Energy Policy 36 (2008) 4552–4557

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Effects of climate change on the built environment ☆

Simon Roberts *

*Arup, 13 Fitzroy Street, London, W1T 4BQ, UK*

A R T I C L E   I N F O

Available online 23 October 2008

*Keywords:*
Passive house
Flood resilience
Summer overheating

A B S T R A C T

New buildings will have to be designed to cope with the effects of climate change. These include warmer weather in which keeping cool will be important, more extreme and wet weather, and increased subsidence risk. Flood risk areas will increase, requiring measures for both resistance for initial protection and resilience for rapid recovering.

At the same time, new buildings must use less fossil fuel in a low or zero-carbon world. Homes, offices, schools and other buildings will need to maximise passive measures of more effective insulation, improved airtightness and greater thermal mass. They will also need to make more use of solar energy and other renewable inputs. New buildings will incorporate a range of new technologies to reduce their energy use, and to cut the energy needed to build them, including the embodied energy in the materials they contain.

## 1. Key challenges

This review examines the effect of climate change on the built environment with an emphasis on new build. Adapting existing stock is the subject of a separate review (Roberts, 2008).

While the built environment is broad, extending from cottages to factories and airport terminals, the building sectors considered here are those that are both large in number and have high occupancy. They are homes, offices and schools, as covered in recent reviews (CIBSE, 2005; UKCIP, 2005).

The predicted effects of climate change present a number of primary challenges for buildings. These include winter storm damage, an increase in the risk of flooding, increased demand for summer cooling, increasing thermal discomfort in buildings, increased subsidence risk in subsidence-prone areas (UKCIP, 2005), water shortages and prolonged drought.

For example, wetter winters are expected to increase by up to 15% by the 2020s and by up to 25% by the 2050s. The number of cooling degree-days (to a base temperature of 22 °C) in London already shows an increase over 1976–1995 of around 20, rising to around 60 (CIBSE, 2005), and is expected to increase by 200% in the southeast of England by the 2080s (UKCIP, 2005).

In responding to these primary challenges, changes in building design must also be considered in the context of mitigation, meaning low running costs in carbon terms while comfort is maintained. Design principles include super insulation, high-performance windows, ventilation heat recovery systems, and thermal storage using building mass (UNEP, 2007).

Buildings account for approximately 45% of total energy consumption in the UK (CIBSE, 2004). This means that future buildings must make use of low-carbon microgeneration technology, such as ground-coupled heat exchangers and photovoltaic systems. In addition, solutions to addressing these challenges must consider reducing the embodied carbon content of construction. This is achieved through choice of materials, such as low embodied energy cement, as well as off-site manufacture and modular construction.

For housing, solutions must work within the ambitious build programme in the UK. 120,000 new homes are planned for the Thames Gateway, in the warmest and lowest-lying region of the country (ECI, 2005).

There is a significant move to single occupancy, in which per capita energy consumption increases markedly. From 1996 and 2050, the average number of people per household is expected to decrease from 2.4 to 2.1 (ECI, 2005). Almost 70% of the expected rise in household numbers in England between 1992 and 2016 is expected to be in single-person households, half of whom are likely to be pensioners (ECI, 2005).

## 2. State of current science

In reviewing the current state of science, we must bear in mind that building and construction are complex processes involving

---

☆ While the Government Office for Science commissioned this review, the views are those of the author(s), are independent of Government, and do not constitute Government policy.

* Tel.: +44 20 7755 2906; fax: +44 20 7755 3378.
*E-mail address:* simon.roberts@arup.com

0301-4215/$ - see front matter © 2008 Queen's Printer and Controller of HMSO. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2008.09.012

various actors, especially in non-residential buildings. These different actors may optimise their own part of the process, but there is often no system to optimise the total building process (UNEP, 2007). So, while science certainly features, optimisation can also involve simply encouraging best practice in construction techniques. This review extends the interpretation of 'current science' to reflect this.

### 2.1. *Weather extremes*

In areas prone to flood and/or storm, homes could be built to be more resistant to natural disasters (Arup, 2006). Housing designs must include a strong wall system and a roof construction that uses surface material that is both glued and connected with nails in the strongest pattern possible. The roof itself must be strapped to the wall system with ties that meet local wind zone requirements.

In flood risk zones, prevention is better than cure and can be achieved by building on high ground or on stilts. Flood-resilient design techniques can be used to minimise the damage caused when floodwater does enter homes (ODPM, 2005). Single storey dwellings and basement areas are inherently vulnerable to flood damage and also present a high risk of serious injury. Walls with cavities generally take longer to dry out than other forms of construction. Door thresholds should be raised and service entry points and meters should be above predicted flood levels. Anti-backflow valves for sewer and drain pipes should be fitted. The use of plasterboard and gypsum-based materials should be avoided. Glass patio doors, large windows and conservatories with large areas of glass should be avoided because they are susceptible to damage due to hydrostatic and hydrodynamic forces.

Accepting that water will enter a building, the building should be designed accordingly to allow easy drainage and quick drying. Construction materials can be chosen that are expected to suffer damage but are cheap and easy to replace. Design features that enhance or speed up the drying process might include additional weep holes at the bottom of cavity walls to allow water to drain out. Solid ground floors should be used, or suspended floors need access for inspection and debris clearance (BRE, 2007). In lightweight construction, care is needed to alleviate differential movement, corrosion or rot following wetting.

Mould growing after a flood can cause allergic reactions and can be avoided through integrated design and adequate ventilation.

Building features that provide extra protection against wind-driven rain (BRE, 2007) include recessed window and door reveals, and sills with a drip that overhangs the external leaf.

Turning to summer heat, the CIBSE publication, *Climate Change and the Indoor Environment*: *Impacts and Adaptation* (CIBSE, 2005), showed the results of using dynamic thermal computer modelling of 13 case study buildings. CIBSE Design Summer Years were morphed onto climate change projections for the 2020s, 2050s and 2080s.

In all the case studies, warmer climate conditions point to the need to limit summertime heat gains to spaces as far as possible. This is the first and most energy-efficient way to reduce the need for mechanical cooling. Limiting heat gains means employing solar shading, reducing the density or power output of lights and machines, possibly lowering the density of occupants, and providing the ability to reduce ventilation to minimum levels during hot periods of the day. For buildings with exposed thermal mass, it also means enabling the spaces to be purged with cool air at night and during periods of cooler weather to maximise the capacity for passive heat absorption by the building fabric (BRE, 2007).

Mechanical air conditioning is a last resort, but is the most direct approach to providing comfort cooling. Domestic air conditioning is widespread in many countries with warm climates, particularly the USA.

The CIBSE publication found that buildings with high thermal mass combined with an intelligent ventilation strategy performed best. Newer buildings performed better than older ones, indicating that they benefit from higher levels of insulation and airtightness. Thermal mass is in itself not a panacea, however. Care needs to be taken that the mass does not store unnecessary heat gains which can destroy the passive cooling effect of the mass. It is also essential to ensure that there is an effective way for the mass to dissipate the heat removed from the space during passive cooling or, again, the mass will warm up over time and lose its passive cooling potential.

Overheating risk will be a particular problem for naturally ventilated buildings. This is a design strategy, especially for offices, that avoids the use of mechanical systems by relying on pressure differences to move fresh air through buildings, powered by wind or buoyancy effects. The performance of a naturally ventilated building is known to be very dependent upon the quality of its design. Temperatures in a poorly designed building can be expected to be in excess of those outside the building during hot spells. Given these problems, a more resilient approach might be to combine passive and mechanical systems in such a way as to minimise energy use and carbon dioxide emissions as far as is possible within project constraints. This is the so-called 'mixed mode' approach using comfort cooling to provide acceptable temperatures by 'peak lopping' above 25 °C. Proactive building management would be required to ensure that the systems are used in the most effective way.

The number of subsidence claims each year is closely linked to hot dry summers (BRE, 2007) whose frequency is likely to increase. Sites most affected are likely to be those on shrinkable clays. To avoid foundation movement, foundation depths may need to increase.

### 2.2. *Low-energy design*

Energy consumption by buildings can be reduced with thermal insulation, airtight structural details, high-performance windows, ventilation, and heat and cold recovery systems (UNEP, 2007).

A well-insulated thermal envelope without thermal bridges is a passive way to obtain a low demand for heating and cooling along with improved thermal comfort. There are two key components to a well-insulated building shell: high levels of insulation with minimum thermal bridges, and airtight construction.

Insulation is also a double-edged sword (CIBSE, 2005). It prevents a building from losing heat, but in hot weather this can increase the risk of overheating. However, if sources of heat within the building have been minimised, insulation can prevent unwanted conductive heat gain through the building envelope during warm periods.

Good airtightness is beneficial, as it enables ventilation rates to be controlled more effectively (CIBSE, 2005). The maxim of 'seal tight, ventilate right' applies as much to limiting summertime overheating as to reducing energy use for winter heating.

Windows are still the least insulating part of the thermal envelope. They typically have a heat loss coefficient four to ten times higher than other thermal envelope elements (UNEP, 2007). At one time this led to the use of very small window areas at the expense of the daylight level. Now typical window areas have increased in line with the development of improved-insulating glazing. Nevertheless, most glazing choices involve a trade-off between the requirements for air conditioning, space heating and electric lighting. For instance, clear glass lets in lots of visible light and solar heat, reducing the need for heating and electric lighting, but increases the need for cooling relative to reflective glass.

Internal heat gains are an important contributor to overheating in buildings (CIBSE, 2005). An obvious precaution is to limit these gains wherever possible, by switching off lights and appliances at night or using low-energy devices.

All discharge lamps including fluorescents require a control gear (called the ballast) to create the right condition to start the discharge and to regulate the voltage and current (IEA, 2003). Ballasts have significantly improved their performance since the first use of fluorescent lamps. The high-frequency ballast is an electronic gear with 30% lower electrical losses than the best electromagnetic types.

Occupancy sensors are generally accepted as an effective energy saving technology, despite their earlier difficulties caused by improper settings, placement or selection (IEA, 2003). Daylighting dimming can enhance lighting quality by maintaining a constant, uniform light level and providing greater light-level flexibility to the occupants. Daylight switching can cut lighting operating hours for lights and reduce their electricity use.

The state of science in low-energy design is seen in current passive houses (UNEP, 2007). A passive house is a building in which a comfortable interior climate can be maintained without active heating or cooling systems. For European passive construction, a prerequisite to this capability is an annual heating requirement that is less than 15 kWh per square metre per year, which is not to be attained at the cost of an increase in use of energy for other purposes. Furthermore, the combined primary energy consumption of the living area of a European passive house may not exceed 120 kWh per square metre per year for heat, hot water and household electricity. The combined end energy consumed by a passive house is therefore less than a quarter of the energy consumed by the average new construction that complies with applicable national energy regulations. The basic features that distinguish passive house construction are:

- compact form and good insulation, with a U-value $\leqslant 0.15\,\mathrm{W/(m^2K)}$,
- orientation and shade for passive use of solar energy,
- energy-efficient window glazing and frames with U-value $\leqslant 0.80\,\mathrm{W/(m^2K)}$ and solar heat-gain coefficients around 50%,
- building envelope air leakage $\leqslant 0.61\,\mathrm{h^{-1}}$,
- underground fresh air ducts that exchange heat with the soil,
- highly efficient heat recovery from exhaust air, with a recovery rate of over 80%.

### 2.3. Microgeneration

Heat pumps can provide space heating, cooling, water heating and in some cases heat recovery from exhaust air. There are currently only a few hundred installations for individual dwellings in the UK, although the market is mature in Scandinavia and the USA (ECI, 2005). Heat pumps are effective when ground-coupled, but it is important to keep the ground in thermal balance over the year, with as much heat taken out in winter as is put back in the summer for cooling, unless the system is abstracting groundwater.

Solar water heaters are simple, reliable, well known and widespread (ECI, 2005). They are probably the microgeneration technology closest to being commercially viable. The most advanced designs concentrate solar radiation onto a small-diameter tube to maximise heating efficiency. Usually an installation of around 4 square metres is needed for solar hot water, producing sufficient output to keep a 200 L tank topped up. Solar water heaters can provide all of summer demand and around 50% of current year-round demand in an average house.

A biomass boiler with automated fuel feeding from a hopper can provide space heating for the whole house as well as water heating (ECI, 2005). Their application in the UK is in its infancy, but the technology is mature in other parts of Europe, especially Austria. Biomass consisting of wood chip or pellets should be sourced locally, but wood pellets brought from Scandinavia by ship still have a low carbon impact.

Micro combined heat and power (micro-CHP) units provide heat as the by-product of the generation of electricity, thus using a resource that would otherwise be lost in centralised power generation. For dwellings, the unit is similar to a conventional boiler and is designed as a drop-in replacement. The power generation unit can be a Stirling engine, reciprocating engine or fuel cell. Though all are at early stages of commercialisation, their power and heat efficiencies are expected to range from around 20% for larger Stirling engines (with up to 70% provided as heat) and up to around 35% for fuel cells (with up to 55% of fuel converted to heat) (ECI, 2005).

For photovoltaics (PV), a typical current residential installation of 12 square metres could generate around 1300 kWh per year, with a peak of around 1.9 kW (ECI, 2005). Efficiencies start from around 4–6% with amorphous silicon to around 15% and potentially 20% for crystalline silicon. The output from PV depends on the particular installation since shading can reduce output severely and orientation is also important.

Wind turbine technology is approaching maturity with inland wind farms, but its application at building scale is still very limited. Part of the problem is that the wind tends to be slow and turbulent at roof level in an urban context, so few working systems currently show reasonable output.

### 2.4. Embodied carbon and methods of manufacture

The cement industry is estimated to contribute 5% of all anthropogenic $CO_2$ emissions (UNEP, 2007). On average, 50% of these emissions stem from chemical changes of the raw material, 40% from fuel combustion and 5% from each of electric power and transport (Kruse, 2004). There are several ways to produce cement, each using different amounts of energy. A modern dry process, which can use as little as 830 kWh per tonne of clinker, is more efficient than a wet process (1390–1670 kWh per tonne). Increasing blended cement production, which includes materials that do not require processing in the cement kiln, such as fly ash or slag, reduces $CO_2$ emissions as well as energy consumption.

There is renewed interest in making modular, prefabricated building elements as a solution to the dual problems of a housing shortage and a persistent low level of quality in construction (ECI, 2005). 'Modern methods of construction' or MMC (a new term for high-quality prefabrication) have inherent advantages. Quality control is easier in a factory environment than on a building site and fewer days are lost due to inclement weather. However, prefabrication using mainly lightweight building materials may lead to an increase in summer overheating and an energy penalty from residential air-conditioning demand.

Using modular units, which can be joined together to create larger or smaller homes, is considered to be a sustainable construction technique (Arup, 2006). This is because the units are flexible and their large-scale factory production creates less waste. These homes can easily be moved, should the land be needed for a different purpose or is no longer suitable, and because they can be moved in sections, the energy used to create them is not wasted when the structure is relocated.

Deciding how best to build adaptive capacity can be a difficult process. There is uncertainty about how factors related to the climate will change in the future, and about non-climate aspects. To help decision makers implement climate change adaptation, UKCIP, working with the Environment Agency, has published an eight-stage framework for taking account of climate risks and uncertainties (Willows and Connell, 2003).

## 3. Future advances to 2050

Delivering buildings that provide the optimal balance between a high quality indoor environment and reduced carbon dioxide emissions—whether through an entirely passive or mixed mode approach—is a challenge that will be increasingly important in the future.

### *3.1. Prediction and modelling*

Important climatic variables for the assessment of overheating risk, usually associated with naturally ventilated buildings (CIBSE, 2005), are dry bulb temperature, solar irradiation and wind speed. For the cooling capacity of air-conditioning plant, the temperature and humidity of the external air is also important. It is essential that the industry have standardised climatic data and standardised methodology for performance prediction. Tools need to be appropriate and take account of future climate factors so that design is able to go beyond compliance, which tends to aim at the lowest common denominator.

In 1998 the UK Climate Impacts Programme (UKCIP) released the first set of comprehensive climate change scenarios for the UK (CIBSE, 2005), subsequently updated in 2002 as the ‘UKCIP02’ scenarios (Hulme et al., 2002). The climate projections in the UKCIP02 scenarios are subject to a number of uncertainties beyond those in the emissions scenarios. There is a general agreement on the need for finer-scale spatial and temporal scenario information, with enhanced regional climate change scenarios and scaling for local climate scenario information (EEA, 2007). The imminent ‘UKCIP08’ scenarios address many of these points. The challenge will be to make best use of them.

Future comfort expectations are likely to change in ways that are not predictable at the present time. People may adapt to higher temperatures, which would call for appropriate overheating risk criteria to be developed. On the other hand it may be that with increasing disposable income people will expect higher levels of summertime thermal comfort than are typical in today’s naturally ventilated buildings (CIBSE, 2005).

### *3.2. Thermal design and the urban heat island*

It is possible to achieve acceptable levels of summertime thermal comfort under the projected warmer future climates using passive cooling measures with modern building materials and modern design methods, as described earlier. However, such buildings remain atypical of most construction in the UK, and in some cases may be difficult to realise due to site restrictions, cost, external air quality, noise pollution or other constraints, particularly in the refurbishment of existing buildings and in urban areas. There is also an urgent need for training in the use of techniques to minimise energy use (ECI, 2005).

However, if comfort expectations and modes of building design and use remain as they are today, attention needs to be paid to providing mechanical cooling by the most energy-efficient approaches (CIBSE, 2005). Solar absorption coolers are one example of a low-carbon cooling technology (Burns et al., 2007; Marques da Silva, 2005).

The issue of low versus high thermal mass in design will also be critical. Beyond conventional strategies, phase-change materials have a part to play. Researchers have identified a number of materials that meet most of the specifications (see Toolbase services, http://www.toolbase.org/Technology-Inventory/HVAC/phase-change-materials). For example, paraffin compounds (linear crystalline alkyl hydrocarbons) are commercially available from petroleum refining or polymerisation. Some manufacturers have demonstrated processes that successfully incorporate paraffin beads into wallboard. More research is needed to improve its performance and reduce costs.

The importance of cities as the home for the majority of British people means that understanding and modelling the urban heat island effect is likely to be important (Hacker et al., 2007). UK employers lost an estimated £168 million a day in productivity during one week of the July 2006 heatwave (Owen et al., 2006).

Cool roofs built from materials with high solar reflectance or albedo and high thermal emittance may reach temperatures considerably lower than their low-reflectance counterparts (GLA, 2006). If this technology is not used, high roof temperatures will accelerate the deterioration of roof materials. In buildings with poor roof insulation, they will also contribute to an increased demand for cooling energy and a decrease in thermal comfort on upper floors. Green roofs, in addition to green spaces, provide multiple benefits for air quality, mitigating excessive heat and enhancing biodiversity (Wilby, 2006).

### *3.3. Windows and illumination*

Insulation-filled and evacuated windows are now under development and have the potential for energy-efficiency improvement over today’s windows. Insulation-filled windows use translucent fillers, including aerogels, a silica-based material with the highest known insulation value of any solid. These fillers retard heat transfer through a window, but do not provide a clear view. They may find application more in skylights than in windows.

Evacuated windows have the air removed from between the panes, creating a vacuum. This reduces heat transfer, lowering the U-value. However, a vacuum creates structural pressures on a window that, in combination with normal pressure variations caused by wind and vibration, can compromise its integrity. A possible solution to this problem is the use of small glass pillars between the panes, which provide some stability but also reduce the window’s clarity.

Research is under way to develop ‘smart windows’, also known as chromogenic or optical-switching windows (Madison Gas and Electric Company, 2007). One of these technologies, electrochromic glazing, is already commercially available. Other technologies under development will enable windows to alter their transmittance in response to temperature (thermochromic) or light (photochromic) fluctuations.

There are several new types of daylighting systems that are being developed, either to reduce the amount of daylight arriving in buildings, or to enhance our use of daylight (Andersen, 2005; IEA, 2003). Shading systems for diffuse light can be based on prisms, holographic elements or sun-protecting mirror elements. For direct sunlight, options involve reflecting louvres, light shelves and light guiding shades. Examples of daylight redirecting systems without shading are anidolic mirror ceilings, and zenith light guiding elements with holographic elements. Daylight transport systems would be based on light pipes and optical fibres.

Ventilation is very important for passive cooling. Windows remain the most effective natural means of ventilating a building. But modern windows often do not ventilate well. Sash-type windows with top and bottom openings work best. Providing effective ventilation with building security and low noise ingress is a key challenge.

### 3.4. *Parasitic heating*

Internal gains, particularly in office buildings, are often a significant component of space heating (CIBSE, 2005). Their effect will become more important with the increased use of solar shading. The three main areas where worthwhile savings are possible are light emitting diode (LED) lighting, vacuum insulated panels in cold appliances, and consumer electronics (ECI, 2005).

LED technology has the potential to approach 100% conversion of electricity to useful light, with a long service life of about 100,000 h. Such lights also allow design flexibility in colour changing, dimming and distribution. Currently issues are relatively low overall light output, poor colour rendering and achieving the advertised service life (UNEP, 2007).

In household appliances, most energy is related to heating or the removal of heat (ECI, 2005). Less than 10% is used in motor control and about 10% goes into the electronics such as displays and controls. Therefore significant savings can be achieved through concentrating on reductions in their heat requirement through measures such as improved insulation or lower temperature washes.

### 3.5. *Flooding and disaster relief*

There is general agreement on the factors and techniques that need to be considered for flood-resistant and flood-resilient building design. But while the advice is in the main derived from experience and a common sense approach, there is a general lack of scientific experimental data underpinning the recommendations. A systematic approach is needed.

The ‘hardware’ approach to disaster mitigation should be accompanied by a ‘software’ dimension of education, and skills training etc. Disaster risk reduction (DRR) is a broad and relatively new concept. There are different definitions of the term in the technical literature but it is generally understood to mean the broad development and application of policies, strategies and practices to minimise vulnerabilities and disaster risks throughout society.

### 3.6. *Microgeneration*

Micro-CHP units operate to match the heat demand of the building they serve, but it is also possible to turn them on at other times, for instance, to generate electricity when prices are high. The heat generated could then be stored in a high-pressure water vessel for use later. This and other new concepts are needed to achieve ‘quality CHP’ in which both heat and electricity generation can be fully utilised.

In PV, the vast majority of solar cells on the market today are so-called first-generation cells made from single crystals of silicon. They are expensive to produce because of the high costs of purifying, crystallising and sawing the single silicon wafer (Physics World, 2007). Second-generation solar cells aim to reduce these costs by using thin films of silicon and other, compound, semiconductors, such as copper indium diselenide and cadmium telluride, mounted on glass substrates. But while they are much cheaper than monocrystalline silicon cells, these second-generation devices suffer from structural defects that make them less efficient than their single-crystal counterparts. To overcome these limitations, researchers are working on third-generation cells that, if practicable, would yield extremely high efficiencies but be as cheap to produce as thin-film devices.

One of the ‘benefits’ of climate change in the UK may be higher yields from solar energy, due to longer sunshine hours in summer and mid-seasons.

Wind in urban areas or around buildings is unpredictable and subject to significant disturbance (ECI, 2005). A cleaner, more concentrated flow can be achieved by channelling or ducting wind into a turbine. This approach is most suited to high-rise blocks with stronger winds and higher load factors. These technologies are still in development and may have some associated noise management issues.

In the longer term, energy storage will be required once the penetration of intermittent renewables reaches a critical threshold. Facilities will have to be incorporated into the electricity network at household as well as substation or national level (ECI, 2005). These devices will be capable of smoothing intermittent generation and demand profiles, enabling each generator to operate at maximum efficiency. Storage may range from seconds to a season. Technologies for electricity storage include flywheels, batteries and hydrogen stores for fuel cells.

There is also the potential to use smart appliances to shift load to times of low carbon generation (ECI, 2005). At present, carbon intensity is virtually constant during daylight hours but drops at night. In future, carbon intensity will fluctuate more as the penetration of wind, PV and other intermittent generators increases. Smart appliances could be switched on at times of home generation to minimise export of electricity to the grid.

### 3.7. *Occupant behaviour*

In practice, energy use in buildings has been found to vary quite widely even between buildings of similar type. The differences arise from variations in design intent, in building envelopes and systems, in modes of use, in the control and maintenance of services, and in standards of construction and airtightness (CIBSE, 2005). Approximately one-half of the electrical load occurs when the building is unoccupied, due to lights and equipment being left on. The PROBE study of office and educational buildings (Building Research & Information, 2001) is a useful reference exploring these issues.

Technological solutions will only be helpful when building occupants are committed to using energy-efficient systems in an appropriate way (UNEP, 2007). There are many factors that influence the energy consumption behaviour of individuals, such as gender, age and socio-demographic conditions.

## Acknowledgements

I am very grateful for critiques and inputs of more measures by Arup colleague Jake Hacker and one anonymous reviewer.

## References

Andersen, M., 2005. Course materials for 4.430 Daylighting, Fall 2006. MIT OpenCourseWare, Massachusetts Institute of Technology 〈http://ocw.mit.edu/NR/rdonlyres/Architecture/4-430Fall-2006/LectureNotes/lec21.pdf〉 (accessed 1 May 2005).

Arup, 2006. Future-proofing our homes. Arup Associates report 〈http://www.arup.com/arup/newsitem.cfm?pageid=9396〉.

BRE, 2007. Designing Quality Buildings 〈http://www.brepress.com/images/BR487_extract.pdf〉.

Building Research & Information, 2001. Post-Occupancy Evaluation. Building Research & Information 29(2) (special issue).

Burns, S.S., et al., 2007. Technical and economic assessment of solar thermal absorption cooling systems in small commercial buildings. Cogeneration and Distributed Generation Journal 22, 45–56.

CIBSE, 2004. Energy Efficiency in Buildings. CIBSE Guide F. Chartered Institution of Building Services Engineers, London.

CIBSE, 2005. Climate Change and the Indoor Environment: Impacts and Adaptation. CIBSE TM36. Chartered Institution of Building Services Engineers, London.

ECI, 2005. 40% House Report. Environmental Change Institute, Oxford 〈http://www.eci.ox.ac.uk/research/energy/40house.php〉.

EEA, 2007. Climate Change and Water Adaptation Issues. European Environment Agency.

GLA, 2006. London's Urban Heat Island: A Summary for Decision Makers. Greater London Authority 〈http://www.london.gov.uk/mayor/environment/climate_change/UHI_summary_report.pdf〉.

Hacker, J., et al., 2007. Climate scenarios for urban design: a case study of the London urban heat island. In: Proceedings International Conference on Climate Change (ICCC2007), Hong Kong.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich. Available from 〈http://www.ukcip.org.uk/resources/publications〉.

IEA, 2003. IEA ECBCS Annex 36: Retrofitting in Educational Buildings—Energy Concept Adviser for Technical Retrofit Measures, subtask A.

Kruse, C., 2004. IIGCC Briefing Note—Climate Change and the Construction Sector. Institutional Investors Group on Climate Change.

Madison Gas and Electric Company, 2007. Building Shell: Windows Madison Gas and Electric Company 〈http://www.mge.com/business/saving/madison/PA_6.html〉.

Marques da Silva, M., 2005. Solar air conditioning potential for offices in Lisbon. Ph.D. Thesis, University of Strathclyde.

ODPM, 2005. Improving the Flood Resilience of Buildings Through Improved Materials, Methods and Details. Office of the Deputy Prime Minister, London 〈http://www.lmu.ac.uk/as/cebe/projects/flood/flood_resilience.pdf〉.

Owen et al. 2006. Adapting to Climate Change Impacts—A Good Practice Guide for Sustainable Communities. Defra 〈http://www.defra.gov.uk/science/project_data/DocumentLibrary/GA01073/GA01073_4083_FRA.pdf〉.

Physics World 2007. Bright Outlook for Solar Cells. 2 July 2007 〈http://physicsworld.com/cws/article/print/30345〉.

Roberts, S., 2008. Altering existing buildings in the UK. Energy Policy, this issue, doi:10.1016/j.enpol.2008.09.023.

UKCIP, 2005. Measuring Progress—Preparing for Climate Change Through the UKCIP 〈http://www.ukcip.org.uk/resources/publications/documents/100.pdf〉.

UNEP, 2007. Buildings and Climate Change: Status, Challenges and Opportunities. United Nations Environment Programme.

Wilby, R.L., 2006. A review of climate change impacts on the built environment. Built Environment 33 (1), 31–45.

Willows, R., Connell, R. (Eds.), 2003. Climate adaptation: risk, uncertainty and decision-making. UKCIP Technical Report. UKCIP, Oxford 〈http://www.ukcip.org.uk〉.