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Future proof construction—Future building and systems design for energy and fuel flexibility ☆

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ABSTRACT

Buildings of the future must be designed and constructed to reduce energy demand. From a thermal point of view, technologies to minimise heating needs already exist. But in order to reduce future cooling requirements, more positive action will be required. This applies both in commercial buildings, where cooling demand is already significant, and in the domestic sector, where air conditioning is gaining a foothold. A further problem in the housing sector is the rising electrical demand from appliances, which has increased significantly in recent years. In addition to changes in construction practice, such as using means to mitigate the effects of warming climates, better, more sophisticated control systems must be more fully utilised, such as the automatic switching off of appliances, and advanced controls and metering.

A range of alternative energy sources should be integrated in and around single buildings and groups of buildings. Group scale allows more flexibility and will provide higher efficiencies and better control, and is thus the favoured option. Most renewable energy technologies are already understood and the majority are technically proven, though costs are still high in some cases. A combination of renewable energy and storage mechanisms will be needed to decouple energy supply from energy demand. Buildings must be constructed in flexible ways so that they can adapt to allow new technologies to be used. A crucial issue is space for energy storage mechanisms and for alternative fuels.

1. Introduction

Key requirements for buildings of the future are that they should be energy efficient, and capable of utilising different fuel sources, particularly renewables. A further need will be for flexibility in fuel choice as fuels fluctuate in availability over time, and because renewable energy sources can be variable and intermittent in their availability. Storage of fuels, energy, or both, will be necessary.

Government consultation documents such as the *Draft Climate Change Bill* (Defra, 2007) and *Building a Greener Future: Towards Zero Carbon Development* (DCLG, 2006a) both signal important reductions in carbon-intensive energy demand, though the detailed impact on individual buildings is not yet clear. Funding from such sources as BERR (2007) through its Low Carbon Buildings Programme seems to suggest a focus at an individual building level. Implementations such as the 'Merton Rule' (London Borough of Merton, 2003), since followed by many other authorities, place the burden at the development level. Scale is therefore a recurring theme of this paper.

2. State of current science

2.1. Issues and challenges

The most notable current challenge is to make better use of the technologies and techniques for energy-efficient building design that are already available. Though research and development into such technologies and techniques has been ongoing for almost 30 years, their implementation on a broad scale has only increased in the current decade. As a result, the UK has a legacy of inefficient and inappropriate buildings. In addition, buildings have rarely been designed for flexibility and change in their function, or in their source of energy or fuel. The current UK building stock is characterised by a reliance on grid-based electricity supply (used by 99% of consumers according to Hansard (2004), generally from centralised power plant) and mains supplied gas.

The energy mix in the future is expected to be very different. Renewable energy sources and on-site generation for heating,

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cooling and power will become more common. The variable availability of most renewable energy sources implies a need for storage, on site or at some convenient location, or connection to some type of grid or network with storage capacity.

Several of the most common renewable energy sources will require space within, on and around buildings. It will be needed to accommodate energy capture devices such as solar panels and to store fuels such as woodchips and other forms of biomass. Fuel stores of up to several cubic metres can be required for domestic installations. Even older properties, built at a time when solid and liquid fuels were more common, and which were provided with on-site storage, cannot now easily be reconfigured. The space for such storage has often been built upon or converted to some other use. While such storage space may not be at such a premium in larger-scale commercial developments, they are often not designed with future energy requirements in mind.

Building space is very limited and many contemporary designs make no allowance for possible extra requirements. Indeed, the space given over to energy services has been falling with changes in the size and type of equipment. The space required for fuel conversion devices such as biomass burners and for energy storage, such as thermal heat stores, is far more than current gas-based systems' need. Domestic combination boilers that have no hot water store now make up an increasing fraction of installations, in excess of 50% in 2003 (DCLG, 2003). Not only are stores missing, but where they are installed conventional cylinders are typically 30% too small for use as thermal hot water stores for solar systems. There is also a possible conflict between the need for space for alternative energy systems and the need for high-density urban development. Such built environments are designed with little if any space for systems and devices for small-scale energy capture.

This means that maintaining flexibility and ensuring that building energy demand can be satisfied will involve reducing that demand, particularly at peaks. Peak demand reduction will be necessary for heating and electrical services, and increasingly also to deal with potential cooling demand, which is likely to be exacerbated by global warming. This management of peak demand can be achieved by promoting a combination of passive measures, new energy sources and storage systems. Those techniques currently termed 'passive design' will need to be pursued with greater vigour, supported by improved thermal simulation techniques for buildings to optimise their performance. For domestic buildings, post-completion testing, as specified by The Code for Sustainable Homes (DCLG, 2007), could help ensure that the actual performance of buildings in use matches expectations and predictions more closely. The European Directive on Energy Performance of Buildings should also prove to be a driver for the commercial sector. However, care must be taken that this emphasis on building performance does not lead to a rush for litigation. There must be an awareness that with passive measures and more natural comfort conditioning, some flexibility in expectations is also required. Better controls and metering are also key requirements for reducing demand.

One area in which flexibility and understanding may be required is the use of alternatives to full air conditioning, especially given the likelihood of rising temperatures. Natural ventilation will need to be considered on its own or as part of mixed-mode ventilation, and alternatives to conventional cooling must be incorporated.

The increasing electricity-based energy demands from buildings, up by more than 150% since the 1970s (BERR, 2002), create a particularly difficult challenge. The largest increase has come from the spread of consumer electronics. This means that a focus on reducing heating energy demands or finding alternative heating sources will not be a sufficient response. Growing electricity demand may also make it harder to optimise the performance of technologies that rely on providing a balance of heat and electricity, such as combined heat and power.

2.2. Current key advances/technologies

Though challenges exist, there is much that can be achieved with present and near-future technologies, both to reduce demand and to supply energy.

There are obvious building design features that could and should be optimised to reduce demand. They include the location and orientation of buildings on a site; thermal insulation levels; glazing type; the use of shading, particularly external; night-time ventilation to pre-cool buildings in summer; the positioning of rooms on the appropriate facades once orientation is set; the use of exposed thermal mass (heat capacity) in the structure to moderate extremes of temperature; the use of low-power appliances to reduce energy use and heat gain; and control mechanisms to switch off or minimise the use of appliances. All of these techniques are known. They are already being applied to some buildings, often at modest or no additional costs. Several of these technologies have been recommended by reports associated with the UK Climatic Impacts Programme (Arup Research and Development et al., 2005). They should now become generally applied. For older existing properties novel insulation methods such as thin vacuum insulation panels could be considered for upgrading performance.

Santamouris et al. (2007) have described a range of passive measures that can be used to reduce cooling demand, such as new surface coatings. One further interesting option is for phase change materials to be embedded within walls and other construction elements so as to moderate temperature variations and act as enhanced thermal heat capacity. Several pieces of research have already proved the basic technology, such as work carried out by Darkwa and Kim (2005). Low-energy cooling using renewable energy, and techniques such as night-time ventilation or natural cooling, also need to move into the mainstream. These technologies exist now but require exploitation in the immediate future.

Some of the problems involved in reducing demand, and the need to match supply and demand, can be addressed through better smart control systems. Though sophisticated controls have been used in commercial buildings for some time, they have not been fully exploited and are generally under-utilised. This will need to change, and the same technology will need to be used more widely in the domestic sector. The natural accompaniment to such changes will be the wider use of smart metering. These technologies exist but can develop further in the near future if linkages for communication systems and sensors are installed.

The second area of advance is in the supply from alternative energy sources. This is likely to include

- *Biomass fuel sources*: these offer much potential and are already being well exploited in some locations. The technologies exist, are proven, and operate at economic cost.
- *Flat-panel and evacuated tube solar thermal collectors*: the technology is proven and functional, but cost is a barrier at present, particularly since the systems are usually designed only to meet hot water needs and are summer based. There is potential to use these systems in a large fraction of the building stock.
- *Solar photovoltaic systems*: the technology is proven though still expensive with long payback. Most cells currently in the marketplace are first generation, and use crystalline silicon,

or second generation, using thin-film technology. More novel third- and fourth-generation devices are covered later. Photovoltaic arrays composed of modules or areas of cells could add value as architectural elements, which can be offset against their initial high costs.
- *Wind turbines*: the technology is well understood and widely used on a large scale and at virtually economic cost. Emerging small systems that can be mounted on individual houses have become popular though with often disappointing results. More care is needed in urban settings over their choice and installation. Effort is needed to convince some sections of the general public that large-scale wind turbines are suitable as part of the energy supply mix.
- *Ground source heat pumps*: the devices generally require electrical power, so unless renewable energy sources are used there is still a significant emissions issue. The technology is understood and viable though access to suitable land is needed, which could be compromised by high-density building and restrictions on use of such devices in urban locations.
- *Pico- and micro-scale hydropower*: this can only be utilised in specific locations but within such limits offers good potential. Micro-scale hydro is regarded as being below 100 kW and pico-scale below 5 kW.
- *Small-scale and micro-CHP (combined heat and power)*: may be more widely used. But, as with ground source heat pumps, the fuel source must be clean, assured and secure. It may be beneficial to take an overall view of which carbon reduction methods using CHP offer the best opportunities—an issue discussed by Sullivan et al. (2006).

Many of the renewable options can be applied now or in the near future. Two potential limitations with all of them are the availability of products to install and the skilled labour to install them. Some additional details on each technology are available from a variety of sources including DCLG (2006b) and Smith and Pitts (1997).

In summary, the majority of the key advances mentioned here are already possible. But they will require modification in the design and operation of buildings to take account of storage and space needs and must inherently incorporate flexibility for future variation. The majority of these options can be operated both at the level of the individual building and also at a larger scale such as that of the apartment or office block, or even larger. Significantly greater efficiencies can normally be achieved with larger schemes, though at the cost of some loss of autonomy for the user.

3. Future advances to 2050 and beyond

3.1. Issues and challenges

Many potential advances in technology related to energy supply, storage and demand management can be envisaged. A key challenge will be to ensure the smooth development from research into widespread practice. This is something that the building industry has not always achieved quickly and effectively in the past with regard to energy.

The provision of space for these technologies in and around buildings will continue to be an issue. While some of the equipment envisaged as entering widespread use may get smaller, the nature of some of the technologies may require their separation from buildings, particularly domestic ones, for reasons of safety or to allow access for maintenance. These issues could be addressed through modifications in the Building Regulations, which already refer to some aspects of space requirements for solid fuel use. The size and scale of future energy equipment will continue to be an issue, and the larger-scale implementations may be taken on increasingly by energy supply and management companies.

Another challenge may be posed by the competition for scarce resources to construct buildings and devices and to provide fuels for certain technologies. This will be exacerbated by the impact of developing economies and increasing world population. There may also be competition for agricultural produce between food and fuel uses (BusinessWeek, 2007), although other commentators suggest that this effect is exaggerated in the light of Brazil's positive experience with biofuels.

A further challenge lies in the need to develop control and optimisation systems to allow the use of a range of renewable sources in combination or with conventional sources; for example, to use hot water from solar collectors with combination boilers or with heating devices using a direct source of fuel.

A potential obstacle lies in the roll out of new and alternative heating and energy systems to the wider building market. Taking the domestic sector: there are over 22 million homes in the UK, with approximately 18 million gas-powered heating systems. A move away from fossil fuels towards zero-carbon dwellings (DCLG, 2006a) will imply the replacement of many millions of systems with new technologies. Even the UK's experience of the relatively simple alternative of replacing boilers with condensing types has not been entirely satisfactory (Inman, 2005). In commercial buildings, a limitation has been the under-utilisation of control systems to help operators understand and optimise energy use, part of the limitation being suitable staffing.

A particular issue may also arise from the use of one potential technology, CHP. CHP systems generally use conventional fuels such as natural gas and are often markedly more efficient overall, because they provide electricity and use of the waste heat in the building. But difficulties may arise if building energy performance improves so much that demand for heat is much reduced. Small-scale CHP relies on a balance of electrical and heat demand for optimal operation. One option might be to use it in mixed developments where a variety of demands at different times of the day balance the outputs. Use of a renewable energy source in the CHP unit, such as a biofuel, would also reduce its carbon intensity.

One of the ultimate goals often quoted for future energy development is the transition to the 'hydrogen economy' in which the principal fuel is hydrogen. The production of hydrogen requires a low-carbon energy source. It will require substantial effort to ensure that hydrogen from low-carbon sources is widely available in sufficient quantities. Fuel cells that could be developed for use with hydrogen are currently limited by their reliance on other energy sources such as natural gas (Lomas, 2007). CHP systems using fuel cells are currently under development and may offer opportunities in the medium term.

3.2. Key future scientific advances

This section focuses on three main areas: reducing demand, increasing the use of alternative energy sources including renewables and the use of novel energy storage systems.

In the future, new technologies will permit further reductions in the energy demand of buildings. By reducing peak demand, alternative energy sources become more viable and building comfort more controllable.

New construction techniques may make more common the ability to alter the external thermal response of the building envelope—in effect changing from lightweight to heavyweight in tune with prevailing climatic conditions. Some prototype buildings, which either rotate in their entirety or rotate external facade elements, permit such effects. Novel glazing systems with modifiable transmission properties (photo-, thermo- or electro-chromic glasses) may also enhance the ability to control heat gains to buildings, although the manufacture of large areas of these products at a reasonable cost is some way in the future.

Novel integrated wind energy devices for individual buildings are under development (such as those described by Blanch, 2003) and offer alternatives to the common stand-alone options. They may prove more economical and more aesthetically acceptable in some settings by complementing urban and building design.

Woodchips are commonly used for biomass boilers as a cheap and easy-to-obtain fuel. Wood pellets have much higher energy density and can more easily substitute for other solid fuels such as coal, but are much more expensive at present. Changes in processing technology and new plants offering economies of scale should permit pellets to take a larger share of the market in the medium term, and allow more efficient operation because of their lower moisture content. The space required for storage will also be reduced but not eliminated.

Third- and fourth-generation photovoltaic devices can be expected to enter the marketplace in the coming years. Third-generation devices will use organic and nanotechnology cells, while fourth-generation cells will perform multi-spectrum absorption and will involve biological materials. Both can be expected to have impacts throughout the coming century (Tulloch, 2003), although it is not possible to predict how widespread they will become.

Further developments in small-scale CHP can also be expected to improve efficiency, and to have definite impacts in the medium term in the UK. As was seen above, the fuel source must be secure and have minimal global warming potential. This technology can help reduce carbon emissions but will not do away with them altogether.

A number of researchers have suggested the need to find ways of decoupling the current rather direct link between energy supply and demand through the greater use of energy storage. For instance, the work of Strbac et al. (2006) encourages use of fuel cells and flywheels for larger installations.

Fuel cell technology has existed for more than 100 years, although its practical development really only began with the space programme in the 1960s. The main hope for the use of fuel cells comes from the increasing availability of hydrogen and other energy storage media derived from renewable energy. Many types and scales of fuel cells are in the process of development, but are quite costly at present and have relatively poor cycle efficiency. The technology requires upscaling for major schemes and there are relatively few significant examples at present in the building sector.

There is also a range of further energy storage options that will begin to be exploited, including flywheels, flow batteries and other devices. The penetration and practicality of their use in buildings have still to be fully demonstrated and impacts may yet be some time away. Further descriptions of a range of novel technologies can also be found in Smith (2007).

Overall, the key advances in technology in the medium to long term will be predicated on a number of factors outside the built environment but will revolve around a good combination of reduced demand, new energy sources and efficient, appropriate energy storage systems.

3.3. *Exemplar: Barnsley MBC*

In Barnsley, the local council has taken a very proactive role in energy conservation over a period of more than 20 years and has already achieved in excess of 40% carbon emissions reductions compared to 1990 levels. It aims to meet the government target of 60% reduction (set for 2050) by 2010. The most recent improvements have been achieved by a shift to the burning of biomass in the form of woodchips (rather than coal), sourced from council woodland. This uses material that would otherwise have gone mainly to landfill. A number of schemes are in operation in apartment blocks, schools and offices, both new build and refurbishments. A further expansion into schools is planned from 2008 onwards, linked to the government's Schools for the Future programme. A typical example is the Sheffield Road Flats scheme of 2005 (Britannia House) shown in Fig. 1, in which three blocks of apartments (166 one- and two-bedroom properties) have been provided with heat and hot water via 470 kW of biomass boilers. The development did require the enlargement of fuel storage facilities due to the lower energy density of woodchips by comparison with coal, but this was easily accommodated on the site of one of the blocks. Future plans include schemes with the potential to offer cooling (through absorption systems, again biomass fuelled), to match comfort requirements in new buildings arising from high insulation levels, significant internal heat gains and a warming climate. In recognition of its achievements, the council has been the recipient of a number of energy and industry awards (Bradford, 2006).

Fig. 1. Britannia House, Barnsley—new woodchip fuel store shown on right with raised delivery hatch.

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