# REDUCING CO$_2$ EMISSIONS THROUGH REFURBISHMENT OF NON-DOMESTIC UK BUILDINGS

Andrew Peacock
The Energy Academy
Heriot Watt University
Edinburgh, EH14 4AS
Tel: + 44 (0)131 451 4329
Fax: +44 (0)131 451 3132
a.d.peacock@hw.ac.uk

P.F. Banfill*, S. Turan*, D. Jenkins*, M. Ahadzi*, G. Bowles*, D. Kane[#], M. Newborough[¥], P.C. Eames[§], H. Singh[§], T. Jackson[ψ], A. Berry[ψ]

* - School of the Built Environment, Heriot Watt University
[#] - School of Engineering and Physical Sciences
[¥] - ITM Power
[§] - University of Warwick
[ψ] –University of Surrey

## Abstract

Recent research by the Tyndall Centre in the UK has suggested that a 70% reduction in CO$_2$ emissions will be required by 2030 to mitigate the worst impacts of global climate change. In the UK, approximately 11% of CO$_2$ emissions are attributable to non-domestic buildings. Of the UK non-domestic stock that will be present in 2030, approximately 75% will have been constructed before 2005. Consequently, refurbishment of existing buildings is likely to strongly influence whether these emissions reduction targets are met. This paper catalogues interim research outcomes from a research project (TARBASE) whose aim is to identify technological pathways for delivering a 50% reduction in CO$_2$ emissions of existing UK buildings by 2030. This investigation describes the approach as applied to the non-domestic sector. The approach taken was to describe a series of non-domestic building variants, chosen due to their prominence in the stock as a whole and also by their ability when taken together to describe the range of construction methods found in UK buildings. Technological interventions, grouped by building fabric, ventilation, appliances and on-site generation (of both heat and power) as applied to the building variants were investigated. Their applicability was determined with respect to energy and CO$_2$ emission savings. Emerging research findings from the application of this deployment methodology to mitigation and adaptation strategies for the existing built environment are discussed.

## 1. Introduction

Recent research by the Tyndall Centre in the UK has suggested that a 70% reduction in CO$_2$ emissions will be required by 2030 to mitigate the worst impacts of global climate change [1]. In the UK, approximately 11% of CO$_2$ emissions are attributable to non-domestic buildings [2]. Of the UK existing stock that will be present in 2030, approximately 70% will have been constructed before 2005. Consequently, refurbishment of existing buildings is likely to strongly influence whether these emissions reduction targets are met. The aim of the TARBASE project is to deliver technological solutions which will allow a radical, visible, step change input to policies and programmes designed to reduce the carbon footprint of the existing UK building stock. Developing technological interventions to reduce the energy consumption of existing buildings is a well researched pathway and the findings have been incorporated into the legislative process both in the UK and abroad. Given the weight of knowledge in this field, the results, in terms of take up of technologies has been disappointing and energy consumption so that energy consumption and CO$_2$ emissions attributable to existing buildings have continued to grow. There are numerous reasons why this has occurred but one possible cause may however lie in the character and quality of the data itself. The Sustainable Construction Task Group [3] suggested that one of the reasons for this market failure was that the costs and benefits of refurbishment options are often complex to determine. Following an assessment of the available data

on refurbishment interventions for reducing carbon emissions they concluded that, while there is a wealth of guidance and literature regarding technological intervention strategies for reducing carbon emissions in existing buildings, the data is disparate, too specific or not specific enough. TARBASE aims to contribute to the bridging of these gaps by developing a methodology for assessing technological intervention strategies which attempts to (Figure 1):

- Characterise energy flows for specific buildings, the choice of which is informed by a thorough understanding of the data describing the existing stock. It is not incumbent upon Tarbase to select buildings that could be described as average. The aim is to choose buildings that are prominent in the stock from the perspective of $CO_2$ emissions and that the buildings when taken as a whole reflect variables that are fundamental in describing the wealth of buildings found in each classification. In the UK schools sector for instance, the Government has committed to either refurbishing or replacing the entire stock before 2020. Choice of buildings from this sector has, therefore to be heavily influenced by this policy resulting in choices that have been constructed relatively recently.

Figure 1: TARBASE Project Flowchart
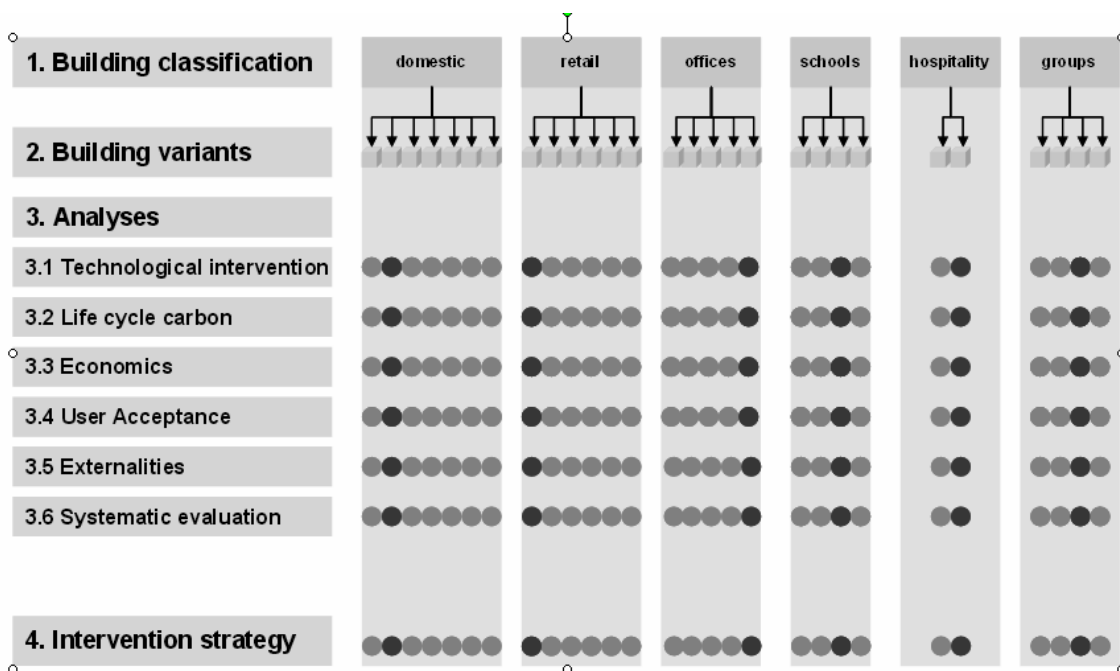


- Produce an assessment vehicle or methodology to develop intervention strategies for these buildings that will provide an understanding of their suitability from the perspective of $CO_2$ savings, engineering veracity, externalities (near term climate change and carbon intensity of network electricity), economics and user acceptance.


## 2. Scope of the Paper

The aim of this paper is twofold; (a) to provide a broad overview of the methodological approach that has been taken in assessing technological interventions in existing UK non-domestic buildings and (b) to provide an overview of some of the key findings emerging from the work in the non-domestic sector.

# 3. Methodology

The methodological approach taken is shown in Figure 2. Following choice of the appropriate building by close analysis of the relevant stock model [4] the construction detailing, likely occupancy characteristics and HVAC plant specification was developed in conjunction with the practitioner community to ensure that 2005 baseline building design described possibilities that were recognisable. A description of the variants in each of the non-domestic sectors considered is given in Table 1. The project as described is a modelling study that builds upon research carried out by the principal authors who applied a similar approach to the assessment of the UK domestic sector [5]. A key finding of this work was the importance in defining the electrical and thermal demand of buildings at a temporal precision sufficient to capture the load diversity. In the domestic sector, this temporal precision was found to be 5 minutes or less, chiefly as a consequence of the wide and disparate nature of domestic electrical loads resulting in whole building electrical demand signatures with daily load factors as low as 7% [6]. In the non-domestic sector load diversity of this nature is less evident and electrical and thermal demand of the building can be represented at hourly intervals with much reduced risk of misrepresenting the data. For instance, Figure 3 shows monitored data from a typical UK office with a floor area of 3,350m$^2$ in an urban location with 400 staff where the daily load factor is approximately 48% [7]. It has also been reported that office load factors can be as high as 69% with schools found to be 33% [8]. By considering the occupancy characteristics, IT equipment and lighting requirements and behaviour the electrical load of the building was estimated using bottom up modelling techniques. From this, a series of incidental gains profiles could be developed for each building studied.

The building description and small gains profiles were then imported into a building simulation environment [9] and using CIBSE TRY climate files for specific locations, the idealised energy requirement of the buildings was estimated using assumed specific thermal comfort limits. The final energy demand of each building was then characterised using bespoke modelling software that allowed transient performance of HVAC equipment in delivering the idealised energy requirements to be characterised. At each step of this process, the energy requirement was compared to published data and benchmarks to ensure that the energy flows were commensurate with those expected.

**Table 1: Tarbase Non-Domestic Variants**

| Variant Number | Description | Age | Floor Area | Construction |
|---|---|---|---|---|
| VO1 | 4 Storey Office | 1981-85 | 4000m$^2$ | Concrete panel/blockwork |
| VO2 | 5 Storey Office | 1991 conversion of a Victorian warehouse | 3000m$^2$ | Solid wall with additional internal insulation |
| VO3 | 6 Storey Office (Deep) | 1986-1990 | 5400m$^2$ | Curtain wall |
| VO4 | 6 Storey Office (Shallow) | 1986-1990 | 5400m$^2$ | Curtain wall |
| VO5 | Small Office | Pre-1900 | 120m$^2$ | Solid wall |
| VR1 | Estate Agent | Pre 1900 | 60m$^2$ | Solid wall |
| VR2 | Convenience Store | Pre 1900 | 150m$^2$ | Solid wall |
| VR3 | Clothes Shop | 1986-1990 | 450m$^2$ | Concrete panel/blockwork |
| VR4 | Supermarket | 1986-1990 | 4000m$^2$ | Concrete/insulated brick |
| VS1 | Primary school | 2000 | 840m$^2$ | Cavity wall |
| VS2 | Primary School | Pre-1900 | 1196m$^2$ | Solid wall |
| VS3 | Secondary School | 2000 | 7735m$^2$ | Cavity wall |
| VS4 | Secondary School | 2004 | 9679m$^2$ | Cavity wall |
| VH1 | 2 Star City Centre Hotel | Pre 1900 | 2902m$^2$ | Solid wall |
| VH2 | Budget Airport Hotel | 1986-1990 | 3500m$^2$ | Cavity wall |

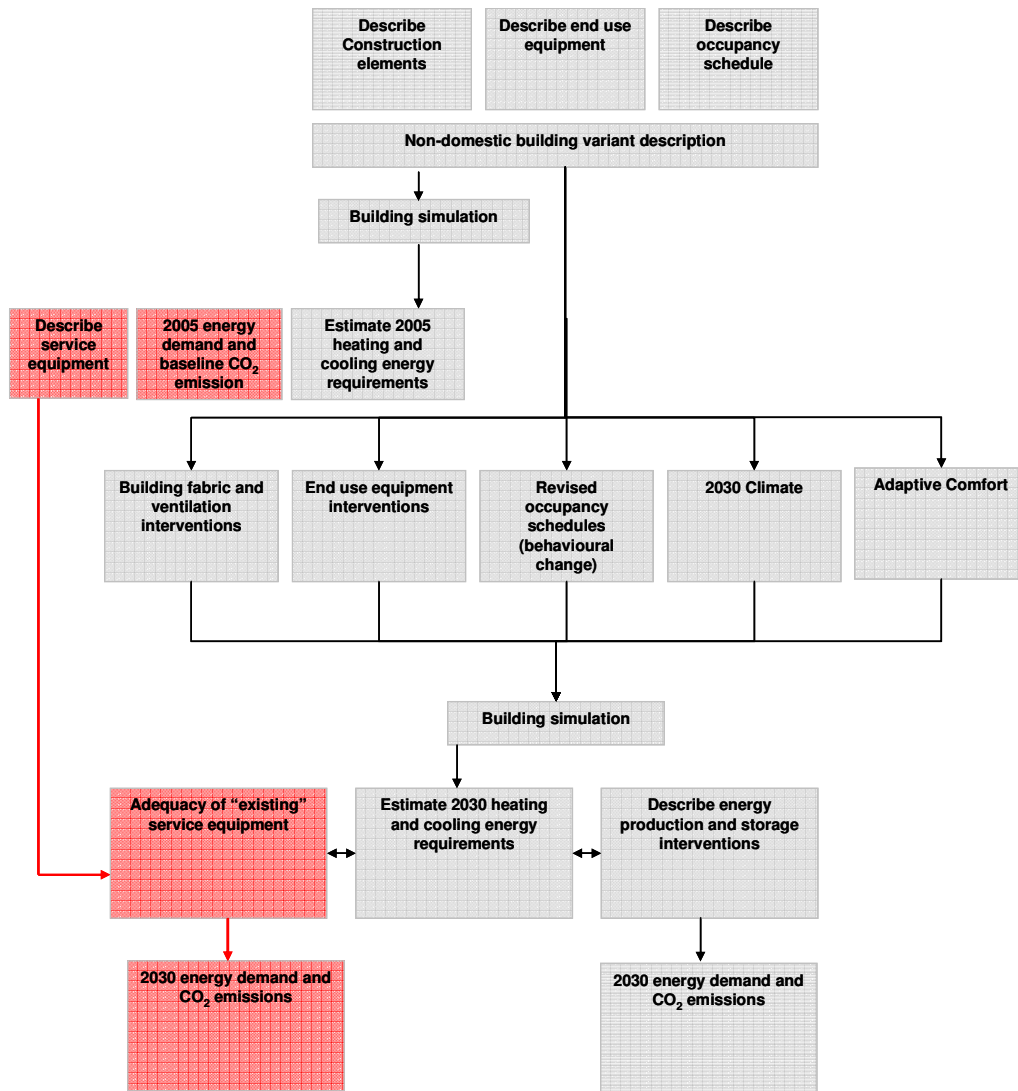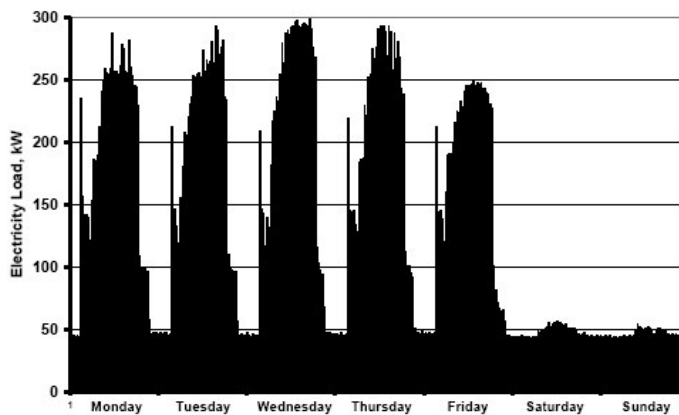**Figure 2: TARBASE Methodological Approach**



Figure 3: Monitored electrical demand of an UK office

## 4. Emerging Outcomes

### 4.1 Intervention sets

Full intervention sets have been developed for each of the buildings outlined in Table 1. Technologies were grouped in end use equipment, building fabric, HVAC and on-site generation categories. An example of an intervention set developed for Building Variant SV4 (secondary school) is shown in Figure 4. The demand side measures included improved lighting (with a luminous efficacy of 150lu/W), increased penetration of IT equipment (in line with UK commitment for 1 computer per pupil) but this in conjunction with efficiency improvement such that current best practise laptop efficiency is assumed and external wall insulation to reduce heat loss of wall to a u-value of 0.15W/m$^2$K. The CIBSE TRY climate files for 2005 were modified using UKCIP02 co-efficients (for 2010-2040) and the Belcher algorithm [10] to produce a climate file indicative of 2030 and the building re-simulated to study the effect of near term warming of climate on energy demand. This further reduced the $CO_2$ emissions attributable to UK schools if it is assumed that no cooling requirement exists. As a consequence of these and several other less significant measures the aspirational target of 50% was approached.

Supply side alternatives would have to be developed if this target or indeed the higher target posited by the Tyndall centre were to be achieved in this school. The supply side options considered were wind and PV sized appropriately for the size of the school grounds and roof and also taking into account potential concerns regarding the vulnerability of PV systems to vandalism. Wind yield for specific turbines was estimated using wind speed data monitored at a temporal precision of 10 minutes for a full calendar year at sites typical of urban and suburban sites. The applicability of wind energy in urban areas is extremely questionable due to the effect of increased surface roughness slowing wind speeds. The wind turbines investigated would not be in operation for greater than 60% of the year on either wind speed sites and capacity factors of below 10% would be typical. Yield from the PV system was estimated using the CIBSE Test Reference Year Climate file for Birmingham where this school was assumed to be located. An appropriately sized mono-crystalline cell with a system efficiency of 14% was found to deliver approximately 25% of the revised 2030 electrical demand of the school. However, approximately 20% of the available generation is likely to fall during the summer holiday period, all of which would have to exported to the grid. Similar, though less extreme supply demand matching characteristics were found to occur during occupied periods of the summer.

It is possible then, for the school buildings to produce intervention sets that could result in the 50% savings. It is likely that they would have to come from both supply and demand side fixes with attendant issues surrounding security of deployed systems and supply demand matching characteristics of the electricity generated. The study described only took account of behavioural or occupancy change with respect to IT equipment usage.

Figure 4: Intervention sets for Building Variant VS4 - Secondary School
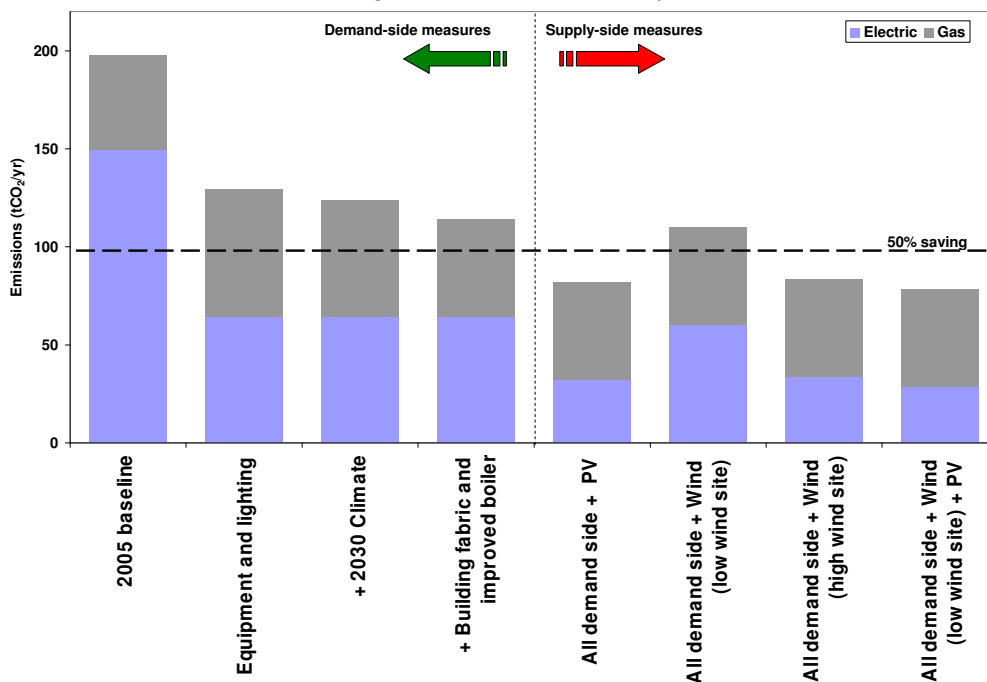
**4.2 Gains and Thermal Comfort** [10]

The co-incidence of solar and incidental gain in a building is a primary determinant of the ratio of heating and cooling required in an office building. The effect of dramatically reducing the incidental gain in an office building was investigated by (a) applying similar lighting interventions as those outlined above in schools and (b) IT equipment interventions that coupled highly efficient monitors and processors with energy management software that ensured that systems were not needlessly left on. The small power load of the Building Variant OV2 (4 storey office) was found to fall from approximately 60kWh/m$^2$ to 24kWh/m. In addition to this substantial fall in electricity consumption, it also has a dramatic effect on the heating and cooling requirement. The result of interventions to end use equipment only is to switch the office from being a heating dominated to a cooling dominated office [Figure 3]. This raises substantial issues as to how regulation might proceed with respect to refurbishment in the future. Small power loads in offices are not regulated in the UK and are seen as the sole responsibility of the building occupiers (rather than the owners or Maintenance Company). A number of studies have identified the issues and barriers associated with the tenant occupant relationship in commercial buildings and the effect of this tension on the uptake of technical interventions aimed at reducing building energy consumption and commensurate $CO_2$ emissions. However, the concept that the actions of the building occupier can switch completely the energy efficiency vector that needs to be chosen also has to be taken into account when devising mitigation and adaptation strategies for a specific building. This blurs the lines considerably between a regulatory approach involving building regulations and an approach that seeks for a specific building a reduction in $CO_2$ emission commensurate with aspirational targets.

The end use equipment interventions can also be viewed as acting as a quasi adaptation strategy to deal with predicted near term warming of the UK climate as the resultant switch to an office that is heating rather than cooling dominated is maintained when the office is simulated using a climate file modified to reflect a 2030 climate.

Figure 5: Effect of end use equipment interventions on building variant VO1 – 4 storey office with and without end use equipment interventions and 2005 and 2030 climate for 5 UK locations



6
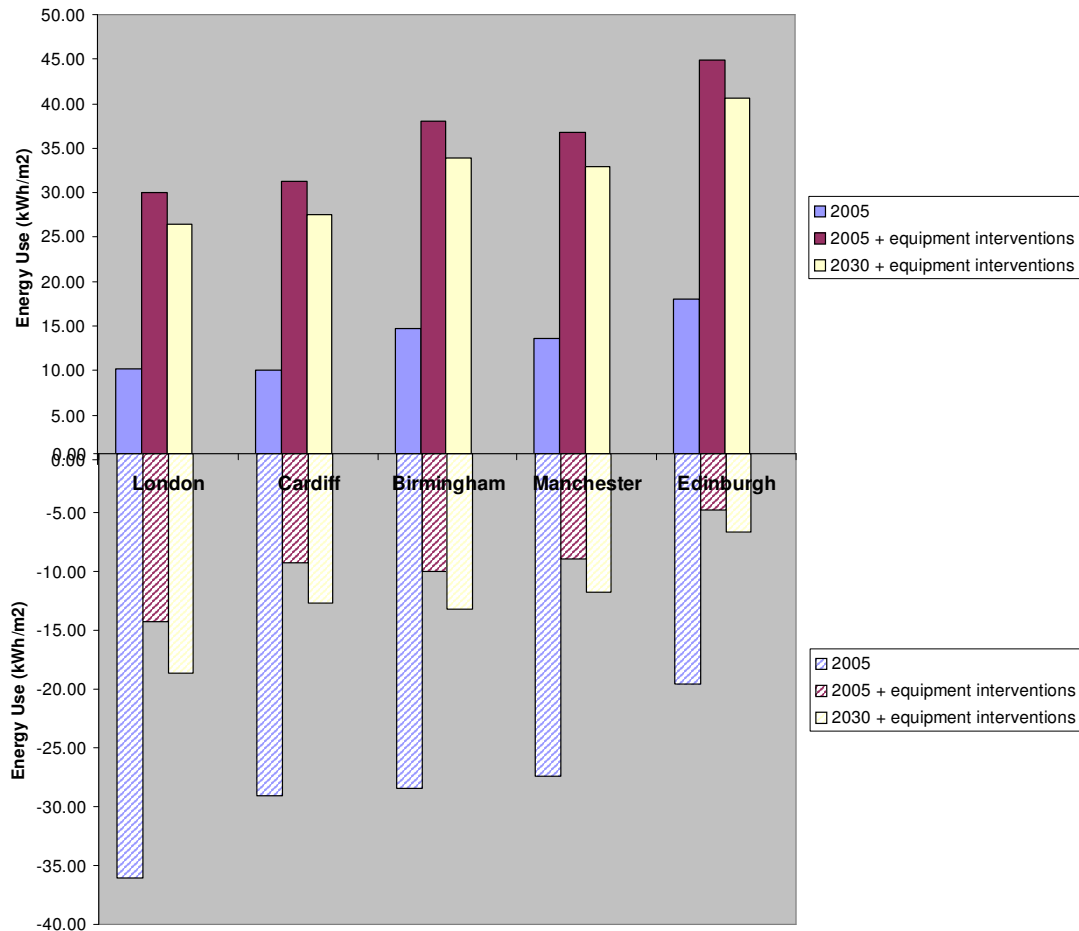
**4.3 Interventions and Network Electricity Futures** [11]

Policy and intervention that aims to reduce the $CO_2$ emissions attributable to the built environment is concurrent with efforts to decarbonise the power sector. In the UK, in common with most developed countries, the age of the electricity generation infrastructure is such that as much as 58% (50GW) of currently installed generation sets may have to be replaced in the next 3 decades [12]. At a network scale, the technologies that could be considered as replacement alternatives in this time frame are likely to be high efficiency coal plant, CCGT, thermal plant with carbon sequestration, nuclear and wind. The TARBASE research group considered the deployment of these alternatives at different levels taking account of the feasible deployment over the timescale identified to fill the looming 'generation gap'. Experimental design techniques were used to investigate different penetrations and combinations of each technology. Using emission data for each fuel type and estimated annual plant efficiency figures the range of potential annual carbon intensities possible in a future UK electricity network was estimated. These ranged from 0.22kgCO$_2$/kWh to 0.62kgCO$_2$/kWh where for instance the lower figure included a fuel mix scenario that included 28GW of wind, 5GW nuclear, and 5GW of coal with carbon sequestration with CCGT plant acting to take up the marginal plant capacity.

This range of possible electricity futures attaches significant risk to the decision making process associated with deploying supply side emission reduction measures in the built environment. Amelioration of this risk is limited as the mechanisms and decision making process by which plant will be deployed are likely to be largely at the behest of market forces with private companies seeking to minimise their capital outlay risks. It is possible for instance to see at present a favouring of new coal plant over new CCGT plant at present in the UK as a consequence of the substantial price volatility attached to wholesale gas markets over the last 5 years. It is therefore by no means certain that the a network carbon intensity at the low end of the range indicated will be achieved.

As intimated, the emissions efficacy of deploying certain supply side technologies is compromised by rising network electricity carbon intensity. To provide an example of this, the deployment of an air source heat pump was modelled taking account of system COP variation and part load performance [10] to meet the heating and cooling requirements of Building Variant OV1 (4 storey office) was considered. The results are shown in Figure 6 for the heating and cooling requirements in its 2005 baseline state. The comparative baseline condition was for heating to be supplied by a condensing boiler and cooling by existing specification cooling equipment – central chiller with distributed fan coil units [9]. The air source heat pump was found to be carbon neutral when the carbon intensity of network electricity was approximately 0.43kgCO$_2$/kWh i.e. at current assumed UK network condition with savings only attributable to the technology when electricity generation involving large scale deployment of low carbon systems is realised.

Figure 6: Effect of carbon intensity of network electricity on the emission reduction efficacy of air source heat pumps as applied to building variant VO4 – 4 storey office
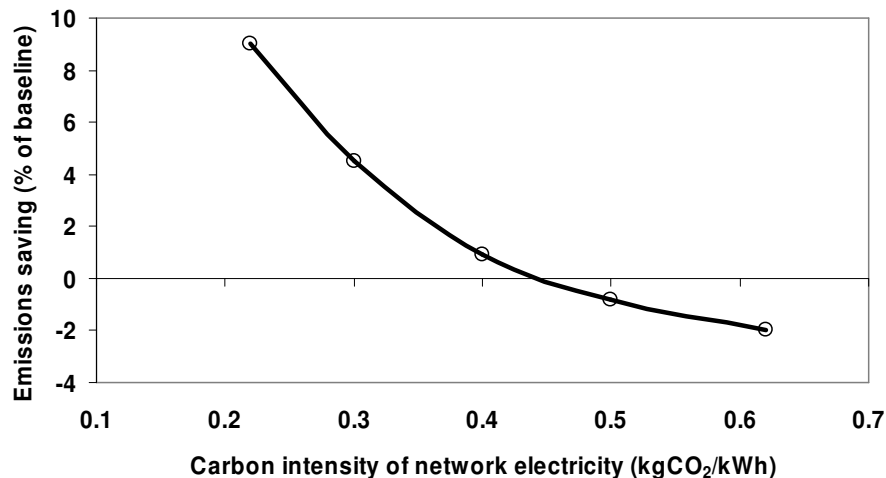
## 4.4 Overheating and warming climates

Although the TARBASE research project fundamentally aims to develop mitigation strategies for the existing built environment, it is becoming increasingly apparent that adaptation strategies will also be required to ensure that buildings are future proofed against extant climate change. As shown in 4.2 synergies exist between the mitigation strategy adopted and the resultant response of the building to near term climate change. However, this example considered the responsiveness of a building which already had a defined cooling requirement.

Meeting thermal comfort and internal air quality standards for schools can be difficult for buildings that, traditionally in the UK, have not used mechanical ventilation and air-conditioning. With a change in internal gains, and global warming predicted to cause a significant rise in temperatures, this issue becomes more problematic. Considering this within the context of low-carbon buildings creates an added hurdle – can low-carbon schools be produced that will provide suitable teaching environments in the future? The effect that future small power and lighting energy use as described in 4.1 could have on reducing the overheating of school teaching areas was investigated using the 2030 climate. The conclusion was reached that, to contribute towards the prevention of mechanical cooling systems in schools, the increase in school IT equipment and lighting should be monitored and regulated. An analogy can be made to the large rise in IT equipment in offices since the 1980's which subsequently drove the need for office air-conditioning as standard in modern offices. However, a cooling requirement would still persist based on regulatory guidelines. Introducing external shading and increasing ventilation in classrooms can reduce overheating significantly but, for many cases, the risk that the school building cannot cope with the overheating problem might still remain. The modelling predicted that classroom temperatures greater than 28°C would be found for more than 8% of teaching hours in both the primary and secondary schools located in London even after reduced lighting, ventilation and shading options had been deployed (Figure 7). Additional passive or mechanical means are required for existing school buildings to avoid overheating in the future. Alternatively, the results may point to the need for flexibility in teaching timing and seasons as a potentially more benign adaptation strategy.

Figure 7: Effect of shading and increased ventilation on overheating in building variant VS1 and VS4 (primary and secondary schools) with end use intervention strategies using 2030 climate scenario
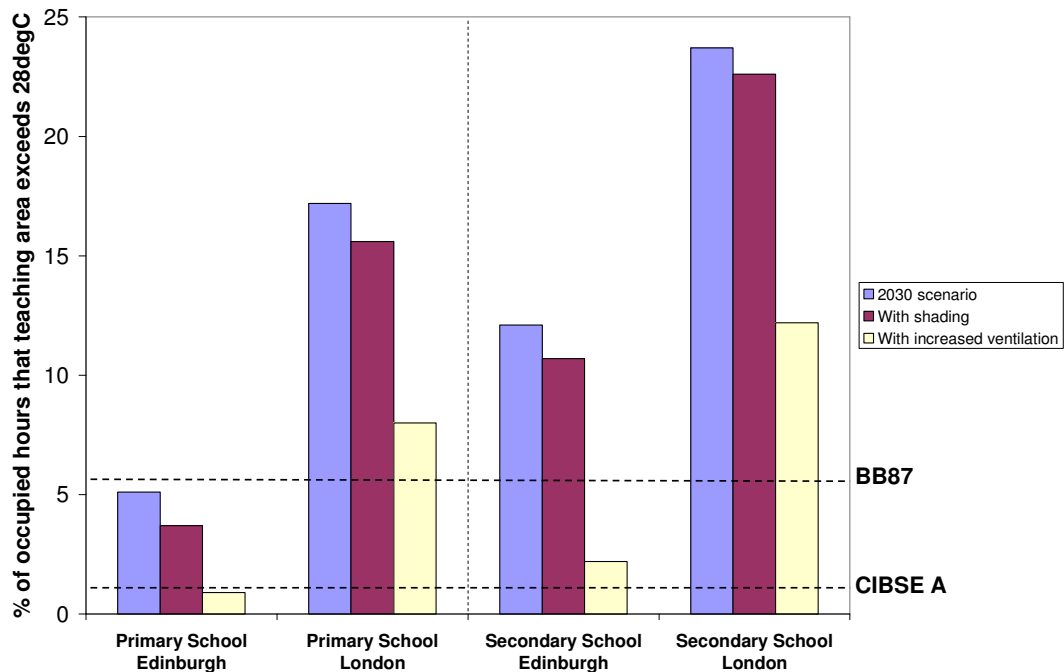
**4.5 Onsite generation**

Consideration has been given to the proportion of electrical demand a building can meet through the deployment of on-site generation. This conceptually has interesting potential as an individual building could move towards autonomy. This concept is being discussed in the UK under the banner of net zero carbon buildings, a concept that is now reaching out to Europe through the secretariat of the European Council for an Energy Efficient Economy (eceee) [13]. To exploring this concept further, Building Variant OV1 (the 4 store office) was used as a template to estimate the proportion of electrical demand that could be met by low carbon, on-site generation.

The chosen onsite generation technologies are photovoltaic (PV), micro-wind. CCHP was also considered but the prime mover electrical efficiency required to ensure that the low (not zero) carbon electricity consequently produced $CO_2$ savings was found to be approximately 47% i.e. medium to long term SOFC systems. As a consequence it was discounted. PV and wind were sized based on the largest systems likely to be situated on Building Variant OV1. So, for example, while larger wind turbines might be installed in a car-park area, a rooftop turbine is unlikely to be larger than 1.5kW due to structural and building planning issues. Similarly, while large PV systems currently exist for non-domestic buildings (e.g. PV Pergola Shell Building in Rijswijk, Netherlands), it is unlikely that an installation of greater than 50% of the roof area would be carried out (due to the physical area actually available on most non-domestic roofs as well as the economic constraints).

Using bespoke PV and micro-wind models the potential yield from on site generation was estimated. For the 4 storey office, using the assumptions indicated above, the potential yield would be approximately 87MWh of electrical generation per year assuming that the building is located in London near a favourable wind site. This would drop to approximately 51MWh if (as is likely) the wind site were not applicable and only PV was deployed. However, the lighting and small power demand of the office assuming no further growth in requirement and 2030 end use equipment interventions would be approximately 143MWh pa. With PV only then, on-site generation would be able to generate enough electricity to offset approximately 1.4 floors of the small power and lighting demand of the 4 storey office. It should be noted that this demand figure does not include electrical demand associated with other aspects of the building e.g. ventilation and air cooling requirements.

## Conclusions and Further Work

The TARBASE project has developed a methodology that allows the effect of intervention sets to be assessed for a range of UK non-domestic buildings. It has also assessed the impact of these interventions on the responsiveness of the buildings to two key externalities namely carbon intensity of network electricity and the certainty of a near term warming climate. For intervention sets to be developed for the sectors considered will require further assessment of the robustness such that both mitigation and adaptation can be accommodated within the same intervention strategy.

## Acknowledgements

## References

1. Bows, A. et al, Living within a Carbon Budget, Tyndall Centre, Co-operative Bank, July 2006
2. The Energy Challenge, Energy Review, DTI, July 2006
3. Making the most of our built environment, The Sustainable Construction Task Group, March 2004
4. Carbon Vision Buildings CaRB project, http://www.carb.org.uk/, accessed January 2008
5. Peacock A.D., Banfill P.F., Newborough M., Kane D., Turan S., Jenkins D., Ahadzi M., Bowles G., Eames P.C., Singh H., Jackson T., Berry A., Reducing $CO_2$ emissions through refurbishment of UK housing, European Council for an Energy Efficient Economy (eceee) 2007 Summer Study, Côte d'Azur, France 4-9 June 2007
6. Peacock A.D. and Newborough M., Impact of micro-combined heat-and-power systems on energy flows in the UK electricity supply industry, Energy, Volume 31, Issue 12, September 2006, Pages 1804-1818
7. Foster G., Low carbon buildings and microgeneration, Carbon Trust, July 2006

8. Walling R. and Bruce G., Distribution transformer thermal behaviour and aging in local delivery distribution systems, CIRED, Vienna, 21-24 May 2007
9. www.esru.strath.ac.uk, ESP-r Building simulation software, accessed January 2008
10. Jenkins D., Liu Y and Peacock AD, Effects of energy efficient office equipment on heat and cooling loads and related $CO_2$ emissions, Energy and Buildings, 40 (2008) 874-881
11. Jenkins D, Tucker R, Ahadzi M and Rawlings R, The performance of Air-Source Heat Pumps in current and future offices, Energy and Buildings, Article in communication
12. Greenhouse Gas Emissions Reduction: A study of options in the generation and transmission of electricity in the UK, DTI, Mott Macdonald, August, 2001