensuring indoor air quality ventilation, Building and Environment, 42, 3261-3276, 2007

29 Chartered Institution of Building Services Engineers (CIBSE), Climate change and the indoor environment: impacts and adaptation, CIBSE Technical Memorandum 36, 2005

30 American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Humidity Effects on Supermarket Refrigerated Case Energy Performance: A Database Review, ASHRAE Transactions, Vol. 111, Part 1, 2005

31 Market Transformation Programme (MTProg), Energy Consumption Modelling for Commercial Refrigeration – Summary, 2006

32 P.G. Jones et al, Energy Benchmarks for Public Sector Buildings in Northern Ireland, CIBSE 2004

33 S. Taylor, A. Peacock, P. Banfill and L Shao, Reduction of greenhouse gas emissions from UK hotels in 2030, Building and Environment, 45, 1389-1400, 2010

34 A.D. Peacock, D.P. Jenkins, M. Ahadzi, A. Berry and S. Turan S., Micro Wind Turbines in the UK domestic sector, Energy and Buildings, Volume 40, 1324-1333, 2008

35 D.P. Jenkins, J. Fletcher and D. Kane, A model for evaluating the impact of battery storage on microgeneration systems in dwellings, Energy Conversion and Management 49, 2413-2424, 2008

36 Wind shear formula for extrapolating wind velocity data to other altitudes for given roughness conditions

37 D.P. Jenkins, R. Tucker, M. Ahadzi and R. Rawlings, The performance of air-source heat pumps in current and future offices, Energy and Buildings, 40, 1901-1910, 2008

38 D.P. Jenkins, R. Tucker and R. Rawlings, Modelling the carbon-saving performance of domestic ground-source heat pumps, Energy and Buildings, 44, 587-595, 2009

39 UK Department of Environment, Food and Rural Affairs (DEFRA), Standard Assessment Procedure for Energy Rating of Dwellings (SAP), 2005

40 UK Department of Environment, Food and Rural Affairs (DEFRA), Guidelines to DEFRA's GHG conversion factors for company reporting, 2007

41 Boussabaine, A. and Kirkham, R. (2004) Whole Life-Cycle Costing: Risk and Risk Responses, Blackwell, Oxford.

42 D.G. Woodward (1997) Life cycle costing -theory information acquisition and application. International Journal of Project Management, 15(6), 335-44.

43 H. Geller and S. Attali (2005) The experience with energy efficiency policies and programmes in IEA countries, International Energy Agency. [Online] Available from: *http://www.iea.org/textbase/papers/2005/efficiency_policies.pdf [Accessed June 2009].*

44 HM Treasury (2003) The green book: appraisal and evaluation in central government. [Online] Available from: *http://www.hm-treasury.gov.uk/media/3/F/green_book_260907.pdf* [Accessed June 2008].

45 F.E. Bowen, Organizational Slack and Corporate Greening: Broadening the Debate. British Journal of Management. 13, 305-316, 2002

46 P. Bansal, Evolving sustainably: a longitudinal study of corporate sustainable development. Strategic Management Journal, 26,197-218, 2005

47 Jones Lang LaSalle. Perspectives on Sustainability. 2009 [cited 13/01/10]; Available from: *http://www.joneslanglasalle.com/ResearchLevel1/JLL_Perspectives_on_Sustainability_CRE_2009_Final.pdf.*

48 Npower. Npower business energy index 2009. 2009 [cited May '09]; Available from: *http://www.npower.com/prod_contribb/groups/wcms_content/@wcms/@resi/documents/digitalassets/npower_buiness_energy_index_6.pdf.*

49 UK Department of Energy and Climate Change (DECC). Table 5.3.1 Industrial electricity prices in the EU and the G7 countries. 2009 [cited 18.01.10]; Available from: *http://www.decc.gov.uk/media/viewfile.ashx?filepath=statistics/source/prices/qep531.xls&filetype=4.*

50 R.H. Bezdek and R.M. Wendling, A Half Century of Long-Range Energy Forecasts: Errors Made, Lessons Learned, and Implications for Forecasting, Journal of Fusion Energy, 21, 155-172, 2002

51 P.P. Craig, A. Gadgil, and J.G. Koomey, WHAT CAN HISTORY TEACH US? A Retrospective Examination of Long-Term Energy Forecasts for the United States, Annual Review of Energy and the Environment, 27, 83-118, 2002

52 G. Pellegrini-Masini and C. Leishman, What drives the uptake of energy efficiency in office buildings in the United Kingdom? A qualitative study of the perceptions of the market's actors, Energy Policy (In Communication), 2010

53 M.P. Miles and J.G. Covin, Environmental Marketing: A Source of Reputational, Competitive, and Financial Advantage, Journal of Business Ethics, 23, 299, 2000

54 J. Haddock-Fraser and I. Fraser, Assessing corporate environmental reporting motivations: differences between "close-to-market" and "business-to-business" companies, Corporate Social Responsibility and Environmental Management, 15, 140-155, 2008

55 J.E. Haddock-Fraser and M. Tourelle, Corporate motivations for environmental sustainable development: exploring the role of consumers in stakeholder engagement, Business Strategy and the Environment, In Press, 2009.

56 I. Henriques and P. Sadorsky, The Determinants of an Environmentally Responsive Firm: An Empirical Approach, Journal of Environmental Economics and Management, 30, 381, 1996

57 S. Brammer, A. Millington, Firm size, organizational visibility and corporate philanthropy: an empirical analysis. Business Ethics: A European Review, 15, 6-18, 2006.

58 M. Branco, L. Rodrigues, Corporate Social Responsibility and Resource-Based Perspectives, Journal of Business Ethics, 69, 111-132, 2006

59 UK Department of Environment, Food and Rural Affairs (DEFRA). Public attitudes and behaviours towards the environment - tracker survey 2009 [cited 27.01.10]; Available from: *http://www.defra.gov.uk/evidence/statistics/environment/pubatt/download/report-attitudes-behaviours2009.pdf*.

60 Eurobarometer, Attitudes of European citizens towards the environment 2008.

61 D.K. Peterson, The Relationship between Perceptions of Corporate Citizenship and Organizational Commitment, Business Society, 43, 296-319, 2004

62 D.B. Turban and D.W. Greening, Corporate Social Performance and Organizational Attractiveness to Prospective Employees. The Academy of Management Journal, 40, 658, 1997

63 D.W. Greening and D.B. Turban, Corporate Social Performance As a Competitive Advantage in Attracting a Quality Workforce, Business Society, 39, 254-280, 2000

64 G.V.A. Grimley. From Green to Gold 2008. A unique insight into sustainable investment attitudes. 2008 [cited 14/05/09]; Available from: *http://www.gvagrimley.co.uk/PreBuilt/Green/05477%20Green%20to%20Gold%202008%20interactive.pdf*.

65 S. Sayce, L. Ellison, and P. Parnell, Understanding investment drivers for UK sustainable property. Building Research & Information, 35, 629 – 643, 2007

66 G. Pivo, Exploring responsible property investing: a survey of American executives. Corporate Social Responsibility and Environmental Management, 15, 235-248, 2008

67 G. Newell, The strategic significance of environmental sustainability by Australian-listed property trusts, Journal of property investment & finance, 26, 522-540, 2008

68 G. Pivo and J.D. Fisher, Investment Returns from Responsible Property Investments: Energy Efficient, Transit -oriented and Urban Regeneration Office Properties in the US from 1998-2008. 2009.

69 P. Eichholtz, N. Kok, and J.M. Quigley, Doing Well by Doing Good?: Green Office Buildings, Working Paper 2008, W08-001, Program on Housing and Urban Policy, Fisher Center for Real Estate and Economics, Institute of Business and Economic Research, UC Berkeley.

70 J. Wiley, J. Benefield, and K. Johnson, Green Design and the Market for Commercial Office Space. The Journal of Real Estate Finance and Economics, 2008.

71 F. Fuerst, and P. McAllister, Pricing Sustainability: An empirical investigation of the value impacts of green building certification, Paper presented at the American Real Estate Society Conference, April, 2008.

72 S. Rawlinson and M. Wilkes, Cost Model: Office Refurbishment. Building Magazine, 20th June 2008, pp.72