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Altering existing buildings in the UK ☆

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ABSTRACT

The profiles of both existing housing and existing public and commercial buildings show that many have very poor thermal efficiency. The UK housing stock is replaced at a low rate of about 1% a year, so to cut energy use it is essential to address the challenges of existing buildings. This will involve reducing energy demand through passive measures such as retrofitted insulation, replacement of windows and proper airtightness, while ensuring adequate ventilation. Active measures include upgrading improved boilers and adding locally produced energy from wind, biomass, solar power and other sources. The introduction of Display Energy Certificates will increase energy awareness but there will also need to be a programme of increased demolition for the worst-performing homes. In addition, buildings will need to be adapted to cope with worse weather, higher temperatures and increased flood risk as climate change takes effect. Overheating, rather than excessive cold, is set to become a growing problem for householders and employees in existing UK buildings.

1. Key challenges

This review mostly concerns the domestic sector, which accounts for most existing buildings, and uses four times more energy than the commercial sector and seven times more than public administration (BERR, 2007). The review also discusses non-domestic buildings briefly.

Housing stock turnover is low, at about 1% a year (TRCCG, 2008). The Sustainable Development Commission's estimates suggest that 70% of the UK's 2050 housing stock has already been built (SDC, 2007). This means that the adaptation of existing homes is crucial.

Space heating is the largest consumer of household energy. Demand for carbon-intensive energy across the UK must be reduced as part of the mitigation of climate change. This is particularly so for electricity, given the UK's high proportion of coal-fired power stations. But although local consumption of natural gas is less carbon intensive, concern for energy security means that demand for natural gas must be reduced as the UK becomes increasingly dependent on imports. Alongside reducing energy demand, local forms of renewable energy must be exploited for the long term, including solar, wind, biomass, waste and micro-hydro (UK-GBC, 2008).

For adaptation to the effects of climate change, relevant factors are high summer temperatures, weather extremes, an increase in areas at risk of flooding, and water stress.

Behaviour and lifestyle choices will be key because of the 'rebound' effect where increased amenity is taken instead of carbon savings. Higher comfort expectations have meant that the mean internal temperature is estimated to have risen from about 13 to 19 °C between 1970 and 2001 (UCL, 2007). In Austria, this rebound is estimated to be around 15–30% of the savings that would otherwise occur (Haas et al., 1998).

2. State of current science

2.1. Profile of domestic building stock

Buildings dating from the 19th and early 20th century have solid walls and single glazing (Everett, 2007). They had to be well ventilated, to supply the combustion air for coal fires and to get rid of fumes from oil and gas lamps. Building standards improved throughout the 20th century. From the 1930s onwards, cavity walls were introduced with an air gap between two separate skins of brick, largely as a method to prevent damp penetration. From the 1950s onwards, these were replaced by brick or block cavity walls (TRCCG, 2008).

Apartment buildings up to 10 storeys high were constructed using load-bearing masonry walls up to the 1950s, and later concrete floors. Concrete-framed buildings followed. Blocks of over 30 storeys began to be constructed in the 1960s, initially of pre-cast concrete, then of *in situ* concrete from 1970, with steel frames and concrete floors from the 1990s onwards.

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The coal fire remained the normal way of heating UK homes well into the 1960s. With the introduction of North Sea Gas in the 1970s came gas-fired central heating. Up to this time, space heating was based on heating particular rooms as and when needed, but more recently the tendency has been for all rooms to be heated, regardless of occupation, and to a level that allows light clothing to be worn.

The standard assessment procedure (SAP) is the UK Government's approved methodology for rating the energy performance of dwellings (Arup, 2008; BRE, 2005b). The SAP rating is based on energy costs and is expressed on a scale of 1–100, with a higher number indicating a lower running cost. The assessment takes into account a range of features of a building including construction materials, thermal insulation, heating, hot water, ventilation and lighting, but assumes standard use by typical occupants.

Over 40% of properties built before 1919 have a SAP rating of less than 41. Two-thirds of all properties have SAP values of 41–70, irrespective of age, whereas 60% of properties built since 1990 have SAP ratings greater than 70. Hard-to-treat homes generally have features such as solid walls, no gas supply, or no loft space, or are high-rise blocks (CLG, 2006).

2.2. Energy reduction measures for domestic buildings

Cost-effective measures that can be undertaken without a major renovation include sealing and simple improvements to the thermal envelope (Harvey, 2006).

Proper air tightness is the key to minimising heat loss due to ventilation (Everett, 2007). Draught proofing results in fairly small savings but is very cost-effective (CIBSE, 2007). It involves using draught-stripping, replacing leaky windows and closing off unused chimneys. About 80% of houses had some draught proofing by 2001 (BRE, 2003). It is cost-effective to add loft insulation where there is less than 150 mm already in place (BRE, 2005a). The Building Regulations have been tightened and typically around 250 mm of insulation is required where laid between joists (BRE, 2005b).

Most domestic buildings have cavity walls and about 60% of these did not have insulation by 2004 (EHCS, 2004). The thermal performance of cavity walls is normally improved by filling the cavity with insulation, which can reduce the heat loss through the walls by up to 40% (EST EEBPH, 2003). The type of insulation that can be used is limited by the need to inject it through holes or slots made in the inner or outer leaf of the wall. Suitable insulation materials include polystyrene beads, sprayed recycled cellulose and blown glass wool. The injection of insulation into the cavity may be compromised by common construction details, defects (e.g. dirty wall, mortar 'snot', narrow or variable width of the cavity, blockage by pipes or cables) or poor distribution of injection holes.

More extensive retrofits include upgrading windows, external and internal insulation and insulation applied to ground floors. Older buildings often have no insulation at all, so wall and roof *U*-values, the measure of their thermal conductance, will be high, of the order of 1–2 $W/m^2 K$. Upgrading such buildings to post-1990 standards would reduce wall and roof heat loss by a factor of 50–80%.

The performance of most first generation double glazing is poor, with *U*-values of 3–4 $W/m^2 K$ resulting from poorly insulated frames and narrow air gaps (e.g. 6 mm) (UCL, 2007). Double-glazed windows with whole window *U*-values of 1.2 $W/m^2 K$ are becoming available in the UK and are likely to be the norm within 10 years (Strathclyde University, 2006).

If a property is in a poor state of decorative repair, external insulation may improve its appearance as well as its thermal performance. Where the aspect is important, external insulation may be applied to side and rear walls, which often account for most of the overall wall area. This tends to counter the preconception that existing solid-walled dwellings are 'thermally irredeemable'. Solid walls should be seen as an untapped opportunity, rather than as a barrier. Where external insulation is possible, solid-walled dwellings can easily outperform cavity-walled dwellings (UCL, 2007).

The two main ways of insulating externally are ventilated rainscreen systems or rendered insulation systems. In the rendered system, insulation is fixed mechanically or with an adhesive to the existing wall and a reinforced render finish is applied directly to the insulation. External insulation protects the fabric of the building, improves airtightness and is relatively easy to install, leading to faster construction.

Internal insulation typically involves lining, the inside face of the wall with plasterboard on a frame and filling the void with insulation. Benefits of internal insulation are lower cost and that the external appearance of the building is not affected. Disadvantages include significant disruption, loss of floor space and the possibility that thermal continuity is not maintained, for example at the connection between floor and wall.

For ground floors, the disruptive nature of retrofitting insulation means this measure is only likely to be economically viable during major refurbishment of the floor (BRE, 2005a). For suspended timber floors, retrofitting insulation will be much less disruptive but only if there is access to the void below and enough space for safe installation. Concrete floors (in particular suspended pre-cast concrete floors) may be insulated above. The insulation is placed below a timber-base flooring system or a thin cement screed. The insulation should be rigid and have adequate compressive strength. Suitable insulating materials include mineral wool boards and batts and foam insulation.

In a carefully documented retrofit of four representative houses in the York region of the UK, the installation of new window and door wooden frames, sealing of suspended timber ground floors, and repair of defects in plaster reduced the rate of air leakage by 60–70% (Bell and Lowe, 2000). This, combined with improved insulation, doors and windows, reduced the heating energy required by an average of 35%. A reduction of 50% could be achieved at modest cost using well-proven early 1980s technologies, and a further 30–40% reduction through additional measures.

There is a direct relationship between air quality and air humidity. Early superinsulated houses attempted to control energy losses due to ventilation simply by reducing ventilation. However, the air quality they experienced meant that the user had to be committed to live in them (Dunster et al., 2008). Furthermore, humidity levels below 40% and above 60% offer good conditions for breeding micro-organisms (Richarz et al., 2007). An inadequate exchange of air generally leads to an increase in the interior humidity. This is almost always the case in older buildings when old, draughty windows are replaced by new types while the ventilation habits of the users remain unaltered. Tightly sealed new windows reduce the 'automatic' exchange of air that had been adequate in the past and this increases, initially unnoticed, the moisture content of the interior air. This situation becomes critical once the surface temperatures drop so low, such as around thermal bridges, that the relative humidity rises locally to 80% or more. It has even been suggested that some old glass glazing might be retained so that condensation shows the need for ventilation.

2.3. Non-domestic sector

About half of all energy consumed in the service sector is for space heating and most of this is for commercial offices, education, retail, hotels and catering (BERR, 2007). Commercial offices show a higher than sector average for heating, and double the average for cooling and ventilation. Health and hotels and catering show the highest energy consumption per unit floor area due to longer occupancy periods and high demand for hot water (BRE, 2002). Framed buildings (including curtain wall or deep plan) accounted for just over half of the sample by BRE in 1998, and are mostly large multi-storey offices and hotels dating from the 1960s or later (BRE, 1998).

Many buildings in the non-domestic sector have poor fabric, inefficient plant, poor controls and low levels of occupant energy awareness (Strathclyde University, 2006). Overheating is common, leading to increased cooling demand. Improved controls and the appropriate use of thermal mass, glazing, shading and ventilation are important to mitigate overheating. The common observation that windows are wide open while the heating is running is symptomatic of poor control and in some cases poor fabric (Strathclyde University, 2006).

Improving insulation is more important than improving solar control for existing, poorly insulated office buildings, while the reverse is true for well-insulated buildings (Arup, 2008). Note that the improvement of the fabric thermal performance increases cooling loads.

Facades using unitised curtain walling are pre-fabricated, so refurbishment usually involves the complete replacement of the facade (Arup, 2008). Stick systems are more suitable for partial refurbishment as the framing members can be removed and the infill panels replaced. Curtain walls can be upgraded in ways which do not require complete replacement, for example by the resealing of the joints, glass replacement, inserting or increasing the insulation in the opaque areas, and the installation of external shading devices to improve solar performance. The refurbishment of a rainscreen wall typically involves the complete replacement of the external skin and is mainly driven by changes to the aesthetics of the building.

2.4. Energy generation

The efficiencies of gas and oil-fired boilers have improved enormously over the past 30 years, from about 65% to over 90% (Everett, 2007). This has been brought about by the adoption of electronic spark ignition, balanced flues and condensing gas boilers. Cost-effective measures that can be undertaken without a major renovation include upgrading the heating system and hot water heater when they are due for replacement (Harvey, 2006).

The time when the building envelope is upgraded is a good time to replace the heating system, as it provides an opportunity for downsizing the system, or for switching to a more efficient heating system. If the old furnace or boiler is kept, one is keeping an inefficient system, and its efficiency will fall further because it will be operating at a lower average load.

Alternative methods of hot water production are renewable or regenerative sources (solar, heat pumps, waste heat from industry etc.) (UNEP, 2007). The European Union Energy performance of Buildings Directive will require consideration of community heating, CHP (combined heat and power) and renewables as an option within all buildings over 1000 m^2 (CT and EST, 2004). The potential for community heating in the UK is enormous. The main opportunities are as part of refurbishment of existing buildings, especially in dense urban areas with high or low-rise housing currently using electric heating or an existing heat network.

2.5. Adaptation to climate change

The overwhelming majority of homes were designed for the climatic conditions prevalent when they were built (TRCCG, 2008). These conditions have changed and are reflected in long-term observational records. Ten of the warmest years on record have occurred since 1990. August 2003 saw the hottest ever maximum temperature in the UK, 38.5 °C at Faversham, Kent. The average duration of summer heatwaves has increased by between 4 and 16 days in all regions of the UK since 1961. There has been a general trend of decreasing rainfall in summer and increasing rainfall in winter, with heavier winter precipitation events. Projections of changing climate over the coming decades indicate that buildings will be adversely affected by overheating and flooding as well as by water stress.

The CIBSE Guide A says that a dwelling is overheated if it is at 28 °C or more for 1% of occupied hours in living areas, or at over 26 °C for 1% of occupied hours in bedrooms (TRCCG, 2008). Passive measures allow householders to maintain comfortable temperatures while avoiding the environmental costs of air conditioning, such as carbon emissions, noise and waste heat. These measures consist of reducing internal heat gains, enhancing natural ventilation and reducing solar gain through the windows and fabric of the building.

Insulation measures, such as installing loft and wall insulation and double glazing, can have a positive effect on keeping homes cool in the summer as well as increasing winter heating efficiency. Double glazing with low-e coatings can reduce heat gain in summer as well as heat loss in winter. However, insulation also reduces heat loss through the building fabric at night. This effect can be compensated for by increasing ventilation at night and during cooler parts of the day, although open windows at night to introduce cool air could mean security problems, exposure to outdoor noise and poor air quality.

Other passive measures could include external awnings for south and west facing windows, ceiling fans in each room, and painting the external walls a light colour to increase their reflectivity. External shutters are widely used in continental Europe. Though external shading is the most efficient, it is a more problematic option in terms of cleaning and maintenance. In some cases it is necessary to protect the shading device from weathering or other external agents that may cause damage (Arup, 2008). In high-rise buildings, wind loads may seriously damage louvres or any external element connected to the facade.

Thermal mass is important because thermally massive buildings have the ability to absorb heat during times of high gain that can then be re-emitted at times of heat demand (Dunster et al., 2008). Such buildings can be 4–6 °C cooler than peak summer daytime air temperatures. Attaining such performance entails proper provision of ventilation, which requires the security issue of open windows to be addressed, calls for user knowledge, and relies on making use of the radiant component of the comfort temperature sensed by people. Retrofit options for ground floor rooms with solid floors include replacing carpets with wooden floors or tiles to expose the cooling effect of the ground (TRCCG, 2008). Note that the fitting of internal insulation, mentioned earlier, would be a retrograde step in this context.

Green roofs can reduce the amount of heat penetration through roofs and in this regard play a similar role to roof insulation. They reduce the roof temperature by absorbing heat into their thermal mass and because of evaporation of moisture. Note that the roof structure might need to be modified to bear the extra weight of the roof (CIRIA, 2007), and particular attention to waterproofing systems will be needed.

Resistance measures to flooding involve identifying and blocking all potential entry points (TRCCG, 2008). For short-duration floods, entry points include doors, airbricks, sinks and toilets, and gaps in external walls around pipes and cables. For longer durations, measures will need to be taken to prevent water entering through the walls. In deep floods (over 0.9 m), exclusion of water might actually be discouraged as the imbalance between external and internal water levels can cause structural damage to the walls.

Resilience measures to flooding are aimed at reducing the time and cost of recovering from a flood that has entered the home. Unlike resistance, the benefits from resilience measures are cumulative. Each improvement can be made individually since they work independently. Many of these adaptation measures can be installed when the householder is conducting planned maintenance or redecoration. Typical resilience measures include fitting rising hinges so doors can be removed, using water-resistant paint for the lower portions of internal walls, raising electrical points above flood level with wiring drops from above, relocating meters and the boiler above flood level, and replacing carpets with vinyl and ceramic tiles and rugs.

With regard to water stress, the average UK daily consumption of water is around 140–170 L per person, with one-third of this being used for personal bathing (TRCCG, 2008). Water efficiency can be improved by simple, cost-effective measures such as low-flow taps and showers, water-efficient white goods and variable and low flush toilets. Reduced hot water consumption also saves energy, and reduced overall use of water saves the embedded energy in water purification, delivery and treatment.

3. The future

It has been proposed that by 2050, the average existing property should have a SAP rating of 80 (the level of today's new build) and for there to be no homes with a SAP rating lower than 51 (today's average) (ECI, 2005). A number of innovative insulating technologies described in this section will play a part in this programme to alter existing buildings.

While the introduction of 'Home Information Packs' will start to inform homeowners of the thermal performance of dwellings, there is currently no strategy to ensure a minimum level of efficiency for all occupied dwellings (http://www.homeinformationpacks.gov.uk/). A total of 9% of properties in England have a SAP rating below 30 (ODPM, 2003). Many of these are solid-walled properties and use electricity as their main fuel. The vast majority are occupied by low-income families; the poorest people purchasing the most expensive warmth. Under the '40% House' scenario, the demolition rate should increase from 20,000 per year now to 80,000 per year (ECI, 2005), concentrating on those with a low SAP rating or deemed unhealthy under the Housing Health and Safety Rating Scheme.

Models of building energy use are a central part of the design process, but research has repeatedly shown the discrepancy between modelled and real building energy use (UK-GBC, 2007). This is a serious problem which can significantly impact on the potential to achieve carbon reduction targets. Methodological improvements need to be based on sufficient empirical data rather than further modelling. Establishing a national building performance database in order to properly understand energy use will be key (UK-GBC, 2007). This will be helped by the introduction of 'Display Energy Certificates,' initially for non-domestic buildings (CLG, 2008).

3.1. Insulation

Conventional insulating materials will continue to be selected on the basis of their cost and specific performance (CLG, 2008). However, as regulations become ever more stringent, the need to minimise the thickness of insulation required is likely to become more significant.

Vacuum insulation panels (VIPs) are one of the emerging technologies that achieve this. They consist of a micro-porous core structure enclosed in a thin gas-tight envelope, to which a vacuum is applied. VIPs have a thermal performance five to ten times better than conventional insulation. However, VIPs are fragile compared with conventional construction materials and edge effects are significant, requiring careful design and fabrication. Another technology is multi-foil insulation, which is made up of multi-layered reflective films only a few micrometres thick. These layers, which are separated by wadding such as foam or sheep's wool, are sewn together to form a thin insulating blanket. The total thickness of a multi-foil is about 30 mm.

Insulating paints are based on nanotechnology. The two main producers claim good thermal properties due to low conduction through the paint and heat reflection during summer, which is likely to be dependent on the colour of the paint.

Triple glazing provides very high levels of thermal insulation with centre-pane U-values as low as 0.6 W/m^{2}K. Common in Northern European countries, its use in the UK has been limited to energy demonstration projects.

Vacuum glazing has a similar thermal conductivity to conventional low-e double glazing but with a thickness similar to single glazing. Dot spacers are fitted within the cavity to keep the two sheets of glass apart under vacuum. It is likely to be useful in special applications where, for example, window frames for existing single glazing have to be retained for listed buildings.

The use of aerogel as a replacement material for windows is an interesting area for development. It would offer improved thermal insulation properties over the best-performing glazing systems. Some technical issues remain to be solved such as fragility and lack of complete transparency.

If a house were sufficiently well insulated, solar gains and heat from the occupants and appliances should suffice to keep the internal spaces warm in all except the coldest weather. A space heating system might become very small, or even completely unnecessary. This has been the philosophy of the German 'Passive House' programme, which has looked at not only new buildings, but also retrofitting existing ones to superinsulated standards (Everett, 2007). The '3-Liter House' demonstration project in southwest Germany gave an estate of apartment blocks a thorough thermal modernisation, including at least 200 mm of foam insulation in the roof and walls, triple glazed windows with low-e glass, and mechanical ventilation with heat recovery. Monitoring showed that the space heating energy use was reduced by a factor of 7 to only 30 kWh/m^2 a year, or 3 L of heating oil (LUWOGE, 2006). In the UK, the Association for Environmentally Conscious Builders has proposed a 'Gold Standard' for new houses with roof U-values of 0.1 and 0.14 W/m^{2}K for the walls and floor, together with use of the best triple-glazed windows (AECB, 2005).

Once a building is airtight, all incoming and outgoing air can be controlled and passed through a flat plate heat exchanger, allowing up to 70% heat recovery. However, many fan-driven mechanical heat recovery units can use between 250 and 500 kWh of electricity per year (Dunster et al., 2008). The wind cowl has been developed that harnesses natural wind currents to create air pressure sufficient to provide a healthy fresh air supply to buildings via a heat exchanger, with no running energy cost.

An even more radical renovation for old buildings involves replacement of the existing upper floor and roof with prefabricated units that are lowered into place by crane (Harvey, 2006). For example, a roof unit ready-fitted with solar thermal collectors has been used on a 100-year old residential building in Zurich.

3.2. Overheating

There are various new approaches to reducing overheating. Automatic shading systems control solar gains without the need for blinds (Arup, 2008). Electrochromic glazing incorporates a coating that can be switched from clear to tinted, to provide good solar control performance. Its physical properties are altered by applying electrical voltage to the system. This technology could have a future once costs have been reduced. A thermochromic system consists of a special layer between two glass panes. The modulation of the physical properties depends on the thermal conditions in the environment. Photochromic glazing usually consists of a self-shading glass pane reacting to light, as used in some eye glasses. Since change is automatic, this might limit application to skylights and similar uses where the occupants' view outside is not critical.

Phase-change materials can be applied to lightweight structures to provide the effect of thermal mass, at least over the temperature range of their change. However, information for modelling is not yet convincing. These systems are complex and need to be applied carefully (Arup, 2008).

Turning to occupants themselves, the range of temperatures they report as 'comfortable' turns out to be wider in field studies than in controlled conditions in the laboratory (Leaman and Bordass, 2006). This is a vital finding to take from pioneering thermal comfort research and is the basis for what has become 'adaptive comfort theory'. People are more forgiving of discomfort if they have some effective means of control for alleviating it. However, many modern buildings seem to have just the opposite effect. They take control away from the human occupants, and try to place it in automatic systems that then govern the overall indoor environmental conditions and deny occupants means of intervention. Simpler and more robust systems are required, with greater opportunities for users to intervene.

3.3. *Energy management*

Developments in generation technologies, such as photovoltaics, have been covered in a separate review (Roberts, 2008).

Note should be made, though, of the opportunities for heat pumps. In a retrofitted apartment block in Switzerland, the largest savings in secondary energy use resulted from replacing an oil-fired boiler, at 85% seasonal average efficiency, with an electric heat pump having a seasonal average coefficient of performance (COP) of 3.2 (Harvey, 2006). In the future, heat pumps with better COPs should be available. In a retrofit of homes in Louisiana, the heating, cooling and water heating systems were replaced with a ground source heat pump system. Space and hot water heating previously provided by natural gas was supplied instead by electricity through the heat pump, but total electricity use still decreased by one-third (Hughes and Shonder, 1998).

Smart meters both inform users of energy consumption and encourage shifts in power use to reduce peak demand (Everett, 2007). An experimental scheme in California showed an average peak demand reduction of 13% where customers were given warning of a 'super-peak' price (45 p/kWh). The challenge is to reduce the cost of smart meters, which we know result in less energy being sold and thus mean less income for the power company.

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