Reducing CO_2 emissions of UK non-domestic buildings – conclusions of the Tarbase project

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Keywords
carbon dioxide, buildings, energy, non-domestic, schools, offices, retail

Abstract
Tarbase is a £1.4 million low-carbon building project funded by the UK Carbon Trust and the Engineering and Physical Sciences Research Council under the Carbon Vision Buildings programme. The project has a goal of specifying technologies and practices that could reduce the carbon emissions of existing buildings by 50% or more. This includes the investigation of demand-side and supply-side measures and also accounts for externalities such as a changing climate and a rise in energy tariffs. The non-domestic part of the project has focussed on energy use in offices, retail buildings, schools and hotels. The results make clear that, even within each sub-sector, non-domestic buildings are non-homogeneous. Different solutions apply to different sectors. This fact is demonstrated by taking a series of building "variants", detailed specifications of buildings that could exist (rather than average stock representations). Several intervention packages are defined and applied cumulatively to each variant, with each approach tailored to that particular building. While the target of 50% carbon savings is possible for many buildings, the changes required should not be underestimated. Furthermore, the importance of understanding internal activity is demonstrated, with the effect of internal gains on the performance of various carbon-saving technologies (such as building fabric insulation) often underestimated. This paper explores the main conclusions of the Tarbase non-domestic work and includes discussions on the possibility of passively heating (and cooling) an office, the danger of refurbished schools overheating and the problems with reducing the CO_2 emissions of energy-intensive retail buildings, such as supermarkets.

Introduction
The non-domestic stock in the UK is highly varied and proposing carbon-saving solutions to such a diverse group of buildings is non-trivial. The Tarbase project[1] has, over four years, looked at patterns and characteristics of domestic and non-domestic energy use, with the aim of this paper to overview the results of the latter. The main sectors of interest are offices, schools and retail buildings, although the project is also looking at the hospitality sector. The Tarbase approach is to define a building variant that is indicative of that building type in the UK, and therefore could currently exist (using a baseline year of 2005). This building is then modelled, using ESP-r dynamic building software, to estimate its baseline energy consumption and associated carbon dioxide emissions. The modelling relies on detailed construction, activity and climate data for that specific building type, as opposed to averaged stock information that will not necessarily be relevant to specific building examples. Once this baseline has been ascertained, a series of carbon-saving measures are modelled and applied, cumulatively, to the building variant, thus achieving a final carbon dioxide saving. The year 2030 is used as the date for this refurbished scenario, and hence there is potential for a range of future technologies to be applied to the building. The main objective of the Tarbase project is, for the identified building variants, to reach (at least) a 50% total carbon saving. As this approach is developed, many issues present themselves both relating to the limitations of such a modelling exercise but also the practical barriers that might exist when, in reality, trying to install on a large scale a

hugely varied selection of technologies across the non-domestic building stock. It is also clear that the conclusions made within one sector might not apply for a different sector. Such issues are only made clear when the internal activity of the building is defined in sufficient detail, and this is one of the main themes of the paper – the internal activity of a non-domestic building largely governs how we define that building, and so any carbon savings measures and technologies will need to reflect this. Using average benchmarks as *inputs* to simulation exercises can therefore be misleading. The relationship between the internal activity and heating/cooling requirements of a building 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.

For practical reasons, the detail of each non-domestic building variant investigated (of which there are 15) will not be given here; though one variant (a four-storey office building) will be used to illustrate the methodology.

End-use 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 similarity of equipment type throughout the stock in that most buildings will have a significant number of office-type appliances (though factories and industrial buildings will have energy use dominated by equipment specific to that sector, such as air-compressing units). Personal computers, monitors and photocopying/printing usage are likely to be responsible for a large proportion of the building carbon emissions. Table 1 summarises the changes used by Tarbase for the office variants, though sector specific changes are also made to the other non-domestic buildings as documented. It could be argued that the number of personal computers (PCs) is close to saturation point in the workplace, with one PC per person being quite common for offices (some businesses, such as financial traders, may exceed this ratio but more general offices are unlikely to require more workstations than this). Subsequent discussions will look at PC usage in schools, and how technology can be exploited to maintain IT provision for learning facilities in a low-carbon context. The definition of a desktop machine 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). Research within industry 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[2,3]. Some of these changes would produce noticeable energy reductions while others are being developed with the view of improving worker access to IT technology (and potentially increasing the IT energy consumption). So, to allow a like-for-like comparison, a similar type of usage has been assumed in 2030 as to 2005, in that people are going into offices to work a full day. Clearly, a dramatic change in working practices (e.g. people working from home and not requiring a permanent workstation) would make the comparison being a 2005 office and 2030 office less appropriate – in such a case carbon emissions might be displaced from one building to another (e.g. a dwelling) 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 70 W to 60 W. This allows for improved efficiency while accounting for the fact that requirements of 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/DVD will temporarily increase the power consumption of the machine), can produce far greater energy savings. This is summarised in work by Lawrence Berkeley National Laboratory and US Department of Energy[4]. These changes can produce savings of approximately 70% per computer though there will clearly be user-behaviour issues to be addressed. Some of these issues could be bypassed to an extent, in that mandatory energy management software could be applied to such equipment, thus taking such potential energy savings out of the hands of the actual user.

Savings can also be made from server/network computing (see Table 1). Often, 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[4] 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%.

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 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[4]. In the area of paper output, "multifunction" units are already quite common, i.e. machines that can carry out photocopying, printing, faxing and scanning operations. As well as the practical advantages of such a system, the machine, as it is performing tasks more regularly, 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 causing the introduction of e-paper (thin, portable and reusable electronic displays). This is yet to be seen on a large scale so it will be assumed here that paperless offices will not be the norm by 2030.

Table 1. Summary of small power interventions for office variants

Appliance	2005 baseline	2030 intervention	per appliance 2005 kWh/yr	per appliance 2030 kWh/yr
PC	Standard desktop machine (70W)	Power management (and 60W machine)	372	109
Monitor	CRT screen (61W)	Power management and Cholesteric LCD technology (7W)	209	22
Fax	Separate printer /copier /fax /scanner	Multi-function machine replaces copiers*	132	0
Laser Printers			165	165**
Scanner			38	0
Pcopier/MF			1080	537
Servers	File and web servers always on	Switch off non-vital file servers after hours	767	705

* "On" power consumption of multi-function machine is 720 W c.f. 1354 W of old photocopier

** Also reduction in number of printers due to use of multi-function machines

In the retail sector, some of the above assumptions still hold, though IT equipment is generally used at a lower density. Most retail stores do not require individual workstations for each staff member, though computerised tills are to be expected along with the use of computers for storing customer and product information (though some of this may be outsourced). The Tarbase retail variants will therefore be subject to similar IT equipment interventions as the office variants, though a building requiring chilled foods will usually be dominated by refrigeration energy usage. Significant savings can be made here through the use of covers and blinds, which will reduce the refrigeration energy consumption but also reduce the undesired cooling of the building. With regards to more advanced technology improvements, research in several areas (such as floating condensing temperatures[6] and vacuum insulation panels[7]) shows considerable potential for energy savings – but the applicability to existing buildings is questionable. Such advanced systems might only be installed once the existing refrigeration system is deemed to need replacing. Other identified issues surrounding the energy modelling of a UK supermarket, are detailed elsewhere[8].

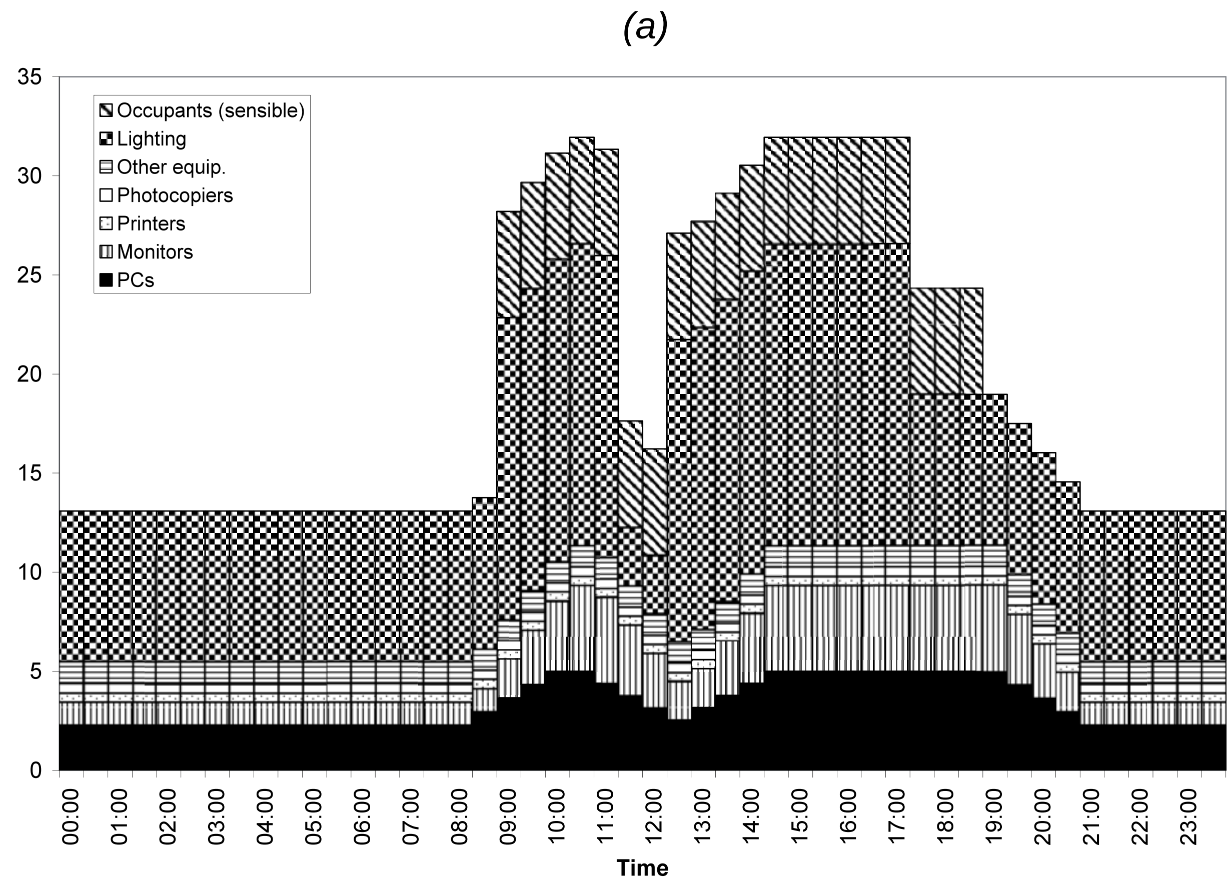
The schools sector is very different. For most UK school buildings, IT usage is growing rapidly with the use of electronic whiteboards and an increased penetration of desktop machines. This will have implications on the internal comfort conditions of buildings that have not traditionally been installed with mechanical ventilation or mechanical cooling. To allow for an increase in IT equipment, while attempting to minimise building carbon emissions, the 2030 Tarbase school variants have their baseline computers replaced with low-energy laptops (e.g. 15 W[9]), with one laptop per pupil ensuring that there is still a growth in IT-associated learning.

Lighting

To determine lighting energy consumption for the non-domestic variants (for 2005 baseline and future 2030 scenarios), a simple lighting model was developed[10]. This model accounts for lighting technology, ballast factor, room sizes and also daylight availability. As well as energy management, technology is again important for producing carbon savings. Fluorescent lighting, for a 2005 office baseline, might range from 70 lm/W (for T12 fluorescent tubes) to 100 lm/W (for T5 fluorescent tubes). While such lighting might also be seen in schools, retail buildings will tend to have more diverse lighting, with halogen lighting (which can be as low as 20-25 lm/W) often present. The use of this latter technology is of 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 incandescent light bulbs. This is somewhat misleading – if halogen bulbs are used instead of fluorescent lighting then lighting energy use will rise significantly. Such technologies should be discouraged as a general lighting option – if spotlights (e.g. "GU10" fixtures) are required, adapted compact fluorescent lighting bulbs can be used at higher efficacy. In relation to future technology, tubular fluorescent lighting is already exceeding 100 lm/W and light-emitting diodes (LEDs) are being promoted as being the future of energy-efficient lighting in all sectors. This technology is predicted to exceed 150 lm/W by 2030[11] 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 less embodied energy than conventional LED lights. In the case of current LEDs, and future OLEDs, there is a small question over 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. It is therefore assumed in this study that all non-domestic lighting achieves 150 lm/W by the year 2030, with the nominal technology being LEDs.

Internal heat gain profiles

While inefficient equipment and lighting are directly responsible for high carbon emissions in the non-domestic sector, they also play a huge part towards the size of cooling (and heating) loads. The internal heat gain profile resulting from this activity



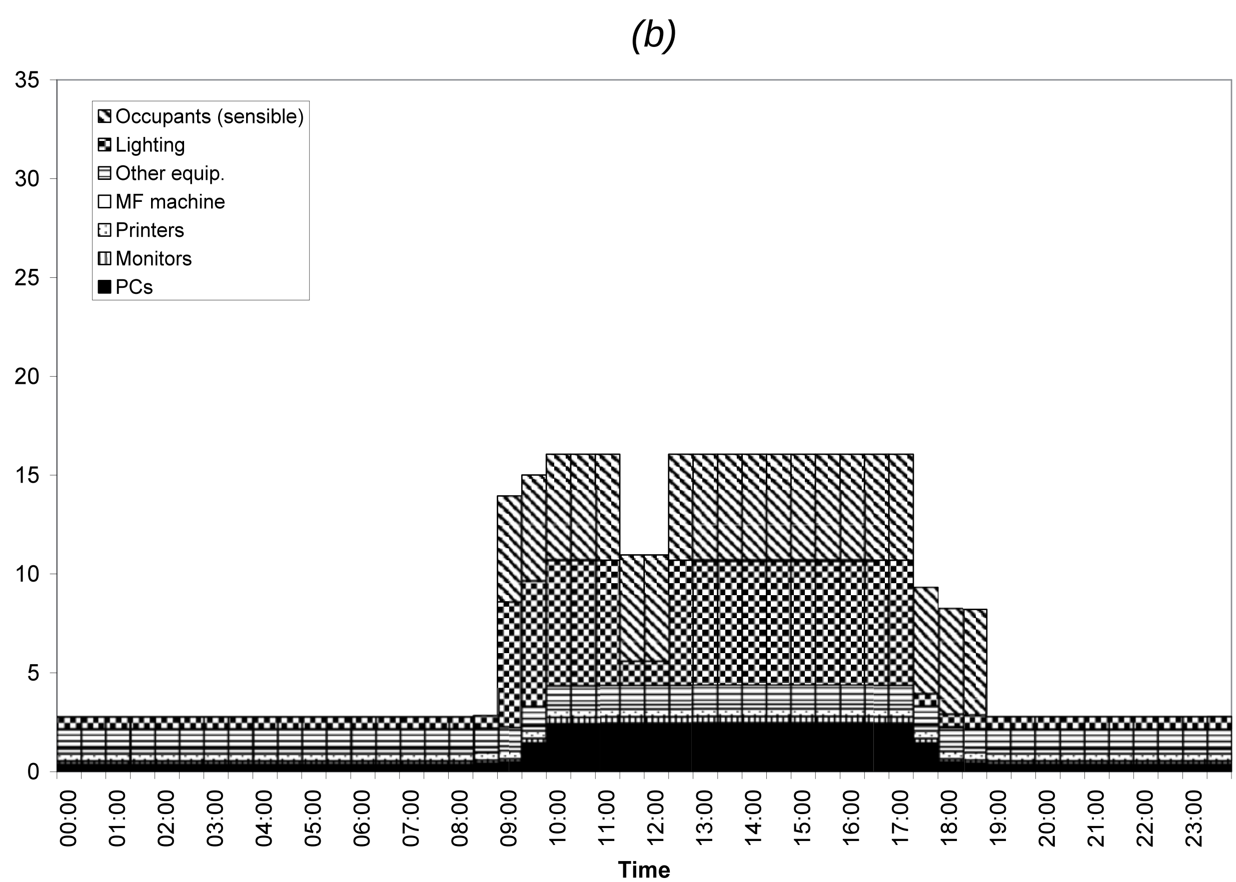


Figure 1. Estimated internal heat gain profile for four-storey office variant for a January day for (a) 2005 baseline and (b) 2030 scenario

Table 2. Overview of 2005 and 2030 building fabric for 4-storey office variant

	2005		2030	
	Description	U-values (W/m^2K)	Description	U-values (W/m^2K)
Walls	Concrete panel, air, mineral fibre, block, plasterboard	0.65	External EPS (150mm) with concrete render (13mm)	0.15
Floor	Carpet, underlay, floorboards, mineral 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

(equipment, lighting and metabolic gains) should not be oversimplified. The shape of such a profile and how it coincides with external heat gains, 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 approaching maximum output. The use of lighting is relatively simple to estimate if typical user behaviour is known, as already discussed. 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[12]. This is achieved by, firstly, identifying all the equipment that might be present in the building (from design guides and empirical data[13,14]). 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 the buildings concerned. These individual demand profiles are then summed together but allowing for usage diversity so that equipment is switched on at slightly different times to prevent an unrealistic power spike. Other small power appliances and equipment (e.g. photocopiers and printers) are averaged throughout the day (as these have less of an effect on the total electrical demand profile due to fewer numbers). This electrical demand profile can be equated to the heat generated by lighting and small power[15] and so, with sensible heat gains from occupants, a total heat gain profile can be produced for a given day. Figure 1 is an example of such a profile for a Tarbase office variant. This demonstrates the previously asserted point: 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 effective refurbishment measures to the building and HVAC systems – it is no longer a "2005 office". This process is repeated for all the non-domestic variants under consideration.

Building fabric

Following the above measures, the next step is to consider the space heating and cooling requirements for this reduced internal heat gain scenario. While cooling (or overheating) has been reduced, the space heating requirements will now be significantly higher. This must be accounted for in subsequent changes to the building.

CONSTRUCTION MATERIAL

When simulating building heating and cooling requirements, the change in opaque fabric elements essentially involves consideration of two factors: thermal transmittance (or U-value) and thermal mass. The former is relatively simple to calculate for a known material. The latter is less likely 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. 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 greater potential for new non-domestic buildings – though the advent of phase-change materials might make retrofitting such measures more practical. 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, partly due to issues of cost and installation. The assumption is therefore made that any retrofit to walls, floors or roof will involve adding a material (externally, internally, or to the cavity) to reduce the U-value. A suitable insulation for retrofitting might be expanded polystyrene (EPS). Table 2 shows the effect on U-values for such a change in the 4-storey office variant, where it is assumed that external insulation is achievable. Other building variants, such as listed or glass-curtain walled buildings, would be subject to different solutions (such as internal or cavity insulation).

Radically increasing insulation for a non-domestic building can sometimes have a detrimental effect. A building with high internal heat gains can lose this unwanted heat through fabric heat loss and infiltration. While this effect is undesirable during the heating season of a building, "poor" building fabric can provide an element of free cooling during the summer, in that heat transfer can occur more effectively between the cooler outside air and the overheated internal air. If a building has higher cooling loads than heating loads over the course of the year, it is possible to increase the total building energy consumption through ill-planned retrofit insulation measures, with unwanted high internal gains from equipment, people and lighting being trapped in the building. However, if reductions to the internal heat gains have already taken place, then the building is more likely to be heating-dominated (as opposed to a 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 heating 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 perspective, more justification towards 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 heating and cooling consumption can be reduced in one measure.

Offices in the UK in the period of 1960-80 were generally built without foresight of the massive influx of IT equipment that was introduced in the 1980s and 90s. As a result, the buildings tended to overheat and so either retrofit cooling systems were applied, internal air quality suffered, or the buildings, which were not of particularly high quality construction, were demolished. There is a danger that this mistake will be repeated for UK schools (see also "Other Issues" section). These building are currently going through an extensive re-building/refurbishment project across the entire country, with the previously draughty and poorly-insulated buildings becoming more airtight and subject to reduced fabric losses. At the same time, internal heat gains are rising due to the use of IT equipment and so the risk of overheating is likely to increase.

GLAZING

Also shown in Table 2 is the effect on U-value of a change in glazing. With the baseline 4-storey office having standard double glazing, there is a noticeable improvement if these are replaced with triple-glazed argon-filled windows (with a low emissivity coating). 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 penetrations in the near future. Even the chosen triple-glazed argon-filled windows would be a challenging target due to expense and installation issues. Also, 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 are often "sub-optimal", in that they must satisfy other building requirements relating to the structure and aesthetic of the building.

INFILTRATION RATES

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 more likely to have an overheating problem than a poorly airtight equivalent which, 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 sealed building experiences warmer external air displacing cooler internal air (during times of very high external temperatures) – however, in the UK this is found to be a rare occurrence, although it can be a significant factor in warmer climates. Therefore, the measures that have been suggested for reducing internal heat gains will reduce, although not eliminate, the overheating problem of an airtight non-domestic building. In some cases it might be justifiable for a southern UK office with "2005 baseline" equipment and lighting to be allowed to have relatively high infiltration rates and high U-values, but a 2030 office (as defined with efficient IT equipment and lighting) is more likely to see the benefit of retrofit fabric measures. As already alluded to, the internal environment of buildings without mechanical ventilation can be particularly vulnerable to retrofit infiltration measures. In a poorly ventilated space, the concentration of internal CO_2 levels and dust mites, as well as humidity levels and high temperatures, can result in unhealthy environments.

HVAC

Heating, ventilation and air-conditioning (HVAC) systems consume significant energy in the office, retail and school sectors. A typical building services approach to sizing the HVAC systems for each Tarbase variant is carried out[16]. 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-load efficiencies of the respective HVAC systems can be quite low. The non-domestic buildings of Tarbase are simulated using dynamic building software (ESP-r) 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 above, each profile being unique to the specific building and being quite different between 2005 and 2030 simulations. The hourly heating and cooling requirements are then passed through bespoke Tarbase HVAC models to produce estimations of heating and cooling energy consumption. This approach therefore allows for an hourly change in part-load efficiency throughout the entire year (for the systems as sized). It should be noted that these results are from simulations which can sometimes show lower heating usage than for real buildings. This is due to the difficulty of simulating poor heating energy management such as, for example, leaving windows open during the heating season, allowing systems to overheat the building and heating being left on during low or zero occupancy. However, the results are similar to suggestions of office heating from other simulation studies[17].

SIZING HVAC SYSTEMS

Although a building simulation might calculate (in kW) the maximum heating requirement at any time, this alone does not indicate how large the boilers would be. Building services engineers would not base such an estimation on the simulation of one year – to ensure that the system 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 often 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

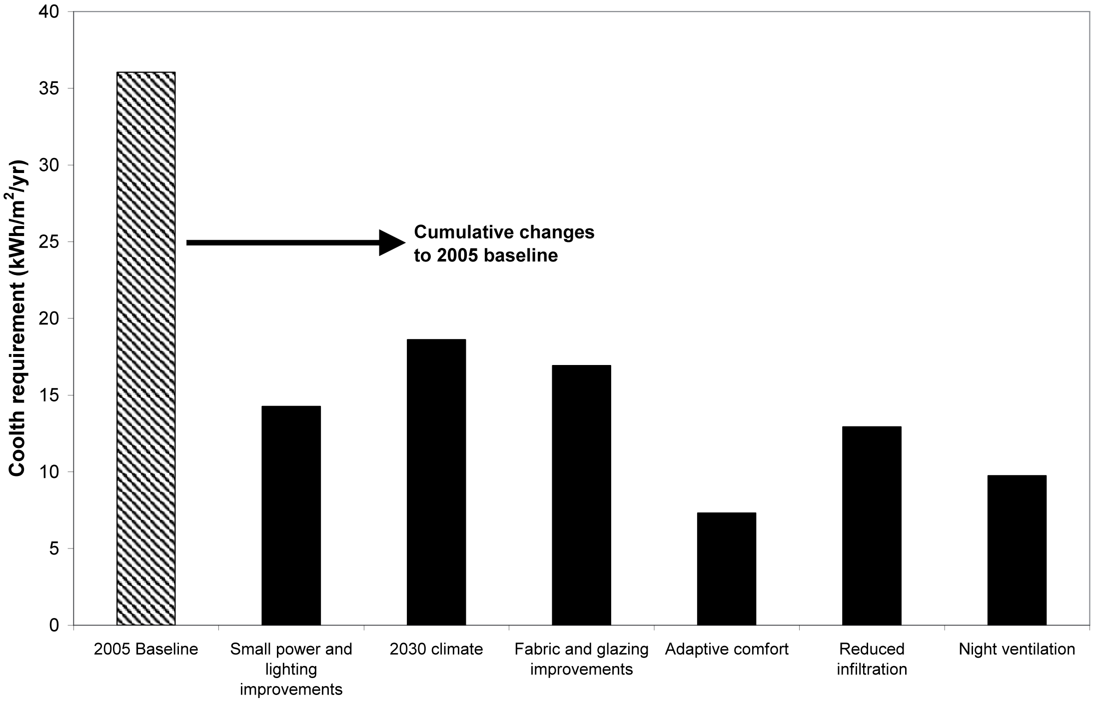


Figure 2. Modelled cumulative effect on cooling requirement of changes to baseline of a London 4-storey office

and external heat gains. Annual "domestic" hot water energy consumption, i.e. for kitchen and toilet areas, is assumed to meet typical benchmarks of 12 kWh/m^2 for all offices and retail buildings[13]. The consumption for schools is based on estimations of water usage per pupil and the energy used to heat such a volume[18]. This is factored into the boiler sizing.

HVAC TECHNOLOGY

Some technologies discussed for heating, ventilating and cooling become more difficult to specify when dealing with existing non-domestic buildings. Firstly, onsite CHP (other than district solutions) was discounted for the non-domestic variants as most of the office and retail buildings tend to have high electrical demands and relatively low thermal demands. 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 might be supplied or part-supplied by one system, might suggest a way of making this work. For example, the project team have previously looked at absorption chillers being used with onsite CHP systems[19]. It was found that, for such a system to produce significant carbon savings, firstly 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 not yet commercially available). In the aforementioned research, it was calculated that the electrical efficiency of the CHP unit would have to be in the region of 46%, extremely high for an onsite system (though larger 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 to electrical output ratio (which is the case for most current technologies) would be well-suited. However, if energy savings refurbishments are performed such that the space heating and cooling demands of the building are significantly reduced, then the justification for tri-generation diminishes. There may be more of an opportunity for tri-generation in industrial buildings; in such cases, even after energy-saving refurbishments, there can be a significant thermal demand from industrial processes making both co-generation and tri-generation more effective.

Other options include the use of night-time cooling, which can also be optimised through the use of exposed thermal mass. The building can jettison heat at night (through the use of mechanical fans) when a set temperature is exceeded, and the building is then cooler the following morning. If exposed concrete ceilings are used in the building, these can be used to absorb any undesirable heat during the day such that the peak temperature of the building is reduced or 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 within the project[19], it is difficult to imagine such a system being retrofitted on a large scale and so has not been included as an intervention for the majority of Tarbase variants (though is discussed below as an approach towards passive cooling, see Figure 2).

So, 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 variants after refurbishments), altering the heating or cooling technologies becomes less of a priority. In relation to this an exercise[20] was carried out to look at the possibility of retrofitting buildings (in particular offices) to produce a near-zero cooling requirement, through changes to internal activity and building fabric. The results for the 4-storey office are shown in Figure 2 – the measures involve (in order of application) reducing small power and lighting; allowing for a warming climate (see "Other Issues"); building fabric changes (see "Building Fabric"); adaptive comfort (see "Other Issues"); reducing infiltration; and night-time ventilation. The graph shows coolth requirement, effectively the heat that would have to be removed throughout the year to maintain comfort temperature. The calculations are based on results at an hourly temporal precision throughout an entire year using ESP-r. The different refurbishment steps taken are similar to the technologies mentioned already in this report. 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 the heat.

Mechanical ventilation, which are present in all baseline Tarbase office and retail variants (though not school), can in theory be reduced through passive approaches, e.g. providing vents or stack systems to encourage air movement from outside. Again, this has been investigated for new buildings[19], showing some small carbon savings, but is 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 with reduced infiltration rates.

Returning to the chosen carbon-saving interventions, for buildings with existing mechanical ventilation a mechanical ventilation heat recovery (MVHR) model was developed. A heat wheel was considered operating at a heat recovery efficiency of up to 70%, where the heat from exhaust air is recycled to warm the incoming supply air, with a small additional electrical requirement for achieving this.

Onsite generation

With a desire to achieve very low, and even net-zero, carbon targets for buildings, the high electrical demands of the non-domestic stock would theoretically require a vast amount of onsite renewable generation. Work by the Tarbase project team[19] has shown that to achieve such targets through onsite generation, unrealistically large systems would have to be installed, whether small-scale combined heat and power (CHP), CHP with absorption chillers (i.e. tri-generation) or rooftop solar and wind technologies. Further Tarbase work on small-scale and micro generation can be found elsewhere[21,22,23,24]. When looking at decarbonising electricity supplies to all buildings, the emphasis should arguably be on near-site and off-site renewable options, supplemented by onsite generation where suitable.

Indicative building CO_2 savings

The Tarbase methodology, as described above, is applied to a series of non-domestic variants to suggest suitable technologies for reducing the CO_2 emissions of different buildings. Figures 3 to 5 show examples of modelled intervention steps, with changes applied cumulatively to three different Tarbase baseline variants: a four storey office building; a supermarket; and a large secondary school. The intervention scenario numbers correspond to Table 3, giving a brief description of the steps taken for each individual building. Table 4 overviews all the interventions applied to 13 of the Tarbase non-domestic variants.

Other Issues

The actual performance of any carbon-saving measure in a building is subject to several additional factors including user behaviour, economics, and also the carbon intensity of the energy used in the building. All of these factors have been looked at by the Tarbase project, three of which are summarised below.

WARMING CLIMATE

When estimating future building energy consumption it is important to allow for the fact that climatic parameters are predicted to change significantly. Existing algorithms[25] are applied to the 2005 climate files[26] used in the baseline simulations to estimate the effect of global warming by 2030. Documented in previous publications[12,20], this can have a noticeable effect on the balance between heating and cooling a building. However, for buildings with high internal heat gains, the effect of warming climate on the building can be comfortably offset by increasing the efficiency of appliances and lighting. Rather than increasing the carbon emissions of buildings per se, the greatest effect of climate change on the non-domestic built environment might be that cooling systems become undersized and, therefore, have a greater risk of failure. This is currently being investigated by a new project at Heriot-Watt University, using probabilistic climate files rather than the above deterministic assumptions.

GRID CARBON INTENSITY

The carbon intensity of grid electricity in the UK is currently quoted as 0.52 kg CO_2/kWh[27], though quite different figures have been used in the recent past (e.g. 0.422 kg CO_2/kWh[28]) due to the use of outdated power generation estimates. The figure of 0.52 kg CO_2/kWh is often a convenient figure to use for producing indicative carbon emissions for building simulations. However, the carbon intensity of the network varies throughout the year and also over the course of a day. This can have implications for the use of several carbon-saving technologies but particularly micro-CHP and heat-pumps. The carbon intensity of the electricity displaced by export from micro-CHP will have obvious effects on the carbon-saving potential of that technology.

Air-source and ground-source heat pumps are possibly even more prone to a variation of this carbon intensity figure, as suggested by previous work[29,30]. If such systems are operating during times of high grid carbon intensity, and heating periods in domestic and non-domestic buildings are often during such times, then the carbon emissions of a building heated with a heat pump can be higher than expected, though this problem can be partly dealt with by intelligent use of thermal storage and control. If the heat pump is being proposed as an alternative to a reasonably low-carbon form of heating (such as a gas

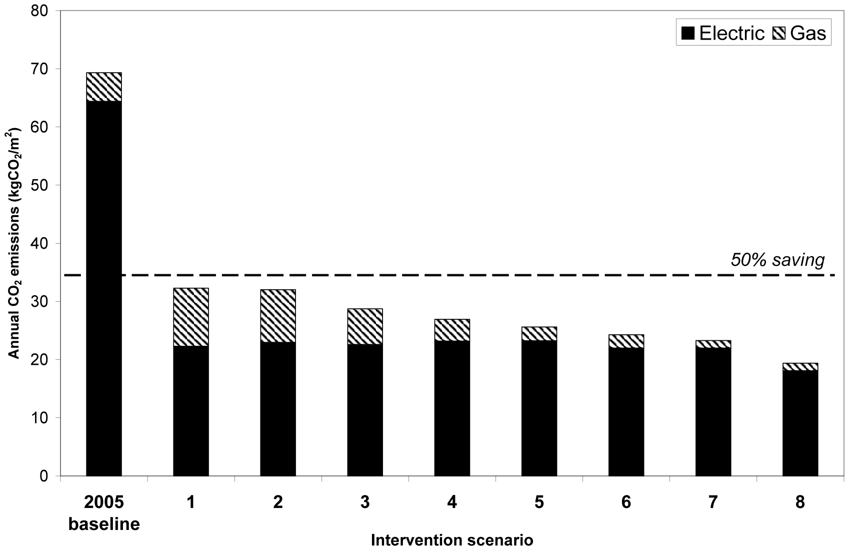


Figure 3. CO_2 savings for interventions scenarios for 4-storey office variant

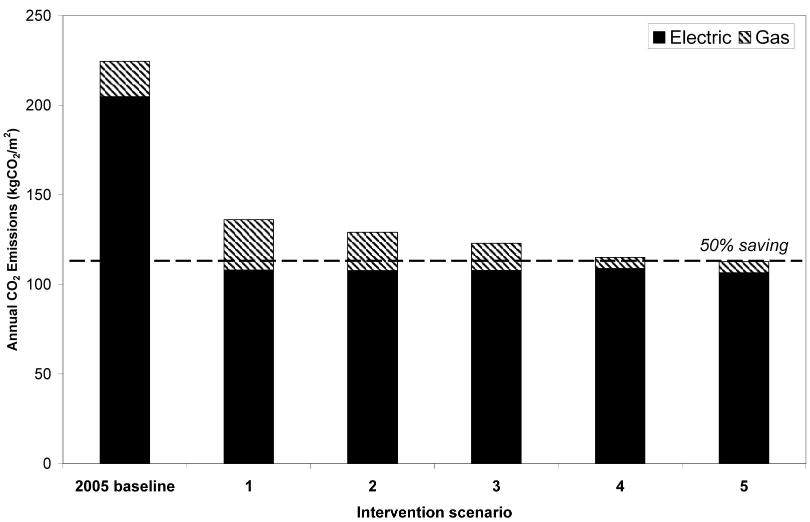


Figure 4. CO_2 savings for interventions scenarios for supermarket

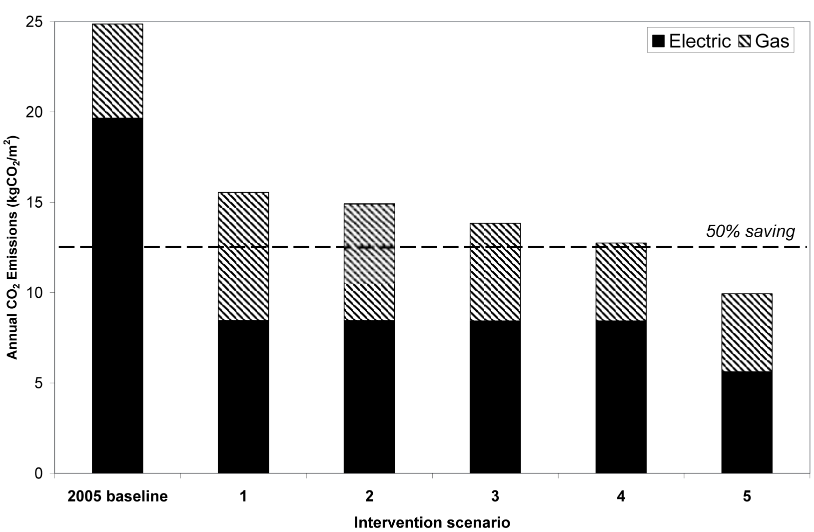


Figure 5. CO_2 savings for interventions scenarios for large secondary school

Table 3. List of intervention scenarios used in Figures 3 to 5

Interventions	4-storey office	Supermarket	Secondary school
1	Various IT energy reduction measures; 150lm/W lighting introduced throughout building	As per office; Covers applied to all refrigeration and freezer units	One Low power laptop per child (15W). Desktops removed. 150lm/W lighting
2	Apply 2030 climate	Cavity wall insulation; triple-glazed windows; condensing boiler; 2030 climate	Apply 2030 climate
3	External cladding, triple-glazed windows and condensing boiler	Infiltration reduced from 1.0ac/h to 0.5ac/h	External cladding and condensing boiler
4	Infiltration reduced from 1.0ac/h to 0.5ac/h	Heat rejected from refrigeration recovered to heat building	75m^2 of solar thermal panels
5	Mechanical ventilation heat recovery system adopted	54kW photovoltaic and 20kW wind turbine	54kW photovoltaic and 20kW wind turbine
6	Adaptive comfort algorithm	-	-
7	50m^2 of solar thermal panels	-	-
8	27kW photovoltaic and 10 x 1.5kW rooftop wind turbines	-	-

condensing boiler), then care should be taken before recommending installation – it should not always be assumed that a heat pump will be a carbon-saving measure (particularly if underfloor heating is not being used which can improve coefficient of performance significantly).

THERMAL COMFORT

The definition of a "comfortable" interior will vary with the building and also with occupant subjectivity. Quantifying this is therefore non-trivial, although empirical work in the office sector does exist that can aid approximations31. Initially, all Tarbase office variants are assumed to meet the 21 to 23°C comfort criteria often specified in design guides13. This approximation assumes a very rigid control system to heating and cooling buildings. The aforementioned empirical work31,32 attempts to quantify suitable comfort temperatures for office workers and the point at which an occupant might act to improve his/her comfort. A relationship is postulated between the temperature outside a building and the comfort temperature within the building, based on actual data collected for office buildings. The approach will not be detailed here but it is used to define the "adaptive comfort" measure and is significant in reducing cooling requirement20. The adaptive comfort intervention essentially assumes that, when achieving comfort conditions, the building controls will follow the defined thermal comfort algorithm.

As discussed, the current UK building programme for schools will have a consequential effect on the energy use and operation of school buildings – both in a way that is intended (such as reducing heating consumption through improved insulation) but also through unintended consequences (such as overheating and air quality problems). The Tarbase school variants assume that there will be no mechanical ventilation (air-change targets of 10 l/s/person are assumed to be met passively through the use of openings and vents) or cooling present. However, to highlight the possibility of overheating in such buildings, a parallel study33 was carried out looking at the internal temperatures of the teaching areas of two of these variants in Edinburgh and London locations. Internal heat gain profiles were constructed using the method outlined earlier and infiltration assumed to be 0.3 air changes per hour (when windows and vents are closed). This 2005 baseline was then altered to account for a change in small power and lighting (based on the suggested Tarbase technological interventions and seen as "new gains" in Figure 6) and also for a change in climate, based on predicted warming by 2030. Overheating is defined using two previous studies13,34 (denoted CIBSE A and BB87 in Figure 6), 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, from the simulations of the building variants, are given in Figure 6 for a secondary school variant. 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 due to the chosen school variant being of relatively recent construction and therefore retains internal heat gains (and is less draughty) than many older school buildings – the results of Figure 6 therefore only apply to schools built to 2000-2004 building regulations (or similar). Most of this overheating, which was only registered if it occurred in the teaching area during term time, occurs between May and September, with June and July being the problem months (the school will be closed for holidays 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. In reality, unless legislation is introduced to the contrary, electrical demands, and therefore internal heat gains, are likely to increase as electronic whiteboards and IT achieve wider penetration throughout the education sector.

To investigate other solutions, the aforementioned study re-simulated the buildings with increased ventilation (20 l/s/person – which would have to be met through mechanical systems) and solar shading around all windows (represented by a 0.8 m external shade installed at the top of all windows). Solar shading had only a small effect on the overheating, suggesting that internal gains are indeed the main problem. Mechanical ventilation showed a noticeable improvement but, at 20 l/s/person, is likely to bring with it other comfort issues, with air change rates now being too high. Even with increased ventila-

Table 4. Summary of all interventions applied to non-domestic 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)						

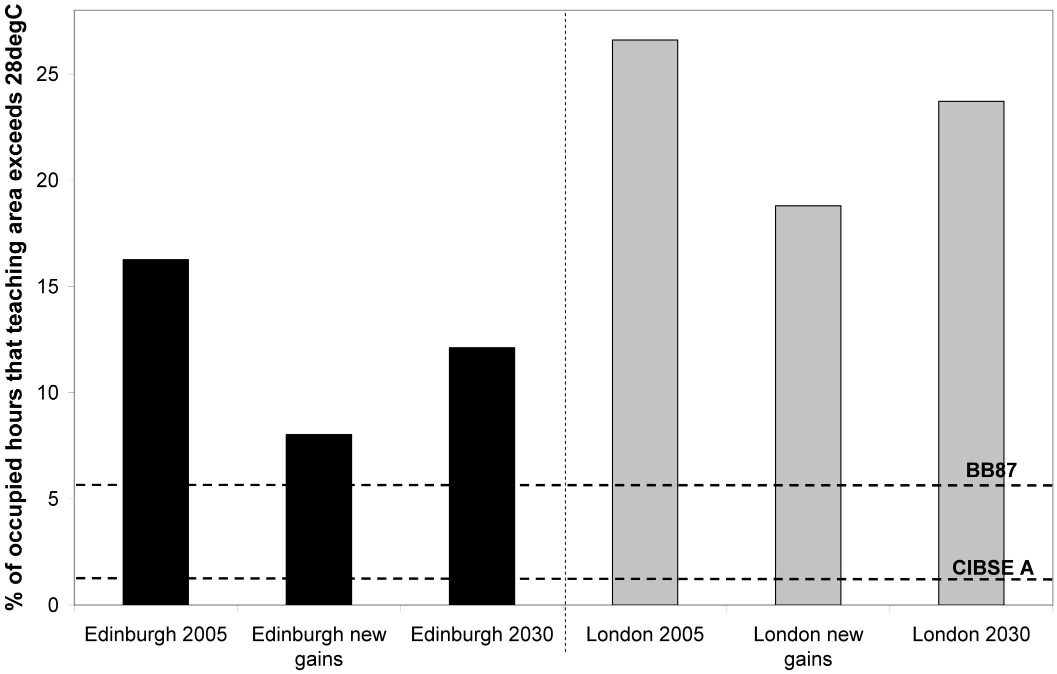


Figure 6. Percentage of total occupied hours in teaching spaces at over 28°C for a secondary school variant

tion and shading, the secondary school variant in London was predicted to experience 12% of teaching hours over 28°C. It would, in such cases, perhaps be advisable to introduce some form of cooling measure (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 Figure 6, the existing 2005 scenario is showing the greatest overheating risk (although, it should be emphasised, the future scenarios are ideal Tarbase suggestions of what could happen – not necessarily what will happen). With recent investigations35 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. 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 emission penalty. The report on this study33 contains more detail and discussion.

Tarbase non-domestic outcomes

Informed by the modelling overviewed above, the following points summarise key outputs of the Tarbase non-domestic research.

- Non-domestic buildings are generally, across the stock, non-homogenous and different solutions apply to different sectors. Even within each sector, particularly retail, homogeneity does not always exist and so average benchmarks of energy use can often be misleading.
- IT equipment and lighting directly cause substantial CO_2 emissions, but also cause internal heat gain profiles that are fundamental to understanding the heating and cooling of buildings (particularly offices). In the temperate climate of the UK, cooling loads are highly sensitive to internally generated heat. Altering these profiles, through energy management and technology selection, is vital to achieving large-scale CO_2 savings but such a measure will change the approach to choosing HVAC and building fabric refurbishments – a cooling-dominated office will require a different strategy to a heating-dominated office. Availability of post-occupancy data for non-domestic buildings is limited but is vital for understanding the extent of this problem.
- Future trends of energy use need to be managed within the UK school sector – if internal temperatures (and air quality) become unsuitable for teaching environments, then mechanical cooling and ventilation might 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 at suitable colour rendering indices. However, technologies such as halogen lighting (used for aesthetically popular GU10-fixture spotlights) are now common within the retail sector and should be discouraged. Halogen lights in particular are often advertised as "energy savers", but this is only true when comparing them to poor-efficacy incandescents.
- Supermarket display refrigeration, with open facades, is extremely inefficient and responsible for large carbon emissions in the food retail sector. They also substantially contribute to heating consumption due to indirect, and undesirable, cooling.

- Non-domestic building-integrated generation will only achieve significant carbon savings (relative to the buildings they serve) if very large systems are installed. Many options are currently difficult 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 within the existing network infrastructure (and should account for the often improved efficiency of near-site/district solutions). Identifying niche technologies for small markets will not help achieve ambitious carbon saving targets for the UK building stock.
- CO_2 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 the entire stock, not just a few exemplars. Surpassing these targets and looking at the goal of "net-zero" carbon for existing non-domestic buildings is 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 onsite CHP without firstly reducing that energy demand. Either we re-address the targets being used for these buildings or we change the approach, and legislation, that governs energy use in the non-domestic sector.

Conclusions

This paper provides an overview of the non-domestic work of the Tarbase project, with a guide through the various steps and publications produced in researching the possible paths for achieving the goal of 50% (and greater) carbon savings for a range of non-domestic buildings, which was demonstrated as technically feasible for three building variants. The recommendations call for a new approach to carbon-saving in the non-domestic sector which shows an understanding of the way buildings are used. The disassociation of "regulated" (i.e. heating, cooling, ventilation and lighting) and "non-regulated" (i.e. small power and end-use technologies) energy use in such buildings is misleading as it implies that such categories are unrelated. For non-domestic buildings these categories are inextricably linked and so reliable carbon-saving techniques cannot be identified without understanding this problem. This is particularly true as we raise our targets, and expectations, for reducing the carbon emissions of the building stock.

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