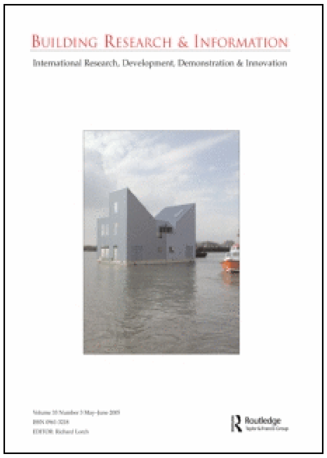

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Examining the carbon agenda via the *40% House* scenario

Brenda Boardman

Environmental Change Institute, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
E-mail: brenda.boardman@environmental-change.oxford.ac.uk

The task of achieving major CO_2 reductions in the residential building stock raises a wide range of policy issues, from the relationship between the rate of demolition and preserving 'heritage' areas, the standards of new build, embodied energy, roof orientation, and the provision of on-site generation. These are all vital, but the paramount task is the refurbishment of the existing building stock. In the UK, 87% of existing homes are expected to be standing in 2050, with a space-heating demand that has been reduced from 14 600 to 9000 kWh per year through the provision of high levels of insulation and measures to avoid the need for air-conditioning. For all homes, old and new, major carbon reductions will require the installation of low- and zero-carbon technologies and reduced energy consumption in appliances. The scale and urgency of the task is identified, with some pointers, to progress the policy debate. The research is based on the *40% House* (2005) report and uses Oxford's UK Domestic Carbon Model. Whilst most of the evidence comes from UK households, the lessons have wider ramifications, both for other sectors and for other countries. Behavioural change will be a vital component, whether from the different professions and trades involved, or from the occupants.

Keywords: building stock, climate change, CO_2 reduction, demolition, design, energy, housing design, housing policy, mitigation, planning policy, UK

Le travail engagé pour réduire de manière importante les émissions de CO_2 dans le parc résidentiel soulève un large éventail de problèmes politiques qui recouvre la relation entre le taux des démolitions et la préservation des zones d'« héritage », les normes des nouvelles constructions, l'énergie intrinsèque, l'orientation des toits et la production d'énergie sur site. Tous ces éléments sont vitaux, mais la tâche la plus essentielle est le renouvellement du parc résidentiel actuel. Au Royaume-uni, 87% des habitations existantes devraient être encore debout en 2050, avec une demande de chauffage qui aura été réduite de 14 600 à 9000 kWh par an par la mise en place d'isolations performantes et des mesures visant à éviter les systèmes de climatisation. Pour toutes les demeures, anciennes ou récentes, seule l'installation de technologies à émission basse ou nulle et d'appareils ménagers à faible consommation d'énergie permettra une réduction importante des émissions de carbone. L'enquête, qui s'appuie sur le rapport *40% House* (2005) et le modèle *UK Domestic Carbon* d'Oxford, précise l'échelle et l'urgence de cette tâche et fournit différents pointeurs pour faire avancer le débat politique. Bien que l'essentiel des faits provienne des ménages britanniques, les enseignements tirés ont des ramifications bien plus larges, tant pour d'autres secteurs que pour d'autres pays. Le changement comportemental des professions et des métiers concernés, tout comme des occupants de ces habitations, sera l'une des composantes primordiales de cette politique.

Mots clés: parc résidentiel, changement climatique, réduction de CO_2, démolition, architecture, énergie, conception des habitations, politique de logement, réduction des risques, politique de planification, Royaume-uni

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Introduction

It is possible to achieve a 60% reduction in the CO_2 emissions from all energy use in the whole UK housing stock by the end of 2050, as required in the UK government's Energy White Paper 2003 (DTI, 2003). That is the conclusion of Boardman *et al.* (2005), but there are numerous implications for policy and practice. About two-thirds of the saving comes from reducing demand and one-third from the introduction of micro-generation and low-carbon technologies into the residential sector. There is only one scenario in the *40% House*[1] report, though others are now being developed. This paper describes some of the implications of this first scenario.

The boundaries of the study were, approximately, the four walls of the dwelling, so there is no reliance on external sources of clean energy, beyond some local combined heat and power (CHP) schemes. Another major constraint accepted by the study is the expected growth in the numbers of houses needed based on two drivers: changing demographics precipitating new household formation as well as replacement of the stock. By 2050, there could be 31.8 million dwellings in the UK in comparison with 25 million presently, largely because people are living in ever-smaller units (2.4 people per household now expected to reduce to 2.1 people per household over the next 40 years), but also because of population increase. Recent projections of population numbers suggest that even this could be an underestimate (Shaw, 2006). There is no identifiable policy that can alter this social trend towards smaller families – energy and housing policy have to accept it and reflect on the implications.

There have been other studies looking at future energy emissions from the domestic sector and all have shown similar opportunities and challenges. There are varying emphases. For instance, Johnston *et al.* (2005) investigated the combined effect of heat pumps and reduced electricity emission factors against a background of a range of energy-efficiency measures – their 'integrated scenario' assumed that the CO_2 intensity of electricity was reduced to the same level as natural gas by 2050.

A low electricity emission factor contributed to the findings of Shorrock *et al.* (2005) and the emphasis was on existing housing, with relatively little demolition by the Sustainable Development Commission (SDC, 2006). In all cases there is recognition of the important task of refurbishment, new building standards and micro-generation, or low- and zero-carbon technologies (LZC). This paper looks at the opportunities for mitigation, using the figures in the *40% House* scenario and does not discuss adaptation. Most of the quoted consumption figures are in delivered energy; where they are useful energy, this is highlighted.

Modelling process

A detailed bottom-up stock model – UK Domestic Carbon Model (UKDCM) – has been developed, largely based on the 1996 English House Condition Survey, supplemented by similar studies in Scotland and Northern Ireland. Wales was based on the West Midlands (Layberry, 2005). This is ongoing work that has been used by the Royal Commission on Environmental Pollution in its 26th study on the urban environment (RCEP, 2007) and is a constituent part of the Building Market Transformation project at the ECI (BMT, 2006). An improved version of UKDCM is to be made publicly available (UKDCM, 2007) early in 2007.

The UKDCM was used in an iterative process to establish the appropriate mix of measures, with the 60% reduction in CO_2 emissions as the fixed end-point. Inevitably, many of the decisions are based on expert judgement, for instance about appropriate levels of demolition rates and the potential for refurbishment of existing properties. The scenario in the *40% House* concept is acknowledged to be a 'best guess' and is being refined through further discussion and research. However, as the team explains, the scenario is very tight – any changes have to be matched by compensating adjustments, which are equally hard. As an example, electricity consumption in lights and appliances is nearly halved, which requires constraint by consumers and manufacturers; any slippage in the implied policies on product standards from Brussels would have to mean, for instance, the installation of more photovoltaics or more demolition to save the equivalent CO_2.

Several data sets have been difficult to complete satisfactorily: there is little information about ventilation rates, storey heights and roof orientation. Others, such as predicted population size, have changed considerably in the last few years, partly as a result of immigration policies and increased longevity. Where the model is sensitive to the variable, particular effort has been made to obtain the best data and to understand the implications of uncertainty. A sensitivity analysis is provided with the model.

The general philosophy in the report was to use cautious judgements (i.e. high rates of household formation, little change in the CO_2 emission factor from electricity) in order to have a robust, but challenging, scenario. This approach was chosen for two reasons: the *40% House* scenario baseline is towards the toughest that could be envisaged, so that achieving the targets identified should allow for some unexpected negative trends. Second, there is a desire to solve the problems within the housing stock and not to rely on other parts of the energy sector to deliver the benefits, for instance through the provision of cleaner electricity.

The detailed policies are rarely identified, but an expectation of changing political and social systems was incorporated by the team conceptually. For instance, a supportive, environmentally concerned population is assumed that can recognize the concept of 'sufficiency': many Western households do not actually need ever-higher standards of living in the home. Despite this, the scenario does include, per person, greater warmth, more space, more hot water and a slightly higher level of appliance ownership to avoid criticism of an unrealistic 'hair shirt' approach. Interacting with this growing environmental awareness is the introduction of personal CO_2 allowances.

None of the technologies being modelled is unknown, though some of them are not yet commercial (e.g. high-performance light-emitting diodes, vacuum-insulated panels for refrigerators, and 300 mm cavities in walls). There is, therefore, a phased introduction of certain technologies in recognition of the need for further development and cost reductions, for instance in fuel cells for micro-CHP and photovoltaics, which reach peak installation rates after 2030.

Relative fabric standards

One of the central set of decisions concerns the relative rates of heat loss in refurbished properties and new build. This, in turn, strongly influences the rate of demolition and construction. In the *40% House* scenario, the objective is for the present average level of energy demand for space heating, 14 600 kWh per annum delivered energy, to be reduced to an average of 6800 kWh per annum across the whole housing stock by 2050 (Figure 1). This is a combination of 9000 kWh per annum in refurbished properties and an average of 2000 kWh per annum for buildings constructed after 1996. As over one million of the latter already exist, with a heating demand in excess of 2000 kWh per annum, for buildings yet to be built the standard will have to be nearly zero heating demand from 2016 onwards (a small heating system, such as a wood-burning stove, is still included to provide psychological comfort and to cope with the occasional severely cold spell). The balancing act involved means that should the 2016 Building Regulations not deliver zero heating demand in reality, then either the level of refurbishment of existing buildings has to be tighter (less than 9000 kWh per annum for heating) or more homes have to be demolished and replaced with lower-energy new construction or some other adjustment. This assumes that there is little change in the carbon intensity of electricity.

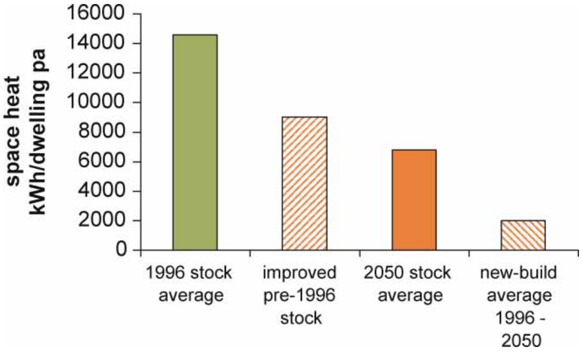

Figure 1 Space-heating demand, *40% House* scenario, UK, 2050. Source: Boardman *et al.* (2005, p. 41)

There is a growing debate about demolition rates (discussed below) and this links in with the interplay between embodied energy and energy in use as portrayed in the two pairs of lines in Figure 2: the bold

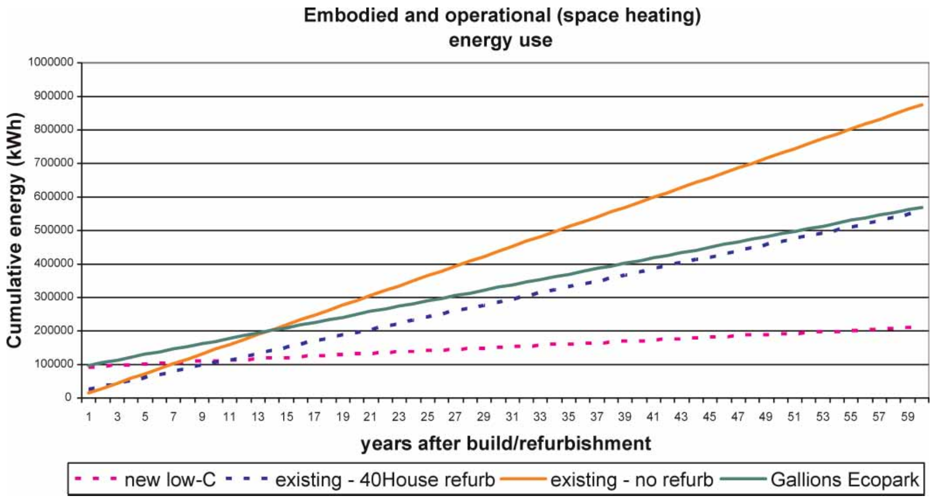

Figure 2 Embodied and direct energy use, sample buildings. Source: based on data from Boardman *et al.* (2005), Joosten *et al.* (2004) and Ireland (2005)

lines refer to existing examples; the dotted lines to proposals for 2050. The Gallions Ecopark in Greenwich, London, is an example of a recent housing development built to a higher standard than the Building Regulations then in force (Part L 2002): it achieved a Building Research Establishment (BRE) Ecohomes excellent rating and four monitored dwellings used an average of 8200 kWh for space heating in the first year (Joosten *et al.*, 2004). Generalizations from such a small sample need to be treated with caution, however post-occupancy monitoring of domestic buildings is rare. In the absence of any better data, this figure of 8200 kWh per annum for space heating is used to compare with standards proposed in the *40% House* report and elsewhere.

The bold line for existing housing represents the average stock space heating use of 14 600 kWh per annum, and the property is not refurbished over the next 60 years, so there is no additional embodied energy – the energy in the existing fabric is ignored. Embodied energy has been estimated at 90 000 kWh for new construction (Ireland, 2005). A simple life-cycle analysis shows that when the embodied energy is included in the calculations (the Gallions line starts on the *y*-axis at 90 000 kWh, not zero), Gallions takes about 13 years to repay the embodied energy through lower heating demand in comparison with an existing building that is not refurbished. Over a period of 60 years, the new building saves energy and, therefore, CO_2.

To achieve the 60% CO_2 reductions in the *40% House* scenario, both the standards of existing and of new buildings have to improve considerably and in parallel. It is the difference between the level of refurbishment and the standard of new construction at any point in time that achieves major energy savings and defines the life cycle CO_2 benefit of demolition. With the pair of dotted lines in Figure 2, an existing dwelling, refurbished to *40% House* scenario standards, does include 15 000 kWh embodied energy (Ireland, 2005) involved in that refurbishment, but achieves roughly the same 60-year energy impact (i.e. embodied plus operational energy) as today's good new build (i.e. the Gallions development). In the *40% House* scenario, the proposal is that Building Regulations have brought the demand for space heating in new properties down to 2000 kWh per annum by 2020 at the latest. It is assumed, in Figure 2, that this new low-carbon building can be achieved for the same embodied energy (90 000 kWh) as the Gallions development; this is probably optimistic. Even if the embodied energy in a low-carbon building is twice as much (i.e. 180 000 kWh), which is probably an excessive allowance, the cross-over point is delayed until 24 years (Killip, 2006). The gap between refurbishment and new build remains substantial. Once space heating is at such a low level, the embodied energy becomes a much more important component in the life-cycle analysis. At the extreme, once a property becomes zero energy demand, then the only energy is that embodied in its construction. This should be viewed as a benefit, not a reason for refusing to build super-efficient homes and highlights some of the varying perspectives on the level of embodied energy. For new buildings, there is expected to be a shift in focus towards low energy both in use and in construction. Another issue is the time lag: the embodied energy has been used (probably in the UK) by the time the building has been constructed, whereas the savings are achieved over the next 60 years through lower space-heating demand. Meanwhile, at present levels of efficiency, there are major benefits of replacing an existing building (without refurbishment) with a relatively low-energy new development even when the embodied energy (and CO_2) is taken into account.

The other implication from Figure 2 is that if the level of refurbishment is improved, but the standard of new building is not (the two central lines in 60 years' time), then they are both delivering approximately the same rate of heat loss and space-heating energy demand, so demolition is of less importance. If these are the relative standards of existing and new homes, the objective of achieving a 60% reduction in the residential sector becomes more difficult. Therefore, it has been assumed in *40% House* that neither standard is static: there are comparable changes taking place in the standards required in both new and existing buildings. As a result, some level of demolition is justified to reduce average space-heating demand.

The *40% House* scenario is so tight that there is no allowance for electricity for air-conditioning anywhere in the domestic sector. This is a difficult decision as the likelihood of more hot summers, as demonstrated in 2003, is increasing with the resultant problems of discomfort and heat stress. Whilst conventional air-conditioning (based on refrigeration cycles) has been rare in UK buildings, the impact of climate change could 'produce a very marked rise in uptake as well as a significant rise in energy use' (Henderson, 2005, p. 549). The exclusion of electricity for air-conditioning is justified if all buildings are adapted and designed to avoid the need for these cooling systems – but it will be a difficult battle to achieve this. Natural ventilation and the stack effect, incorporating night-time cooling, the use of cold-water flows in pipes and radiators, more external shading and shutters, are all ways in which cooler, summer indoor environments could be created. In new buildings there are interactions between the mass of the building and ventilation rates: considerable rates of natural ventilation in summer are anticipated to prevent overheating in new buildings, particularly through night-time cooling (Orme and Palmer, 2003). Night-time cooling is only an option where there is significant exposed thermal mass in which to store the cooling effect of the night-time air and needs to be designed in from the beginning. Another early design decision for a new building is to use the stack effect to produce adequate naturally forced ventilation. Avoiding air-conditioning presents considerable challenges for both new build and refurbishment, but is required in both sectors in the *40% House* scenario.

One of the difficult set of assumptions concerns the ventilation rate in existing homes and the extent to which this can be reduced in future during the heating season. In the model, air movement is reduced to 0.5 air changes per hour (ach) in new buildings and 1.0 ach in existing properties by 2050. A level of only 0.5 ach would require a higher standard of air tightness in construction than is achieved at present and some form of mechanical ventilation to maintain adequate supplies of fresh air. The assumption in the *40% House* scenario is that ventilation systems would be CO_2-neutral – recovering enough heat to offset any electricity for fans.

Refurbishment

The average level of 9000 kWh per annum for space heating in existing buildings by 2050 is challenging to achieve. Around 87% of existing homes are expected to be standing (21.8 million). To get to this level of refurbishment, most insulation measures will be in 100% of properties in most cases (Table 1). Similarly, the *U*-value of the insulation being provided by many of the measures will have substantially improved by 2050. The present standard for lofts of 270 mm already reflects a substantial improvement over the 1996 value, but is now required by several policies (Building Regulations, retro-fits supported by the Energy Efficiency Commitment and Low Carbon Buildings Programme). The exclusion of under-floor insulation from the *40% House* scenario provides some tolerance in these demanding standards: if some existing homes do introduce under-floor insulation, then less intervention is needed in the other components.

The main difficulties concern walls, where a heat loss rate of 0.25 W/m^2K has been identified as the standard to be achieved by 2050. There are two sets of interlocking problems: this level of insulation cannot be achieved for cavity walls with existing materials, where the gap is only 50 mm (assumed to be much of the older stock) and therefore requires different technical solutions. Second, insulation applied to existing solid wall construction is costly and disruptive as well as causing changes in building appearance, the roof-line and external services such as waste water pipes (if done externally) or loss of space (if done internally). An assumption has been made that no new smart material is found for solid wall insulation, so that activity is based on known products. In the *40% House* scenario, the external wall insulation has been applied to a large number of existing properties, whether they are cavity or solid walls, in order to achieve the 0.25 W/m^2K standard by mid-century. This is particularly challenging where the building has townscape importance (but is not in a conservation area). More detailed analysis would identify how many solid walls are externally rendered, so that the application of 100 mm of insulation, between the wall and the rendering, could be made aesthetically acceptable: the appearance would be approximately the same. In Wales, for instance, 47% of the stock (over 0.5 million properties) has solid walls, many of which are rendered (EEPfH, 2006b). Despite this pool of potential interventions, the task of achieving an average heat loss rate in the walls of existing buildings of 0.25 W/m^2K by 2050 is formidable.

Heritage

One area of surprisingly poor statistics is the number and density of residential properties that are listed buildings or in conservation areas. Despite considerable focus, there was no ability to match the best available data with any sensible result. The Oxford team, therefore, had to make some heroic assumptions (Bottrill, 2005) and concluded that 1.2 million dwellings are in conservation areas and about 300 000 individual residential buildings are listed as architecturally

Table 1 Refurbishment measures, *40% House* scenario, 1996 and 2050

Efficiency measure	*U*-value, 1996 (W/m^2K)	*U*-value, 2050 (W/m^2K)	Uptake by 2050 (%)
Cavity wall insulation	0.4	0.25	100
Solid wall insulation	0.5	0.25	15
Loft insulation	0.6	0.15	100
Floor insulation	Varies with dwelling age	Varies with dwelling age	0
Glazing	3.3	0.80	100
Doors	3.5	2.00	100

Note: The 2050 *U*-values are the standard for measures installed then, rather than the average in 2050.
Source: Boardman *et al.* (2005), p. 42.

important. The overlap between the two numbers is not known, but is assumed to be considerable. Hence, about 1.25 million dwellings, or about 5% of the housing stock, are assumed to be sacrosanct because of their architectural and townscape contribution and cannot be demolished. This would be about 25% of the pre-1919 stock if they are predominantly from that age band, as is likely. There is limited information on the present rate of heat loss in these dwellings – these are likely to be different from the mean pre-1919 age category – and little evidence of what standard they could be brought up to, although English Heritage has accepted the challenge of trying to establish these figures (*Green Futures*, 2006). This would cover the way in which sash windows can be double-glazed, the insulation of solid walls and the introduction of various forms of micro-generation. Some measures, such as loft insulation, are invisible and are included in the expected changes to the housing stock in the *40% House* scenario. Many of these buildings have already been subject to considerable transformation with the introduction of bathrooms, down-pipes for sanitation and conservatories. Further transformation could be seen as either a necessary continuation of the trend or further depletion of our heritage. Whatever the decision, the debate is needed, if only to ensure that the occupants of these architecturally important buildings can have a high standard of comfort in future. If not, then the risk is that our heritage will become the next generation of slums.

One implication is that about three-quarters of the pre-1919 stock (3.75 million dwellings) could be demolished if it proves impossible to bring these properties up to an adequate standard of energy efficiency. This would leave the real architectural heritage, as identified by listing, intact.

New build and standards

At present, the national UK rate of construction is 186 000 new homes per annum, of which 20 000 are for registered social landlords and the vast majority are built for owner-occupation. In the *40% House* scenario a total of 10 million homes have to be built in 2005–50 to replace demolished properties and for new household formation: the rough rule of thumb is that around 150 000 homes have to be built each year just for new households and the replacement of demolished properties is in addition. A higher rate of construction was advised by the Barker report in order to create a larger market and lower house prices (Barker, 2004).

The target standard – zero space-heating demand – has already been identified and all of these dwellings have to be designed to avoid the need for electrical air-conditioning, despite a potentially long life and considerable climate change with much hotter summers anticipated. One of the necessary debates is whether this is best achieved by buildings with a high thermal mass, which warm slowly during the day and release their heat at night. Bricks and concrete are the two most conventional materials that provide this thermal mass, although low-carbon alternatives exist, such as rammed earth and unfired clay blocks. However, there are criticisms of traditional methods of construction, such as bricks and mortar, as they are seen to be slow and difficult to control for quality. Building elements manufactured off-site (called Modern Methods of Construction; DCLG, 2006b) can be made more quickly and to more exacting standards, although on-site assembly of manufactured panels can re-introduce problems, especially in relation to air tightness. Concrete provides thermal mass to moderate indoor temperatures, but has high-embodied CO_2. On the other hand, timber and other plant-derived materials can act as carbon sinks in buildings (effectively negative embodied CO_2), but their light weight contributes nothing to thermal mass in a building. An additional concern being voiced by the insurance industry relates to the use of timber-framed dwellings in areas at risk of flooding: the damage done to wood by water can mean that the whole construction has to be demolished, whereas bricks dry out relatively successfully (R. White, personal communication, Director, Institute for Environmental Studies, University of Toronto, Toronto). Reusability and recyclability of materials and whole building elements are concerns for waste management. The debate on curbing energy demand, therefore, sits in a wider debate about building materials and methods and sustainability.

It is for the building industry and its professional advisers to establish the best solutions to these varied challenges. For the *40% House* scenario, the result just has to be low energy demand, whether for heating or cooling, combined with controllable ventilation. It could be that the measures that provide a zero space-heating energy demand will also reduce the need for air-conditioning. However, there is a delicate balance in a well-insulated house between comfort and overheating in summer that is best addressed through a combination of measures that include the following (Orme and Palmer, 2003):

- substantial night-time ventilation (up to 10 ach)
- degree of thermal mass
- level of solar gains during the day
- minimal incidental gains from lights and appliances as a result of improved energy efficiency

A further issue is the difference between the design standard and the way the building functions in practice, as a result of the way it is constructed. The lack of post-occupancy evaluation of recently built homes means that there are virtually no data on what level of energy consumption is being achieved in practice. There is evidence that poor standards of construction and high levels of leakiness mean that the expectations of the Building Regulations are not being delivered (EEPfH, 2004) and that compliance is not being enforced for energy conservation: only fire safety and structural safety are seen as worthy of enforcement by Building Control inspectors (EEPfH, 2006a). A policy is required similar to the R-2000 adopted in Canada:

> every R-2000 home, at completion, must undergo an air leakage test . . . to verify that the leakage doesn't exceed . . . 1.5 ach at 50 Pascals.

This is half the rate typical of newly built conventional homes in Canada (NRCan, 2005). An exacting standard such as this would focus builders' minds on standards of construction and ensure that householders are getting the product they were sold.

It would be useful if best practice could be disseminated more widely and effectively both amongst builders and occupants. For instance, the construction industry is known to be resistant to the widening of the cavity in walls to about 300 mm, because it has implications for additional land take, costs and challenges conventional construction methods. This is despite the evidence at BedZED (a low-energy, low-CO_2 residential development in suburban London) that this is effective and easy to build. Most householders live in relatively few properties during their lifetimes, so have few opportunities to appreciate the benefit of a living in a warm, cosy, energy-efficient dwelling and therefore are not in a position to demand a higher standard of new and refurbished properties.

There are several standards and codes that promote best practice. The mandatory Building Regulations represent the minimum standard, so the government's voluntary Code for Sustainable Homes is being drafted to provide a gentle pull towards future, higher Building Regulation standards (DCLG, 2006c). Both new and conversions of existing homes are covered by BRE's Ecohomes (BRE, 2006). These cover energy use for space and water heating and some lighting. The Association for Energy Conscious Builders has the most ambitious standards (silver and gold), particularly as they include all energy use (Association of Energy Conscious Builders (AECB), 2006; Reason and Olivier, 2006). There are increasing references to the German passive house standard (European Commission, 2006, p. 12; PassivHaus, 2006) which requires close to zero heating and cooling – as advocated by the *40% House* scenario from 2020.

With climate change, some careful modelling and analysis is needed to ensure that buildings have a comfortable internal environment and lower energy demands. There are new dynamics to be considered with the orientation of the building, the use of renewable energy and the avoidance of summer overheating. In order to achieve the high quality and very low CO_2 emissions required from new housing in the *40% House* scenario, design needs to be site-sensitive. Pioneers such as Bill Dunster Associates, the designers of BedZED, have shown how building design can relate to environmental conditions to minimize impacts, although instances of summer overheating at BedZED have been reported (*The Guardian*, 2006). Even with careful design and energy modelling, it is important to allow for ongoing monitoring and remediation once the buildings are built and occupied.

Another issue is the size of new buildings. The average household continues to shrink and contain fewer people, so it would seem logical that the average new home could also be smaller: in the *40% House* scenario, new construction is reduced from an average of 84 m^2 to 74 m^2 to reflect this fact. The proportion of flats being constructed has increased substantially in the past few years, which probably demonstrates this trend: in 2004/05 flats represented 41% of new residential units, up from 15% in 1997/98 (ODPM, 2005a). The energy implications of extra space in new homes are not major: if new homes are super-efficient, the additional space heating burden of an extra 10 m^2 is negligible. However, there are other factors: there may be a relationship between the space available and the quantity of energy-using 'kit' that is installed by the occupant. If there is less space, there can be fewer appliances without necessarily causing any hardship. There is just less room to fill.

The pressure on land and the desire to protect greenfield sites represents an additional factor in the debate about the amount of new construction and, therefore, the size of individual dwellings. There are going to be more households – the present estimate is 33% more by 2050. But this may not need to be as much as 33% more built fabric: there is a choice between denser built form (measured as people per hectare) or spreading developments. The provision of smaller, urban dwellings allows more people to be housed within the curtilege of present towns and cities without the need to extend onto greenfield sites. Again, there are a set of interlocking issues here that need wider public debate: society has to make some choices about the relative priorities of internal private and external public space as well as the considerable embodied CO_2 in creating and maintaining the supporting urban infrastructure (Schiller, 2007).

Other energy uses in new buildings

The Building Regulations have traditionally ignored the use of energy in lights and appliances. The 2002 Building Regulations were the first to introduce mandatory, dedicated, low-energy light fittings: a dedicated fitting cannot take an incandescent bulb. The precedent is continued in the 2006 Building Regulations, so that new markets will be supported through these Regulations, in conjunction with other policies (Palmer and Boardman, 1998). There are now calls to ban the incandescent bulb (Prescott, 2006) to accelerate the use of compact fluorescent bulbs. The constant demand created by constructing 200 000 dwellings a year should promote the design of attractive fittings that utilize new low-energy light sources effectively. In the near future, the emphasis is likely to shift towards even more low-energy light fittings being installed at construction. The use of dedicated fittings is beneficial for the householder as they reduce not only running costs, but also the replacement bulb expenditure: the ballast is incorporated into the holder, not the bulb, so it can be reused. Then, in due course, there could be a performance requirement in the Building Regulations which would, in practice, necessitate the installation of high-performance light-emitting diodes (LED). The efficacy of LEDs is increasing, with recent laboratory examples providing over 100 lumens/W; this compares with 15–17 lumens/W in incandescent bulbs. According to Steve Johnson, group leader of lighting research for the Lawrence Berkeley National Laboratory:

> It is not unrealistic to expect the efficacy of solid-state sources to achieve 150–200 lumens per Watt in the coming decades.
>
> (LDL, 2006)

The exciting opportunities created by organic LEDs (OLEDs) could revolutionize lighting provision, as these provide light from a material, such as wallpaper or cloth; there is no need for a traditional light fitting. At present they have neither the necessary light output nor durability (Department of Trade and Industry (DTI), 2005), although they are already being used in MP3 players and other small displays (Graves, 2006). By 2050, LEDs of either sort are the only light sources in all dwellings in the *40% House* scenario and this is a major contributor to electricity savings: lighting per household drops from 715 to 122 kWh per annum. Even if the present trend to more light fittings per dwelling continues, major savings would still materialize.

Other low-carbon energy uses can be supported at the construction stage. Electric resistance heating for space and water should be avoided – perhaps banned – at least while the carbon intensity of electricity remains high. Additional examples include providing for easy connections to the gas network in the kitchen for cooking, or in the utility room for a gas-fired tumble drier; or making sure that the installation of solar thermal or photovoltaic panels are facilitated through the wires, connections and type of hot water tanks provided. New developments such as these have the added benefit of providing the construction industry with experience, as well as creating a market for manufacturers, that makes retrofit easier and cheaper. There is a conflict at the moment between the small, extra expenditure involved in making these provisions and the house-builders' profit margins.

Even though the Building Regulations do not cover all energy use in lights and appliances, many new homes are provided with fitted kitchens and incentives are needed to ensure that energy-efficient equipment is provided. New trends and policies, particularly linked to house energy labels under the Energy Performance in Buildings Directive, could alter this (see the section on 'Wider policy').

The demonstration of carbon literacy, by both manufacturers and purchasers, is particularly important with lights and appliances where substantial growth in electricity demand has been evident (Shorrock and Utley, 2003; Boardman *et al.*, 2005, p. 11). There has to be some constraint exercised by manufacturers and consumers if this area of growth is to be curtailed, probably supported by new government policies (Boardman, 2006). By 2050, electricity consumption in lights and appliances has been nearly halved (3000 down to 1680 kWh per annum per household). The European Commission has announced a major programme on minimum efficiency standards and labels that should contribute to a new downward trend (European Commission, 2006).

Stock turnover, demolition rates, density and greenfields

There are a series of interactions between the rate of stock turnover (and therefore demolition rates), the density of new construction and the need for greenfield sites. At present, there are 25 million dwellings in the UK and of these about 17 000 are demolished each year. The five-year average over 1996–2001 was 14 600 demolitions per year, but the number rose each year within that period, reaching 20 000 demolitions in 2000/01 (DCLG, 2006a). At this rate the housing stock will not be replaced for over 1400 years.

In the *40% House* scenario, the total number of demolitions links inextricably with the relative standards of new and improved buildings by 2050. The average annual space-heating demand of 9000 kWh for refurbished properties and 2000 kWh for new buildings results in the need to demolish 3.2 million properties between 2005 and 2050. Then the total stock space-heating demand fits with all the other energy demands and installations to enable the 60% CO_2 reduction by 2050. The *40% House* scenario increased the demolition rate to 80 000 dwellings per annum across the UK. This rate was last achieved in 1975, so there is a historical precedent, but not in the immediate past. This higher level of demolition was deemed by the Oxford team to be a sensible compromise between society's concerns for heritage, with obligations to reduce the threat of climate change. Even so, by 2050, the turnover of the housing stock is only down to four centuries, indicating that this enhanced rate may still be insufficient. This is an area where further debate is clearly needed (Kohler and Yang, 2007).

The next set of decisions relates to the characteristics of the 3.2 million dwellings to be demolished. At present, only about 20% of existing demolitions are of unfit properties, so the *40% scenario* therefore demolishes properties equally in all age groups. A debate is required about the need to focus demolitions proactively on energy-inefficient buildings, that are incapable of providing affordable warmth for low-income households. The eradication of fuel poverty by 2016 is a legal obligation on the government (The Warm Homes and Energy Conservation Act 2000), which has become considerably more onerous with the recent increases in fuel prices. Residential energy costs approximately doubled between 2000 and 2006 and this is expected to have put about 2 million families back into fuel poverty, bringing the total for the UK close to 4 million households (J. Saunders, personal communication, NEA, Newcastle). The continuing rise in domestic fuel prices makes tackling fuel poverty an increasingly urgent issue, particularly as providing affordable warmth is one of the four objectives of the government's Energy White Paper (DTI, 2003). The importance of providing healthy housing is being studied by the Commission on Housing Renewal and Public Health (CIEH, 2006).

In 1996, over one-third of the fuel poor (38%) in England lived in homes that had a Standard Assessment Programme (SAP) rating of less than 30 (Department of the Environment, Transport and the Regions (DETR), 2000, p. 136). At low levels of efficiency, properties such as these require a lot of energy and expenditure to keep them warm. It is because of this expense that low-income occupants suffer from fuel poverty. Many of these houses were built pre-1919, probably as solid-walled, terraced houses. There are several programmes designed to improve the insulation of these properties through Warm Front in England (and similar schemes in the devolved administrations) and the Energy Efficiency Commitment. These interventions provide relatively small improvements in many cases and only lift few household out of fuel poverty: about 150 000 vulnerable households between June 2000 and May 2005 (Boardman, 2005). Part of a coherent housing and energy strategy needs to look at the way in which these inefficient, expensive-to-heat properties should be treated and the extent to which they should be demolished, rather than patched up.

When nine major local authorities were given the chance to determine their own housing policy under the Pathfinder Scheme, an immediate emphasis was placed on substantial demolition programmes:

> In the first phase 20,000 homes are being refurbished, 3,000 new homes built and 10,000 demolished.
>
> (H. M. Government, 2005, para. 33)

The local authorities knew which properties no longer warranted retention. This was achieved whilst supporting and sustaining local communities.

Every demolished building results in a considerable quantity of waste materials, some of which can be reused (a brick is used as a brick) or recycled (a brick becomes hardcore) rather than sent to landfill. The higher rate of demolition has, therefore, implications for waste policy and, conversely, waste policy options in the future are determined by the materials and methods of construction now: design for reuse would allow better material recovery in the long-term, which in turn would permit higher demolition rates with relatively low impacts in terms of waste.

The density of the buildings that are demolished, the density of the new construction and the amount of greenfield land required all interact. There are derelict urban sites that previously were built on. As these become used up, there is the risk that new housing will have to be built on greenfield sites, unless new urban sites are created through demolition. Unfortunately, there are completely inadequate data on both existing housing densities and on the density of sites where demolition is taking place (with density based on the plot size only). The one clear principle is that to minimize the need to use greenfield sites, the density of new construction has to be higher than the density of buildings that were on the site previously, and if possible, much higher. If the density is identical, then new sites have to be found for a minimum of 150 000 dwellings per annum to house the expected growth in household formation.

The greatest increase in density would be obtained where a single property with a large garden is replaced by several properties. A bigger challenge is faced if pre-1919 terraced houses, probably at 60–80 dwellings per hectare, are to be replaced (CABE, 2005). However, higher densities in urban areas are known to be occurring, without resorting to tower blocks or other design solutions that may be socially discredited (ODPM, 2005b, p. 36). There are several benefits that flow from greater urban density (Schiller, 2007), for instance: community CHP becomes more viable, there is less need for parking as public transport is local and accessibility to services is good. With thoughtful design, vibrant communities can be created that use local shops and facilities and provide for numerous and varied social interactions. These higher densities also depend upon the size and type of dwelling provided. Smaller properties, for instance, designed for one-person households, young or old, would increase the density of people, with a lesser increase in the quantity of built form. And a higher density of people contributes to the success of the community, the safety of the streets and the local economy.

Low- and zero-carbon technologies and design implications

Although new properties will have been built with zero heating demand from 2020, most have a heating system, for instance a small biomass stove or similar, for extra cold spells and psychological comfort, and all require a method of heating hot water. About one-fifth of all homes still have either gas or electric traditional systems, even in 2050.

One-third of the CO_2 reduction in *40% House* scenario comes from the installation of LZC on the building or in the locality. These are called 'low-carbon or renewable energy technologies' in the 2006 Building Regulations (Annex B, Part L) and some can alternatively be described as micro-generation (usually those that generate electricity). They provide either heat for space or water heating, or electricity, or both (Table 2). Low-carbon technologies are less carbon-intensive than existing sources because they provide CHP, or have a high coefficient of performance, such as heat pumps. The zero CO_2 measures use renewable sources: the sun, biomass or wind. All homes have one or more of the low- and zero-carbon technologies by 2050.

Both technical development and lower unit costs are required to increase the market share of these technologies, hence the need for government and utility policies. The main LZC used in the *40% House* scenario is CHP. By 2050, 63% of homes will use some CHP, 22% of it from a local, biomass or waste-fired scheme in urban centres, and the other 41% are individual systems in the home in less-dense suburbs. Initially, these are based on Stirling engines, with a heat-to-electricity output in the ratio of 6.0:1 (a slight improvement on existing models). By 2050, half of the individual systems use hydrogen-powered fuel cells, with a heat-to-electricity ratio of 1.6:1. These are major changes to the systems in households, but 45 years reflects three replacement cycles, as the average boiler lasts ten to 15 years, so incremental changes are possible. CHP has two added advantages: it uses the traditional wet central heating system in the home and requires minimal infrastructure changes inside the house. Second, the heating system is switched on and electricity is most needed at the same time because the house is occupied, for instance in the late afternoon on a winter's day. The CHP-generated electricity, therefore, contributes disproportionately to peak electricity supply (G. Sinden, personal communication, Environmental Change Institute, University of Oxford, Oxford), which is a major bonus for the electricity system: peak electricity is the most expensive to provide.

Community CHP has an added advantage as it is flexible and can accommodate the declining demand per dwelling, as a result of lower rates of heat loss in the building fabric, by extending the network to an additional property. In practice, this requires careful contracts with the company providing the CHP to make sure it is prepared to invest in extending the heat network, rather than resist the development of low CO_2 buildings.

Space heating is also provided by ground-sourced heat pumps in rural areas where neither the gas nor a heat network exists (9% of households). These properties are assumed to have sufficient land to bury the pipes underground. The heat pump provides the added benefit of being able to work in reverse mode and extract heat from the house in summer and return it to the ground.

Most of the above systems would provide hot water as well. In the average property, the quantity of energy for hot water required is about the same per person in both 1996 and 2050, but less per household. The expectation is that there is a growth in demand for hot water, but that this is offset by increasing the average efficiency of the boiler. The other source of heat for hot water is solar thermal,

Table 2 Low- and zero-carbon technologies for the home

	Heating only	Heating and electricity	Electricity only
Low-carbon	Heat pumps	Combined heat and power (CHP)	–
Zero-carbon	Solar thermal, biomass boiler/stove	CHP using energy from waste or biomass	Solar PV, micro-wind

with 5 m^2 on 60% of the roofs, which allows the space-heating system to be switched off completely in summer. These installations provide nearly 1600 kWh of useful heat per annum – it is useful as it goes directly into the hot water tank.

The other source of electricity generation in the home – in addition to that coming from CHP – is photovoltaics, with 30% of homes having an average of 20 m^2 each by 2050. Such a large provision of photovoltaics is fairly controversial, particularly as it produces most supply in the summer. The expectation is that the cost of photovoltaics will reduce substantially as a result of world demand and possibly new technology by about 2030–40, and most of the installations occur after that period. The excess electricity produced by photovoltaics in the summer could be exported to the grid or used to form hydrogen in the house, for the car or CHP.

Recent experience of the quality of domestic installations under the Major Demonstration Programme (Pearsall and Hynes, 2003) has identified the need for a thorough, systems approach to photovoltaics. The size of the inverter, the positioning of the trip switch and the quality of the installation all affect the actual amount of electricity obtained by the householder (Jardine, 2007). The choice of panel technology will alter the quantity and cost-effectiveness of the installation as the different photovoltaic technologies vary in efficiency from about 5% to 15% and in energy yields (kWh) by a factor of 20% per installed capacity (Jardine and Lane, 2003).

In total, 90% of homes would be generating some of their own electricity, which has substantial implications for the design of the homes, as well as for the electricity supply system. One potential development could be the growth in local energy islands, similar to the development in Woking (Woking Borough Council, 2001; Oakley, 2005) and the plans for Greater London (London Climate Change Agency, 2005). At a sufficient scale, one person's surplus is another consumer's demand, so that neither needs to interact with the national grid. Some of these need no additional skills on the part of the householder (e.g. photovoltaics), but some, like CHP, have considerable maintenance implications if they are to function effectively.

One of the implications for future design is the extent and orientation of the roof space provided, or at least space for solar technologies. In the *40% House* scenario, 60% of households have 5 m^2 of solar thermal and 30% have 20 m^2 of photovoltaics, implying that at least some properties have 25 m^2 of appropriately orientated roof space. If the average existing house is two floors each of 40 m^2 to give a total of 80 m^2 in area, this means the roof has just over 30 m^2 facing in opposite directions on each of two pitched roofs. Photovoltaics ideally are orientated towards the south, but yields are at least 95% of optimum between south-east and south-west (Jardine and Lane, 2003), with similar conditions for solar thermal. Nearly every property with an individual roof (i.e. excluding flats) has to have a sufficient sloping area facing south or west from now onwards. The central ridge may no longer be the ideal design for a roof if the maximum solar benefit is to be obtained for LZCs in the housing stock. This is reflected in the recent choice of 'art-eco' by the Joseph Rowntree Foundation, with long slopes of roof over part of the fabric (Joseph Rowntree Foundation, 2005). The roof design links with the need to reduce the amount of south-facing windows and shading to avoid overheating in summer.

A further aspect for debate concerns the characteristics of the buildings that are housing the LZC and the resultant energy implications. All LZC are easiest to install in new buildings through the Building Regulations or planning permission. The output from many LZC, such as photovoltaics and solar thermal, does not vary with the property on which it is positioned. However, with CHP from fuel cells, the greatest output will be obtained if it is installed in less efficient buildings with substantial heat demands, as indicated by a low SAP rating. The latter category overlaps with pre-1919 and heritage properties. The high heat output results in a high electricity output, some of which can be exported to the grid as it would be surplus to the household's demands. This has the effect of showing that the demolition rate is not a significant variable: the CHP has converted the inefficient property into a lower carbon dwelling because of its exported electricity. If there is any diminution of the level of CHP installation, then the rate of demolition becomes much more significant. Whether it is appropriate to install these expensive technologies in some of the worst housing is a further debate.

One final issue raised by the quantity of LZC proposed is the interface between the system and the occupants. Good-quality monitoring that provides useful information and is highly visible is assumed to involve the householder and contribute to carbon education. Not all systems are provided with monitors or even adequate controls (Keirstead, in press), indicating again the need to look at the human–technology interface holistically. Zero production from a photovoltaics panel indicates that the trip switch has been triggered by a power surge or cut and needs to be reset. Without prompts from a monitor or visible trip switch, the occupant would be ignorant that the system is malfunctioning and the investment is providing nil return.

Low-carbon, planning and building policies

Many of the trends incorporated into the *40% House* scenario imply a much greater focus on energy consumption, at every stage of the building's conception and life. One policy that is beginning to demonstrate this new imperative is the requirement from local authorities that, to obtain planning permission, a specified proportion of energy should be provided from on-site sources. This approach was initiated by the London Borough of Merton and is being replicated by other local authorities for commercial and residential properties (Adrian Hewitt, Principal Environment Officer, London Borough of Merton, personal communication). Recent government planning guidance has confirmed this approach stating that local planning authorities should 'specifically encourage' small-scale renewable energy schemes, both in new developments and in some existing buildings (ODPM, 2004, para. 18). Further encouragement for the installation of micro-generation technologies, community energy and renewable heat comes from the Climate Change and Sustainable Energy Act 2006, both in relation to climate change and fuel poverty. In new homes, the requirements of the Energy Performance in Buildings Directive and the Sustainable and Secure Buildings Act 2006 are that the installation of renewable technologies is 'considered' at the point of construction.

The introduction of mandatory household energy labels in June 2007, under the European Union Energy Performance in Buildings Directive, is the first stage in transforming the residential sector and means that buildings can now be seen as a 'product'. In the past, the installation into existing buildings of optional energy efficiency measures, such as cavity wall and loft insulation, was difficult because it relied on informed self-interest and a decision to spend capital now in order to save future running costs. The energy label will, gradually, provide the single code that summarizes the energy efficiency of the whole building fabric and heating system and, hopefully, provide greater motivation. The European Commission is proposing to extend the Energy Performance of Buildings Directive 'substantially' in 2009 through the introduction of 'minimum performance requirements for new and renovated buildings (kWh/m^2)'. This will 'include a majority of existing buildings' (European Commission, 2006, p. 12). There has never been a minimum energy performance standard for existing residential buildings in the UK, so this could be a powerful piece of new legislation that begins to address the primary problem – the existing housing stock.

Policies that require the installation of low- and zero-carbon technologies (with the consequent improvement in skills and lowering of costs) also force a focus on lowering demand: the smaller the total demand, the lower the amount of micro-generation that has to be provided. At least that is the theory. In reality there may be some confusion between compliance with the Building Regulations and different planning permissions stages (outline and detailed). The real advantages would be more certain if policy brought together all the standards that affect low CO_2 buildings and their construction: planning permission, design for Building Regulations and compliance with the Building Regulations (after construction) into a more coherent process. This could extend to the proper commissioning of any LZC system to ensure that it has been correctly installed and is performing appropriately. In that way, the householder could obtain a guarantee that the expected savings and supply are achieved in reality and that the building is low carbon in operation.

The specific details in the Building Regulations are likely to result in more energy-efficient designs, but these need to 'minimise the need for cooling through passive means' (Henderson, 2005, p. 549), as well as confirming that the standards are delivered, through the use of pressure tests.

The delivery of a national housing and energy policy is likely to involve greater responsibility, and funds, for local housing authorities. They are the people who know where the worst housing is for demolition, can impose standards for new buildings through planning permission, and can judge the relevance of the different micro-generation technologies for financial support. Each local authority could be required to improve the average efficiency of the properties in their area by a specific proportion, each year, as set by central government. Greater local responsibility could be linked to the annual Home Energy Conservation Act (HECA) reports, but with a higher standard of accuracy and detail. For instance, the present HECA reports include demolitions, but not new construction and are often based on models that have a large number of default values. Because they show theoretical energy consumption, based on adequately warm homes, they are indicating a decline in energy use, whereas in reality residential energy demand is still growing. An accurate local authority policy would probably have to be based on an address-specific database of household energy-related parameters, which would have immense benefits for the eradication of fuel poverty as well.

Wider policy

The enormous amount of activity required by 2050 if a 60% CO_2 reduction is to be achieved in the housing stock will have to be stimulated and supported by some clever policies, particularly in relation to existing buildings and consumer behaviour. Much of the focus has to be on the standards to be achieved by individual measures and products, with the general assumption that this occurs through market transformation (Boardman, 2004). Indirect policies, such as higher prices and energy taxes, are not discussed, partly because their effectiveness depends upon efficient products being available and identifiable: higher prices should follow, not precede, stringent product policies. Therefore, a strong product policy approach is assumed as the main component of demand reduction together with constrained consumer purchasing and the introduction of micro-generation. This fits well with the bottom-up approach adopted for UKDCM.

Market transformation is an appropriate framework for the type of product policies envisaged in *40% House*. A strategy is evolved, linking a suite of policies across time. The initial starting point is always a method for measuring the energy consumption of the product (for instance, an occupied house) so that the best and the worst can be identified and labelled. Then, combinations of education (increasing awareness of the implications of the label), procurement and fiscal incentives to develop high new standards are strengthened by policies to remove or upgrade the least efficient properties from the market. As a result, the distribution of the housing stock is shifted towards lower energy and CO_2 impacts. This would be a useful conceptual basis for a new approach to energy use in the housing stock.

Another strong policy focus in the UK will have to be on the eradication of fuel poverty and the tensions between demolition rates, level and targeting of grants and rising fuel prices. For instance, the installation of equipment, such as shutters and grids, to avoid the need for air-conditioning of existing buildings creates some policy problems because its value depends on a theoretical calculation: spending now to avoid a cost that might occur in the future. This is a particular challenge for policies to help the fuel-poor avoid summer overheating. Ideally, these policies would be funded under the Energy Efficiency Commitment of the utilities, but is likely to be difficult to justify because of the lack of present-day cost-effectiveness.

Many of these necessary interventions involve capital expenditure, particularly in relation to LZC: the extra cost of efficient appliances is usually negligible; with insulation it is several hundred pounds; and for LZC and double-glazing, the additional cost is usually thousands of pounds. There seems little likelihood of all individual householders purchasing the substantial quantity of new equipment with their own money at the rate envisaged in the scenario. A suite of policy interventions will be needed to ensure that this revolution occurs and to enable the unit price of an installation to be lowered. These policies would need to reflect the value to the country through the avoidance of large centralized investment or imported gas as well as significant improvements in security of supply: there would be a 38% decline in residential gas demand and by 2050 the housing stock would be a net exporter of electricity to the rest of the UK economy. In addition, peak electricity demand would have been decreased by 25 GW, removing the need for replacement nuclear power. One policy option might be to support the development of Energy Service Companies (ESCo) that undertake design, installation, financing, operation and maintenance of LZC. In return, the ESCo extracts a fee, together with the lower running costs, from the occupants (Saxena and Hinnells, 2006). This is more cost-effective in new build than in refurbishment.

An example of potential policy would be stamp duty rebates for householders who undertake certain improvements within six months of purchasing a property. There could be allowances to be set against income tax for the expenditure on energy-efficiency improvements to parallel the Enhanced Capital Allowances given to industry and commerce. Potential improvements will be ranked in future in the Home Information Packs (HIPs) proved by the seller to the buyer, so that the new owner would not need a further audit. The policy has just to trigger the action.

This links with another generic issue – the methods of energy auditing buildings. At the moment, the Standard Assessment Procedure (SAP) and its associated carbon index are based on details of the fabric and heating system, with either no coverage of other energy uses, or common default values (e.g. electricity for lighting is a multiplier of the dwelling area). A large part of the reduction in demand for electricity comes from stronger policies on appliances, which are not dealt with in detail in this paper and which are excluded from the SAP. This approach is probably necessary when dealing with the design standards of new buildings, but it is not helpful for the majority of the population and most policies. The government is defining the detailed policies required under the Energy Performance of Buildings Directive and these will include the HIPs provided to potential house-purchasers in future. The HIP must be based on an accurate and believable auditing system if it is to retain user confidence. There are proposals for an A-to-G-type rating system, similar to the European Union Energy Label for appliances. In the majority of transactions, there will be an existing fitted kitchen and a number of fixed light fittings. The HIP might ignore these additional energy uses, which would be confusing for householders: it should cover 100% of the CO_2 emissions from the property. This may mean the development of two types of energy audit: one for new build, focusing on the fabric and heating system, the other for existing buildings including all the equipment already in the property. In both cases there will have to be a normative option, with identical levels of energy service assumed, to allow comparisons across different buildings. The type of energy audit and awareness of electricity use in lights and appliances obviously interact though feedback from informative utility bills, and display monitors in the kitchen also help.

The substantial reduction in the electricity used in future appliances envisaged in the *40% House* scenario and in proposed European legislation (European Commission, 2006) means that the incidental gains will be lower in future. Buildings with a zero energy demand for space heating will have to achieve this through high standards of construction, and not rely on useful incidental gains.

One of the underlying assumptions in the *40% House* report is the introduction of free carbon shares, known as personal carbon allowances (PCA) or personal carbon trading. This, or a policy with a similar effect, is essential if consumers are to take personal responsibility for their carbon emissions. Under this scheme, the free-carbon shares are spent when purchasing electricity, gas, petrol and flights (Fawcett, 2005; Starkey and Anderson, 2005; Bottrill, 2006). These will require individuals to have a greater understanding of the sources of carbon whilst allowing for personal preferences on where to try and economize, e.g. the balance between flying, driving and installing microgeneration. They should have the crucial effect of transforming people into informed and carbon-literate consumers.

Conclusions

The need to limit our impact on the climate requires changes in most aspects of our lives – some subtle, some substantial. This is particularly true with the design of new homes, as these will have the longest life. Design always has had to achieve multiple goals; the importance of climate change means that energy and CO_2 emissions have to have a high priority. Some of this refocusing has to take place at the beginning of the project – the orientation, amount of south-facing roof, the deployment of the stack effect, the size and density of the dwelling, building system. The new focus is being encouraged by policies, for instance that a fixed proportion of energy has to be found on site. As a result, the relationship between the architect and the building services engineer is changing: function has to precede form.

With existing homes, the challenge is greater because of the sheer number of properties: 87% of today's homes will still be standing in 2050. To reduce the average heat loss by one-third and to ensure that air-conditioning is not needed are tough targets and require determined effort.

The heritage debate is important. How important is linked to the continuing confusion about how many properties should be labelled 'heritage'. Only one-quarter of pre-1919 homes are in a conservation area or listed, but some of the discussion implies that almost all properties from this age band should be preserved as being of architectural and townscape value. The larger the number of protected buildings, the more vital it is to balance the competing demands of heritage, carbon conservation and the fuel poor. Which heritage homes can be fitted with advanced double glazing? What about internal wall insulation, ventilation systems, floor insulation, microgeneration? One implication of the *40% House* scenario is that the complete protection of large numbers of pre-1919 dwellings risks concentrating too much of the CO_2 reductions onto other properties and of compelling further generations to live in homes that are expensive to heat, as well as polluting, just because they are more than 100 years old.

The demolition debate builds on the discussion about heritage and wider issues. The present rate of demolition results in an imperceptible turnover in the housing stock – new construction is adding, but rarely replacing. One solution would be to focus the installation of low- and zero-carbon technologies, particularly CHP, on the most energy-inefficient dwellings. The high heat demand – and consequent high electricity output – would provide the best return from the capital invested in the CHP and reduce the carbon impact of that property. Otherwise, the inefficient homes have to be replaced through a higher rate of demolition and the subsequent construction of homes that need no heating, if the target of a 60% CO_2 reduction by 2050 is to be achieved.

All these issues demonstrate how energy and housing are now inextricably linked. The *40% House* scenario gives one detailed description of the tasks involved. What is now needed is a clear, coherent strategy to demonstrate how the UK's building assets contribute to a carbon-constrained world.

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Endnote

[1] The title *40% House* investigated the premise that the UK residential sector has the potential to deliver a 60% reduction in CO_2 emissions from 1997 levels by 2050, so that the typical home becomes a '40% house'. In reality, if the expected growth in the number of houses materializes, it has to be closer to a 30% house.