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Technical options and strategies for decarbonizing UK housing

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The implications of some technical options for decarbonizing the UK domestic sector are explored. The main focus is on interactions between dwellings and the energy supply and conversion systems that support them, rather than on the detail of the dwelling stock. Synergies between the electricity supply system, intermediate energy-conversion systems and the dwelling envelope make it possible to achieve 60–70% reductions in CO_2 emissions with plausible combinations of existing and/or emerging technologies. Sensitivity analysis shows that a halving of the carbon intensity of the UK electricity system, plausible improvements to dwelling envelopes, and extensive use of second law energy-conversion systems (typified by, but not restricted to, heat pumps and combined heat and power) to supply space and water heating render total CO_2 emissions insensitive to demolition rates. As a result, increased demolition rates may be unnecessary to achieve deep cuts in carbon emissions from dwellings. Additional insights from this study are the strategic importance of decarbonizing the electricity system and the importance, in developing policy for this sector, of synergies between all components of the energy supply, distribution, conversion and end-use system.

Keywords: building stock, carbon intensity, climate change, CO_2 reduction, decarbonization, demolition, energy, housing

L'étude décrit les implications de plusieurs options techniques de décarbonisation du secteur intérieur britannique. Elle insiste davantage sur les interactions entre la fourniture d'énergie, les unités d'habitation et les systèmes de conversion dont elles sont équipées, que sur les caractéristiques des enveloppes des bâtiments. Des synergies entre le système de fourniture en électricité, les systèmes intermédiaires de conversion de l'énergie et le parc résidentiel permettraient d'atteindre entre 60 et 70% de réduction des émissions de CO_2 grâce à des combinaisons plausibles de technologies existantes ou émergentes. L'analyse de sensibilité montre qu'en diminuant de moitié l'intensité carbone du système électrique du Royaume-uni, des améliorations plausibles apportées aux enveloppes des bâtiments et l'utilisation extensive de systèmes de conversion obéissant au deuxième principe de la thermodynamique – les pompes à chaleur et les systèmes de cogénération de chaleur et d'électricité en sont des exemples types, mais non exclusifs – pour assurer le chauffage des locaux et la génération d'eau chaude, rendraient le total des émissions de CO_2 indépendant des taux de démolition. En conséquence, l'accélération des démolitions pourrait ne pas être nécessaire pour réduire de manière significative les émissions de carbone du parc résidentiel. Parmi les autres constatations de cette étude, citons l'importance stratégique de la décarbonisation du système de génération d'électricité et l'importance, pour l'élaboration des politiques de ce secteur, de synergies entre toutes les composantes de la fourniture, de la distribution, de la conversion et des systèmes d'utilisation finale de l'énergie.

Mots clés: parc résidentiel, intensité carbone, changement climatique, réduction des émissions de CO_2, décarbonisation, démolition, énergie, logement

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Introduction and context

What can be done to achieve significant reductions in CO_2 emissions from the UK housing sector? Previous studies have established the technical feasibility of reductions in excess of 60% by 2050[1] based on detailed technical scenarios (Johnston, 2003; Johnston *et al.*, 2005), and have begun to establish some of the synergies that might make even larger reductions possible. This paper does not set out to repeat this detailed numerical exercise, but to present a more qualitative exploration of technical options and strategies, and in particular to clarify the effects of constraints on and interactions between key subsystems in the energy supply, distribution, conversion and end-use system. The overall objective of this exercise is to arrive at a more strategic evaluation of the potential for decarbonizing UK housing, and to examine some of the system interactions between the dwelling stock and energy supply systems. The main justification for this is that in each of the most critical areas, significant improvements in performance can be achieved by a range of policies and technologies. The future is sufficiently underdetermined, in terms both of policies and technologies, to allow an approach that focuses on the overall physical performance of subsystems to provide valuable insights by beginning to identify which developments and combinations of developments are capable of making a significant contribution to decarbonizing the UK domestic sector and which are likely to be marginal.

To this end, the first substantive sections of the paper review the potential for the reduction of energy demand in existing and new housing. These sections are followed by reviews of technologies for reducing the carbon intensity of delivered heat and electricity and the interactions between them. The final section presents a simple model of the energy use and CO_2 emissions from the domestic sector and analyses the results.

Domestic energy use and CO_2 emissions

The age structure of the British housing stock is illustrated in Figure 1. The median dwelling was built between 1939 and 1959. Given the slow rate of construction in the first six years of this period, the median construction date is likely to have been after 1950 and the median age, therefore, likely to be no more than 56 years. Fewer than 20% of existing dwellings were built before 1918.

This age structure is largely determined by historical patterns of population growth and household formation – from 1801 to 1901 the population of England and Wales grew nearly fourfold, from just over 8 million to more than 32 million (Jevons/Flux, 1906). Over the next century, population grew more slowly, by a further factor of 1.6 (Government Actuary's Department, 2001), but mean household size fell from around 7 to less than 3. Even with no demolition, one would therefore expect around 75% of all of existing dwellings to have been built since 1900. The combination of rapid population growth, falling household size and the demolition of large numbers of dwellings built in the 19th century means that less than 10% of the current stock was built before 1850. It is clear from this brief description that the housing stock in the UK is very far from steady-state. Patterns of construction, renovation and demolition are dynamically determined and statistics such as implicit dwelling life based on the ratio of total household numbers to annual demolition rate have little to do with the actual longevity of housing and, despite suggestions to the contrary, carry no direct implications for public policy towards the stock.[2]

Figure 2 presents estimates of contributions of various elements to the heat loss of the average British house. Shorrock and Utley (2003) estimate the mean heat loss in 2001 to have been approximately 259 W/K, having fallen from approximately 376 W/K in 1970.

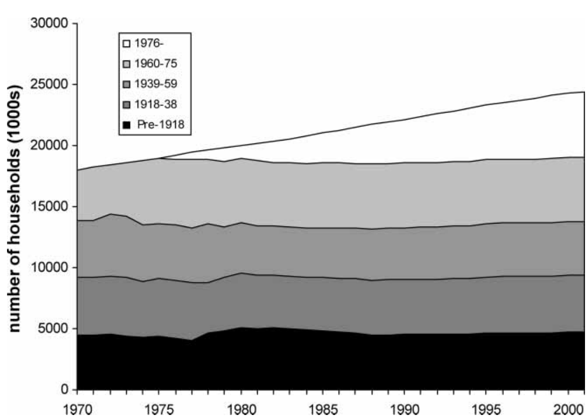

Figure 1 Age structure of the British housing stock (Shorrock and Utley, 2003)

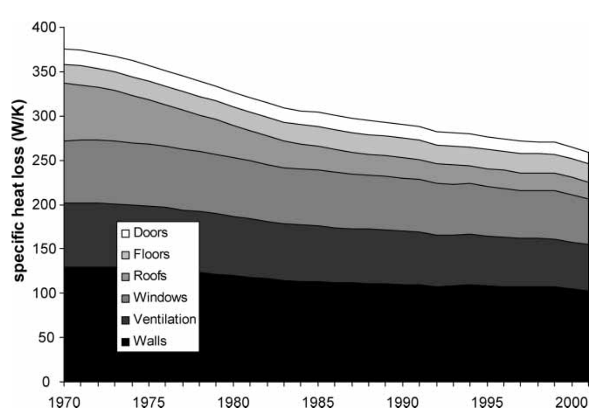

Figure 2 Heat loss of average dwelling in Britain (Shorrock and Utley, 2003)

A total of 40% of the reduction is accounted for by insulation of roofs, the rest by modest improvements to walls and windows, and by reductions in air leakage. By 2001 most walls, whether solid or cavity, remained uninsulated and perhaps 40% of windows remained single glazed.

Large changes have taken place in energy supply to the housing stock since 1970. In 1970, solid fuels still accounted for almost half of delivered energy. By 2001, 90% of delivered energy use was accounted for by natural gas and electricity. Associated with this shift in energy supply was a steady increase in energy-conversion efficiency for space and water heating – from an estimated 49% to 70%. Together with fuel shifts and reductions in dwelling heat loss, the overall effect has been to reduce the carbon intensity of space heating (defined as the additional CO_2 emissions needed to increase the mean internal temperature of a typical dwelling by 1 K) by a factor of approximately four.[3]

In parallel with this reduction in carbon intensity of space heating, the real cost of space heating fell by a factor of more than two and its affordability (defined as the ratio of change in real cost to change in gross domestic product per capita) rose by a factor of almost five. Similar changes took place with respect to the cost of water heating. As a result, CO_2 emissions for the whole of the domestic sector fell by just 22% over the period. Most of the reduction in carbon intensity of space heating has been taken by an increased population (up from 54 million to 58 million), as increased comfort (stock mean internal temperature is estimated to have risen from less than 13° C in 1970 to almost 19° C in 2001), in more households (up from 18.0 million to 24.4 million). In 1970, space heating was a spatially, temporally and azimuthally[4] limited respite from cold. By 2000, the norm was to heat every part of the dwelling continuously to a temperature close to the neutral for light clothing and modest activity levels,[5] regardless of when or whether it was occupied.[6]

Changes in performance of new dwellings

The development of energy performance standards in Building Regulations began in the mid-1960s, but the most significant changes have come in the last decade. Figures 3 and 4 illustrate the potential impacts of the changes that took place in 1995, 2002 and 2006, based on calculations using SAP 2005. SAP is an implementation of the BRE Domestic Energy Model (BREDEM) (Anderson *et al.*, 1985; Shorrock and Anderson, 1995; Anon., 2006), which has been designed, among other purposes, to support the development and implementation of the UK Building Regulations.[7] The implementation

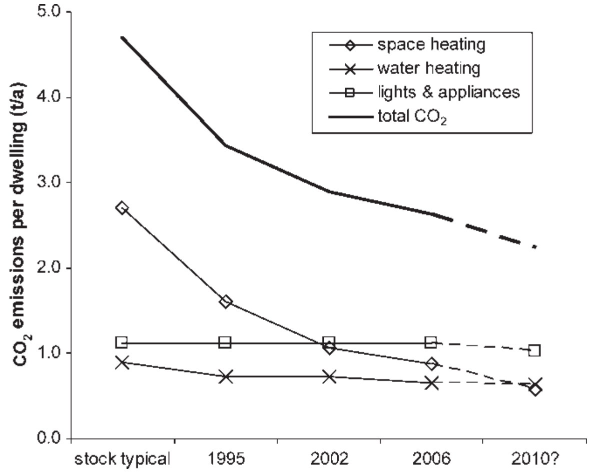

Figure 3 Predicted CO_2 emissions for an 80 m^2 semidetached house under Building Regulations for 1995, 2002 and 2006. Indications are also given of emissions from a dwelling of the same form (1) built under a possible 2010 revision of the Regulations and (2) from a dwelling typical of the current stock

of SAP 2005 used in the present work is a parametric version developed by Lowe, Roberts, Bell and Wingfield. Prediction using such algorithms is unavoidable in the absence of reliable energy-use data from statistically significant samples of new dwellings.

Calculations have been undertaken for a number of standard dwelling types developed during the course of work on the 2006 revision to the Building

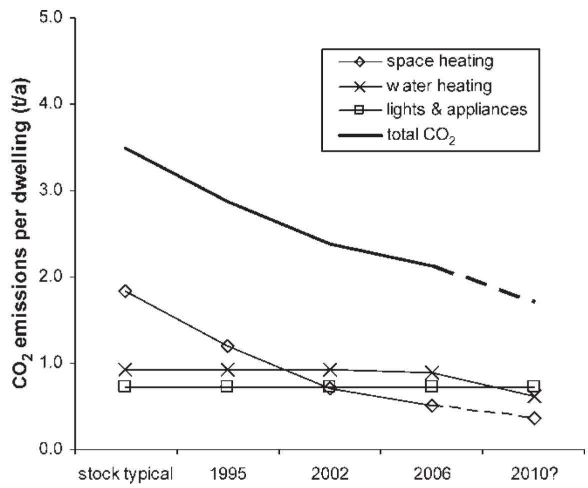

Figure 4 Predicted CO_2 emissions for a 50 m^2 flat under Building Regulations for 1995, 2002 and 2006. Indications are also given of emissions from a dwelling of the same form (1) built under a possible 2010 revision of the Regulations and (2) from a flat typical of the current stock. Note that the graph shows current energy use against date of construction. It is not a time series of energy consumption and does not, for example, imply that electricity consumption in UK housing is static

Regulations for England and Wales. Two are presented here as follows:[8]

- 80 m^2 semidetached house, heated with gas, with a glazing ratio of 25% (window area to total floor area)
- 50 m^2 edge of a mid-floor flat, heated electrically, with a glazing ratio of 25%

These dwelling types have been chosen to span a range of size and compactness. Figures 3 and 4 also include an indication of emissions from dwellings built under a possible 2010 revision of the Regulations and under conditions typical of the housing stock as a whole. The 2010 projection assumes that CO_2 emission targets for gas-heated dwellings are 20% below those required by the 2006 revision to Part L.[9] The 'stock typical' calculations assume the following:

- wall *U*-value of 1.0 W/m^2 K, equivalent to a mix of insulated and uninsulated cavity walls
- window *U*-value of 4.0 W/m^2 K, equivalent to a mix of single glazing and first-generation double-glazing
- in the case of gas central heating, a heating efficiency rate of 72%

Uncertainties surround the analysis presented in Figures 3 and 4. These include the following:

- Despite minor modifications, algorithms for hot water consumption in SAP date from the 1980s. Overall use will have been affected by changes in equipment and behaviour (powershowers, dishwashers, reduced cooking) that have taken place since the original algorithms were defined.
- Although algorithms for lighting have been updated in the 2005 revision of SAP, algorithms for electrical appliances in SAP date from the 1980s. Data presented by Shorrock and Utley (2003) suggest that electricity use for lights and appliances excluding cooking has risen sharply over the last 30 years, but this rise will have been partially offset by a fall in energy use for cooking.[10] Figures 3 and 4 might underestimate overall CO_2 emissions for lights and appliances by as much as 15%.

The precise descriptions of the dwellings analysed above and values of the resulting CO_2 emissions are much less important than the qualitative processes of change that the analysis captures and the sensitivities of the conclusions to the inevitable uncertainties in assumptions. There are a number of observations to make on these two figures:

- Provided that realized dwelling performance is broadly consistent with regulatory requirements, the figures reflect a qualitative shift in the balance of energy use and CO_2 emissions in dwellings, from dominance by space heating in the stock as a whole to dominance by water heating and electricity for lights and appliances in new dwellings. This shift is particularly dramatic in the case of small, compact dwellings. For the 50 m^2 flat illustrated in Figure 4, space heating is predicted to account for less than one-quarter of total CO_2 emissions under the current Building Regulations and just over one-fifth by 2010.[11]
- As residual space heating declines, it becomes progressively more sensitive to uncertainties in envelope and heating system performance, and both internal and external temperatures. For a dwelling compliant with the 2006 revision of the Building Regulations, SAP 2005 predicts that a 2 K rise in external temperatures would reduce emissions from space heating by around one-third, if internal temperatures remained the same. Since demand for space heating is determined by the temperature difference across the dwelling envelope, a rise in external temperature of 2 K would be offset to first order by a similar rise in internal temperatures.
- While the main focus of regulatory development has been on space heating, tougher minimum requirements for boiler efficiency and insulation of hot water storage systems are likely to have led to a reduction in total energy use for water heating.
- An absence of empirical data unfortunately make it impossible to be certain that these reductions are being achieved in practice. While total CO_2 emissions from dwellings are reasonably accurately known, there has been no systematic monitoring of energy use to determine the impact of successive revisions of the Building Regulations, or to determine the split between end-uses within the overall total. Some measurements of internal temperatures have been made (Summerfield *et al.*, in press), which appear broadly consistent with SAP 2005,[12] but there has been no systematic measurement of the thermal properties of dwelling envelopes in the UK stock. There is still less certainty with respect to demand for water heating and cooking.
- Despite the uncertainties, it is possible that regulatory developments, particularly over the last decade, will mean that total CO_2 emissions from new dwellings are now 40–50% lower than the stock mean. Predicted emissions from space and water heating from new dwellings may be 50–60% lower than for the stock as a whole.

- As noted above, further reductions in CO_2 emission targets are expected in or shortly after 2010. Emissions of CO_2 from new housing built to these standards are likely to be dominated by electricity – this is trivially true in the case of electrically heated dwellings, but is also the case in dwellings heated with gas – for the semidetached house shown in Figure 3, 46% of total emissions stem from use of electricity. The carbon intensity of grid electricity is therefore a key variable in determining overall CO_2 emissions. This in turn suggests that the decarbonization of grid electricity should be a key goal of energy and environmental policy – a conclusion to which the author will return to below.

Potential for improved performance in existing dwellings

What might be done to improve the performance of existing dwellings? This discussion is important because on current trends, dwellings built before 2000 will constitute between 65 and 70% of the total stock in 2050.

One of the most important factors determining observed patterns of refurbishment in dwellings is the durability of subsystems. The least durable subsystems tend to be heating systems, which, in the UK, are not expected to last much longer than 15 years, and may need replacing in less than ten years.[13] The physical lifetime of window frames should be many decades, but sealed glazing units may begin to fail within 20 years.[14] Typical domestic roof coverings are normally expected to require replacement within 50 years, and although masonry external walls can and do last for centuries, they are likely to require significant maintenance – re-rendering or re-pointing – at intervals of 50–100 years.

Many measures for improving the carbon performance of existing dwellings involve replacing existing subsystems and are characterized by high fixed and low marginal costs.[15] Such measures are unlikely to be economic unless applied towards the end of the life of each subsystem. Clearly refurbishment strategies that recognize this fact and take account of the maintenance cycle of each dwelling or group of dwellings will tend to be cheaper than strategies that do not.

Figure 5 shows the impact on emissions from space heating of two series of measures applied to typical existing solid- and cavity-walled dwellings. Note that Figure 5 does not include any reduction in demand for space heating that may follow from higher external temperatures in mid-century. The following paragraphs set out the assumptions underpinning the choices of measures for Figure 5.

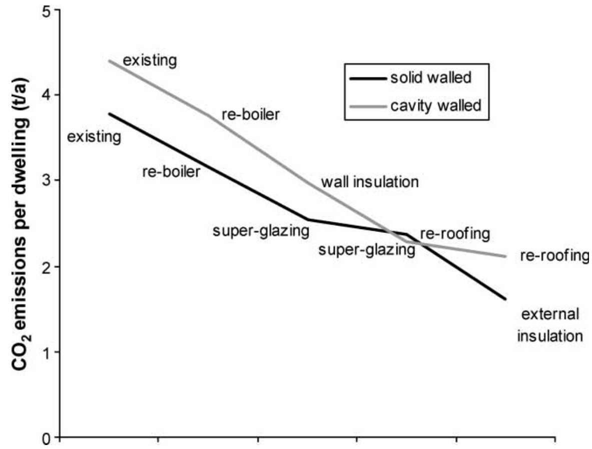

Figure 5 Technical options for reducing the impact of space and water heating in existing dwellings. Dwellings in each case are two-storey, 80 m^2 gross floor area with 25% glazing. The solid-walled house is assumed to be terraced; the cavity-walled house is assumed to be semidetached. The horizontal axis has been deliberately left unlabelled

Boilers

In most UK dwellings, the primary heat source is a gas boiler. Boilers in existing dwellings are likely to be non-condensing, with seasonal efficiencies in the region of 70%. Following an amendment to the Building Regulations in April 2005, almost all new boilers will be condensing, with nominal seasonal efficiencies (SEDBUK ratings) of at least 86%.

Super-glazing

This measure assumes that existing windows, with a mean *U*-value of 4 W/m^{2}K (representing a mixture of single- and first-generation double-glazing), are replaced with windows with a *U*-value of 1 W/m^{2}K. Though this level of performance currently requires triple glazing, at the time of writing double-glazed windows are shortly to be available in the UK with whole window *U*-values of 1.2 W/m^{2}K (Olivier, personal communication, 2006). Although neither level of performance is typical of current window replacement in the UK, it is in the author's view likely to be the norm within ten years. The reduction in heat loss achieved by replacing first-generation double-glazing (*U*-values between 3 and 4 W/m^{2}K, achieved by poorly insulated frames and air gaps as narrow as 6 mm) with state-of-the-art double-glazing is as great as that achieved by replacing single glazing with first-generation double-glazing. One may regret the poor performance and short life of much existing double-glazing, but on the other hand it provides an opportunity to upgrade the performance of existing dwellings significantly.

It is also worth noting that many existing external doors are poorly insulated. Even where doors are double-glazed, the performance of opaque panels is often worse than that of the glazing. Alternatives exist, e.g. insulated external doors mass-produced in North America achieve the feat of being better in all respects (strength and physical security, air-tightness, conduction heat loss, durability and avoidance of endangered tropical hardwoods) and often cheaper than the uninsulated equivalents sold in the UK.

External wall insulation

External wall insulation is assumed to achieve a U-value of 0.25 W/m^{2}K. This is significantly lower than is currently typical in the UK, but is consistent with the low marginal cost of additional insulation in such systems.[16] The simplest methods of external wall insulation involve bonding slabs of insulant to the existing wall and then rendering directly onto the insulant. This is assumed to reduce air leakage as well as wall U-value. Insulation of cavity walls has negligible impact on airtightness.[17]

For both cavity- and solid-walled dwellings, the measures are assumed to be applied in an order that takes rough account of the expected life of the various subsystems.

Remaining solid-walled dwellings can be crudely divided into two groups: those with significant aesthetic value and those without. Dwellings in the latter category are often in a poor state of repair, and external insulation done well is likely to improve their appearance as well as transforming their performance. In the case of the former, there may be limitations to the extent of external insulation that can be undertaken. But in the majority of such dwellings, aesthetic value attaches overwhelmingly to the front facade. Rear facades are in many cases already painted or rendered, and external insulation would probably be aesthetically acceptable. Interestingly, the rear facades of many older solid-walled dwellings have more surface area than the fronts due to greater articulation on plan (the typical plan form for terraced and semidetached dwellings built up to the second decade of the 20th century is 'L'-shaped, with kitchens and bathrooms located at the rear of the dwelling in a projection occupying one-half to two-thirds of the total width of the plot). Front facades are also often more heavily glazed. Thus, as much as two-thirds of total wall area can be at the back, and therefore available for insulation. Insulation of solid walls achieves a reduction in U-value of roughly a factor of ten (2.5 down to 0.25 W/m^{2}K). Thus, the reduction in wall heat loss is, to a first approximation, equal to the proportion of wall insulated – insulation of two-thirds of the external wall reduces heat loss by close to a factor of 2.5, achieving an equivalent whole dwelling U-value in the region of 1.0 W/m^{2}K. Internal insulation of front facades would reduce mean wall U-value by a further factor of two or more.[18]

The primary message of Figure 5 is that emissions from space and water heating can be reduced by a factor between two and three in the case both of solid- and cavity-walled dwellings by a series of measures that can plausibly be expected to be implemented in a significant proportion of dwellings over a period of half a century. Crucially, the above analysis contradicts the case that has been argued for some years that existing solid-walled dwellings are thermally irredeemable (Fawcett, 2002; Boardman, 2003; Boardman *et al.*, 2005). Even without external insulation of solid walls, the greater compactness of solid-walled dwellings compared with cavity-walled dwellings means that differences in heat loss are modest.[19] Where external insulation is possible, solid-walled dwellings can easily outperform cavity-walled dwellings. The key factors are the limited (due to the widths of existing wall cavities) and uncertain (due to difficulties with quality control) thermal performance of retrofitted cavity insulation, coupled with the difficulty of dealing with thermal bridging in cavity-walled dwellings. The central conclusion from this brief analysis is that solid walls should be seen as a strategic national opportunity for energy efficiency improvement and CO_2 emission reduction, rather than a problem. As will be shown below, a strategic shift in technologies for heat supply to dwellings would make this conclusion even harder to ignore.

Reducing CO_2 emissions by re-engineering heat supply

In approximately 78% of the 24.4 million households in the UK, combustion of natural gas is the main means of providing space and water heating. Most of the remaining dwellings are heated by electric resistance heating. The two facts represent a major opportunity for reducing the CO_2 emissions associated with heat supply by the application of a range of so-called low- and zero-carbon technologies (LZCs). The present discussion will be based around heat pumps and combined heat and power (CHP), but much of the discussion would also apply to technologies such as solar thermal.

Neither system can be understood in isolation from the rest of the energy supply system and in particular of the rest of the electricity supply system. The next few paragraphs therefore present brief analyses of the reductions in CO_2 emissions that are possible using these two technologies.

Electric heat pumps

Figure 6 compares the carbon intensity of space and water heat provided by three types of system: electric resistance heating, electric heat pumps with coefficients of performance (COPs) ranging from two to four, and a condensing gas boiler with an efficiency rate of 90%. These comparisons are set out as a function of the carbon intensity of grid electricity. For comparison, the carbon intensity of electricity from the national grid was in the region of 0.53 kg/kWh in 2004.

There are two main categories of domestic electric heat pump: air source and ground source. Air source heat pumps connected to radiators currently provide space heating with an annual an COP of around 2.5, but do not generally provide water heating – this is provided by electric resistance heating instead. Under current conditions, such systems roughly break even with gas boilers for space heating, but are roughly a factor of three more carbon intensive for water heating.

Well-designed ground-source heat pump installations on the other hand can provide both space and water heating, with a combined annual COP between 3 and 4. Such systems therefore already deliver heat at below the carbon intensity of gas. Heat pumps of either type are rarely used for heating in the UK, but there are some 200 000 domestic installations in Sweden. As with CHP, heat pumps can be used at a range of scales from a single dwelling to community.

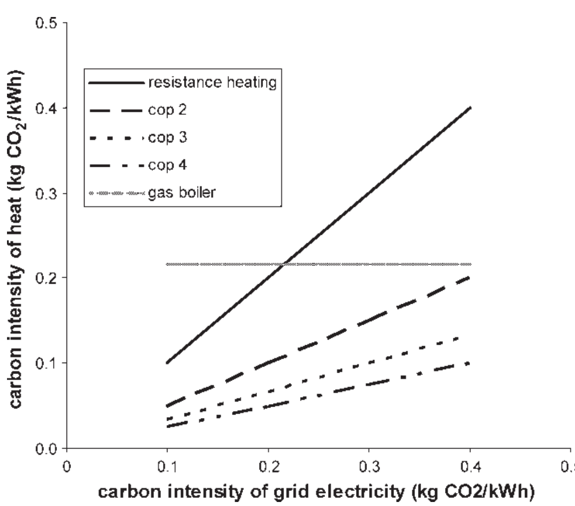

Figure 6 Carbon intensity of space and water heating: comparison of electric resistance heating, heat pumps with annual coefficients of performance (COPs) from 2 to 4, and a gas boiler with annual efficiency rate of 90%. Note that the electricity required to circulate hot water is ignored in all cases

The carbon intensity of heat from heat pumps is likely to decrease further in the future primarily as a result of continued developments in electricity generation. An increasing range of currently available technology is already capable of delivering electricity with a carbon intensity as low as that of natural gas – in the region of 0.2 kg CO_2/kWh. An example would be a system in which half of UK electricity was generated by gas-fired combined cycle plant with an efficiency of 50%, and half came from carbon-free sources such as renewables, nuclear, or fossil generation with carbon sequestration. Figure 7 shows the historical variation of carbon intensity for electricity production since the early 1950s. In the author's view it is very likely that the trend toward de-carbonization of electricity generation displayed over a large portion of the last century will continue for several decades to come. Recent work by Barrett (2006) and Trieb *et al.* (2006) suggests the halving of carbon intensity envisaged here is conservative and that almost complete decarbonization of electricity generation is possible based on currently available renewable technology. If the carbon intensity of grid electricity were halved, the carbon intensity of heat from electric ground-source heat pumps would be as much as a factor of four lower than heat from state-of-the-art condensing boilers.

Combined heat and power (CHP)

CHP uses waste heat from the production of electricity to provide space and water heating for buildings. CHP can be based on a wide range of generation systems – steam

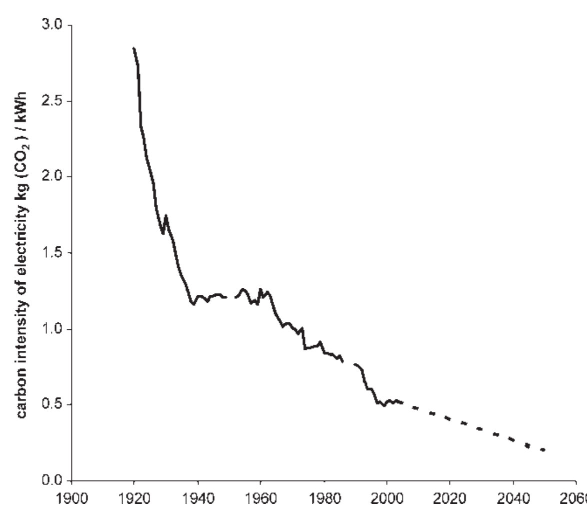

Figure 7 Carbon intensity of UK electricity from 1920 to 2004 with a projection to a carbon intensity of 0.2 kg(CO_2)/kWh in 2050. Data for electricity generation and fuel inputs are from http://www.dti.gov.uk/files/file18945.xls (accessed 6 November 2006). Additional data on fuel inputs and carbon emission factors are from the UK Greenhouse Gas Inventory 1990–2004. Submission 2006. Background Data for Fuel Consumption (http://www.naei.org.uk/reports.php) (accessed 6 November 2006)

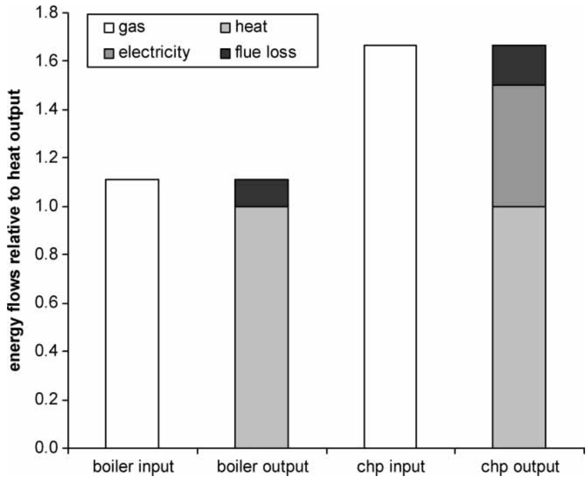

Figure 8 Basis for comparison of gas-fired combined heat and power (CHP) and non-CHP systems for generating heat. The left-hand bar in each case represents the gas input to the system; the right-hand bar the outputs of useful heat, electricity and flue losses. To simplify the analysis, the overall efficiency has been taken to be the same in each case

turbines, Otto and Diesel cycle reciprocating engines, fuel cells, and Stirling engines – and can be implemented at all scales from a single dwelling to a whole city.

Calculation of the carbon intensity of heat from CHP requires carbon values to be assigned to the additional CO_2 emitted by the CHP system compared with a non-CHP alternative and to the electricity generated by the system. The basis of the comparison in the simplest case – a gas-fired CHP system versus a gas-fired boiler – is shown in Figure 8.

Taking:

Q	heat output from CHP and non-CHP systems
gas_{CHP}	gas burnt by the CHP system to produce heat output $\boldsymbol{Q}$
$C_{\text{CHP,gross}}$	gross direct CO_2 emissions from the CHP system
$C_{\text{CHP,net}}$	net CO_2 emissions from the CHP system accounting for the CO_2 value of electricity generated by the CHP system
$C_{\text{el offset}}$	CO_2 value of electricity generated by the CHP system
el	electricity produced by the CHP system in addition to heat output $\boldsymbol{Q}$
γ_l	overall efficiency of CHP and non-CHP systems
z	power-to-heat ratio of the CHP system
c_{el}	carbon intensity of grid electricity
c_{gas}	carbon intensity of natural gas, and
$c_{\text{CHP heat}}$	carbon intensity of heat from the CHP system

then:

$$gas_{\text{CHP}} = \frac{(Q + el)}{\eta} = \frac{Q.(l + z)}{\eta}$$

$$C_{\text{CHP,gross}} = c_{\text{gas}}.gas_{\text{CHP}} = \frac{c_{\text{gas}}.Q.(l + z)}{\eta}$$

$$C_{\text{el offset}} = c_{\text{el}}.el = c_{\text{el}}.z.Q$$

$$C_{\text{CHP,net}} = C_{\text{CHP,gross}} - C_{\text{offset}} = \frac{c_{\text{gas}}.Q.(l + z)}{\eta} - c_{el}.z.Q$$

$$c_{\text{CHP heat}} = \frac{C_{\text{CHP,net}}}{Q} = \frac{c_{\text{gas}}.(l + z)}{\eta} - c_{\text{el}}.z$$

$$\frac{c_{\text{CHP heat}}}{c_{\text{gas}}} = \frac{1}{\eta} + z.\left(\frac{1}{\eta} - \frac{c_{\text{el}}}{c_{\text{gas}}}\right) \tag{1}$$

The message of equation (1) is that for the carbon intensity of heat from a CHP system to be lower than the carbon intensity of natural gas:

$$\frac{c_{\text{el}}}{c_{\text{gas}}} \geq \frac{1}{\eta} \tag{2}$$

Once this condition is satisfied, achievement of the lowest carbon intensity for heat requires the power-to-heat ratio, z, to be as high as possible. Under current conditions in the UK, $c_{\text{el}} > 2 \cdot c_{\text{gas}}$, so inequality (2) is comfortably satisfied. But if, as was suggested above, the carbon intensity of grid electricity is halved over the next 50 years, then gas-fired CHP will no longer outperform gas burnt directly in boilers at any heat-to-power ratio (Figure 9). But note that this conclusion ignores the potential stabilization function of CHP, e.g. in a future grid dominated by non-firm renewables. It is likely that grid

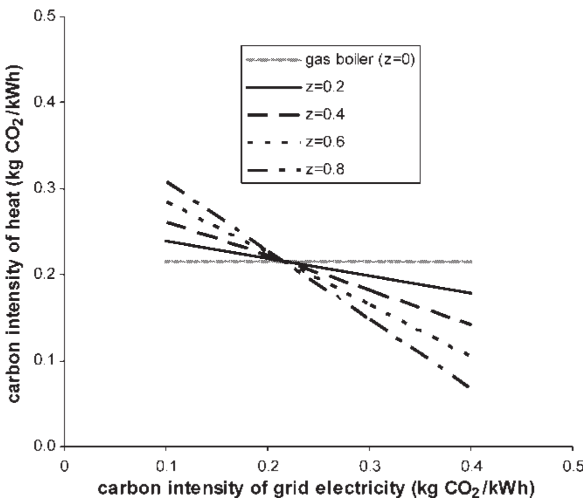

Figure 9 Carbon intensity of space and water heating from gas-fired combined heat and power with an overall efficiency rate of 90%. Note that the electricity required to circulate hot water has been neglected

stabilization would be one of the main functions of fossil-fired generating capacity in a low-carbon future, in which case the carbon intensity of electricity, c_{el}, in the above analysis would not be the mean for all electricity generation, but the mean for the fossil-fired portion. Options such as carbon capture and storage mean that this might still approach zero, but such technologies can, in principle, be applied as easily to large-scale CHP as to electricity-only systems, offering the prospect of heat supply at very low carbon intensities.

The power-to-heat ratios of CHP systems range from two for combined cycle gas turbines and one for systems based on large diesel engines operating in conjunction with district heating systems, down to 0.1 for some single-dwelling micro-generation systems using Stirling engines. As they currently stand, the latter systems would have only a modest impact on overall CO_2 emissions. Feasible technological improvements to Stirling engines might raise electrical generation efficiencies to 20%, equivalent to a power-to-heat ratios of around 0.3. But fuel cell technology is, in principle, capable of delivering an electrical generation efficiency rate of 50% and a power-to-heat ratio in the region of 1.2. The successful commercialization of single-dwelling systems based on fuel cells would transform the landscape for CHP.[20]

The conclusions from this analysis are as follows:

- that under current conditions, heat from CHP can be delivered at a carbon intensity up to one-half that of gas, but that
- maximization of savings currently requires large generators and district heating (Woods *et al.*, 2006)
- the longer-term future of CHP is very sensitive to future technological developments in electricity generation

Prospects for CO_2 emissions in 2050

This section presents estimates of the overall impact of a combination of insulation, strategic shifts in technologies for delivering heat and the partial decarbonization of electricity generation on CO_2 emissions from the UK domestic sector in 2050. These estimates are deliberately based on a simple model of the domestic sector, with the aim of maximizing their transparency.

The model splits delivered energy use into two categories: space and water heating; and lights, appliances and cooking. This split represents the two broad thermodynamic categories of end use in dwellings and the technologies for reducing them – demand for heat at temperatures below 100 °C and demand at temperatures in the range from 100 °C to infinity. Finer subdivision of end uses does not yield significantly greater insight, particularly when considering options for 2050. Estimates of total delivered energy and CO_2 emissions for 2000 are taken from Shorrock and Utley (2003). Predictions for 2050 are derived by splitting the total dwelling stock into three cohorts: dwellings built pre-2000, dwellings built between 2000 and 2010, and dwellings built post-2010. This crude categorization is intended primarily to capture the progressive improvement of dwelling envelopes from 2000 to perhaps 2020.

The total number of dwellings is assumed in all cases to grow by 200 000 per year over the whole of the period. Within this, two rates of demolition are assumed (only dwellings in the pre-2000 cohort are assumed to be demolished):

- 15 000 per year, roughly representing the current rate of demolition
- 200 000 per year, representing a 13-fold increase in the demolition rate

Delivered energy requirements for each cohort of dwellings are as shown in Table 1.

Figures for 2000 have been taken from Shorrock and Utley (2003). Electricity use for lights, appliances and cooking is assumed to do the following:

- remain constant, with efficiency gains offsetting growth in appliance ownership

Table 1 Delivered energy requirements assumed for each cohort of dwellings (kWh/a)

	In 2000	In 2050		
Dwelling cohort	**pre-2000**	**pre-2000**	**2000–10**	**post-2010**
Space and water	18 370	11 022	6 000	4 000
Lights, appliances and cooking	3 449	3 449	3 449	3 449
Total	21 819	14 471	9 449	7449

- be the same for all dwelling cohorts (even the longest lived appliances will be replaced three times between now and 2050).

Delivered energy for space and water heating for dwellings built before 2000 is assumed to be reduced by 40% by measures such as those discussed above. Note that this is a significantly smaller improvement than the factor of two or three suggested above.

Estimates of CO_2 emissions for 2000 have been taken directly from Shorrock and Utley. CO_2 emissions for 2050 assume that carbon intensities for delivered energy are halved – the carbon intensity of electricity is reduced to 0.2 kg (CO_2)/kWh, equal to the current value for natural gas, and the carbon intensity for space and water heating is reduced to 0.1 kg (CO_2)/kWh, equal to half the value for natural gas (this requires a heat pump COP of 2 with the assumed carbon intensity of electricity of 0.2 kg (CO_2)/kWh). The results are set out in Figures 10 and 11.

With these assumptions, the overall reduction in delivered energy is 20% at a demolition rate of 15 000 per year and 31% if demolition is increased to 200 000 per year. CO_2 emissions are reduced by a larger amount – 60% at the lower demolition rate and 64% at the higher. Of the remaining CO_2 emissions, between 50 and 57% are associated with space and water heating and the rest, up to 50%, derive from electricity for lights and appliances.

Larger reductions could be achieved in a variety of ways: reducing the carbon intensity of space and water heating to 0.05 kg (CO_2)/kWh (equivalent to the performance of currently available ground-source heat pumps) would reduce CO_2 emissions by 71% at the lower demolition rate and by 73% at the higher, with grid electricity at 0.2 kg (CO_2)/kWh. Under these conditions electricity for lights and appliances accounts for around 62% of total emissions, and overall CO_2 emissions are relatively insensitive to factors affecting space and water demand. If the demand for space and water heating for pre-2000 housing is reduced from 60% to 50% of the value in 2000, overall CO_2 emissions in 2050 are reduced by just under 10% to approximately 37% of 2000 emissions at the lower demolition rate. Reducing the carbon intensity of electricity generation from 0.20 to 0.15 results in a direct reduction of overall CO_2

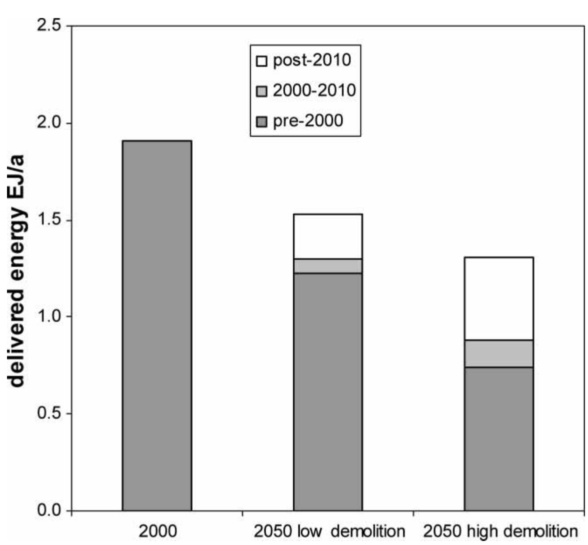

Figure 10 Delivered energy for housing in Great Britain

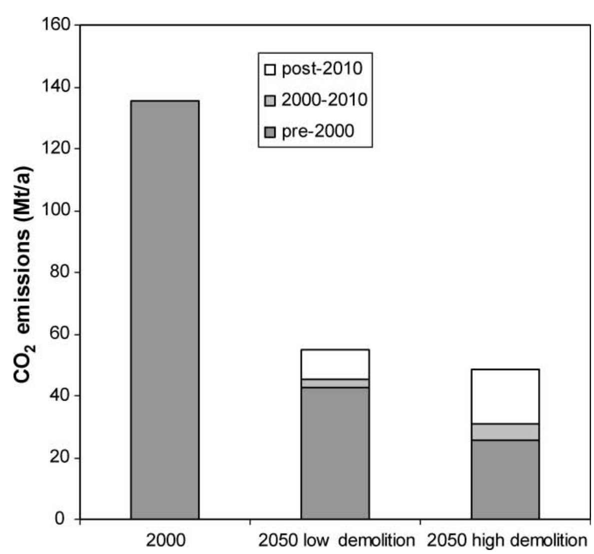

Figure 11 CO_2 emissions from housing in Great Britain

emissions to around 35% of 2000 emissions at the lower demolition rate, and to 30% of 2000 emissions if this step is also assumed to reduce the carbon intensity of delivered heat.

Discussion and conclusions

A range of technical options for reducing CO_2 emissions from UK housing were reviewed, and the interactions between them considered. The underlying models are simple and transparent, and the results appear robust. Much of the analysis is presented quantitatively, but the qualitative conclusions are probably more important than the quantitative.

The main conclusion from the first part of the paper was that apart from those dwellings of high heritage value, delivered energy for space and water heating can be reduced by at least 50% in both solid- and cavity-walled dwellings by improved envelope performance and by increasing the efficiency of gas-fired heating. Where the external insulation of solid walls is acceptable, older solid-walled dwellings are likely to outperform more recent cavity-walled dwellings. In this light, solid walls should be seen as an untapped strategic opportunity, rather than as an insuperable barrier to decarbonization.

Significant improvements in the performance of new dwellings have taken place over the last decade, and further improvements are to be expected over the next decade. These improvements impact overwhelmingly on space and water heating and their effect is that by 2010, electricity for lights, appliances and cooking will account for more than 50% of delivered energy in new housing.

The second part of the paper explores possibilities for reducing CO_2 emissions associated with space and water heating, and with electricity supply. There appear to be a range of technical possibilities for reducing the carbon intensities of both, and, as has been demonstrated above, they interact. The most obvious interaction is between the performance of electric heat pumps and the carbon intensity of electricity supply.[21] Current ground-source heat pump technology coupled with plausible developments in electricity supply can result in a fourfold reduction of the carbon intensity of space and water heating compared with natural gas burnt in condensing gas boilers. Similar synergies would apply to technologies such as ventilation heat recovery and active solar heating. The position with respect to CHP is more complex. The key determinants of the performance of such systems is their power-to-heat ratio and the carbon intensity of the rest of the grid. Power-to-heat ratios for currently available systems range from 0.1 to around 2.0. In the short-term, high performance CHP can more than halve the carbon intensity of space and water heating.

A key implication of the last two paragraphs is that the decarbonization of the electricity system is a necessary condition for the decarbonization of the domestic sector. Low carbon electricity will directly reduce emissions associated with lights and appliances and transform the context for heat pumps.[22]

When plausible assumptions about dwelling performance, the demand for electricity, the performance of the electricity system, and the decarbonization of space and water heat are put together, a number of additional conclusions emerge:

- Large reductions in energy use and CO_2 emissions associated with space and water heating from both new housing and the UK housing stock appear to be technically feasible using technologies that are already available and in use today. The fact that much of the reductions referred to arise from actions taken outside the domestic sector does not reduce their impact. All emissions that take place in upstream systems as a result of supplying the domestic sector are correctly ascribed to the domestic sector.

- The application of available measures to reduce space and water heating will mean that domestic CO_2 emissions will increasingly be dominated by electricity for lights and appliances. Failure to prevent growth in electricity demand for lights and appliances will lead to significantly higher CO_2 emissions in 2050.

- The overall performance of housing is likely to be dominated by synergies between different stages of the energy supply, transmission, distribution and end-use system. The multiplication of modest improvements in the performance of subsystems in multistage energy-conversion systems allows large overall reductions in emissions to be achieved.[23]

- While space and water heating continue to be supplied by direct combustion of natural gas, higher rates of demolition may result in reduced CO_2 emissions. But plausible improvements to buildings and energy supply and conversion systems render the level of CO_2 emissions in 2050 insensitive to the demolition rate. The argument that higher rates of demolition are necessary to decarbonize the UK housing sector requires one to assume an implausible lack of progress in other areas.[24]

- The performance of dwelling envelopes and final energy-conversion systems is therefore likely to be a key determinant of the extent and rate of decarbonization of the housing sector and of the costs associated therewith. Reductions in end-use demand propagate back through the energy supply and conversion chain and reduce all upstream costs. Improvements to envelope and final energy-conversion systems pre-shrink the task of supply systems, e.g. enabling limited tranches of lower cost renewables to achieve significant penetration into a slowly growing or even declining overall demand for electricity. This point can be straightforwardly demonstrated. A combination of the assumed reductions in delivered energy requirement for space and water heating with high-performance heat pumps would mean that the firm capacity needed to support the entire domestic peak space and water heating load in 2050 would be around 34 GW (equivalent to a diversified peak electrical load of 1 kW per dwelling). This is a significant addition to peak electricity load, but by no means out of the question. The inclusion of CHP in the generating mix for 2050 would further reduce this requirement for electricity-generating capacity. Assuming no reduction in delivered energy requirement for domestic space and water heating and the use of direct-resistance heating rather than heat pumps would raise the firm capacity required to support this load by a factor of five or more.

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Endnotes

[1]This was the first such study to have been undertaken in the UK context.

[2]Division of the current stock of 24 million dwellings by the demolition rate of around 15 000 per year yields an implicit

dwelling lifetime of some 1500 years, a figure which has on occasion been used to suggest that the demolition rate is too low.

[3]The factor of 4 is made up of improvement by factors of 1.45, 1.40 and 2.00 in dwelling envelope, end-use efficiency and the carbon intensity of delivered energy, respectively. None of these factors alone is remarkable, but the overall effect is empirically surprising. Note that the author has used both factors and percentages to express magnitudes of change. For systems in which overall change arises from the chaining together of smaller changes to a series of subsystems, it is easier to express all changes in terms of factors, since the factor describing the overall change is then simply the product of the factors that describe the changes in the subsystems. For those who prefer percentages, a factor of y increase is equivalent to an increase of $(y - 1) \times 100\%$. Thus, a factor of 2 increase is equivalent to a 100% increase. A factor of y reduction is equivalent to dividing by y. The equivalent percentage reduction is $(1 - 1/y) \times 100\%$.

[4]Fronts only. As Korsgaard (1968) mused: 'The saying goes that the British feel most comfortable when being roasted on the fireplace side and deep-frozen on the other side, but I wonder if that is really so'.

[5]The neutral temperature is defined as the temperature at which people are on average neither too hot nor too cold. This depends in on activity and clothing levels among other factors. Whether and to what extent the observed increase in internal temperatures has resulted in improved health and well-being is a complex question which will not be examined here. Regardless of the objective benefits, empirically, human populations in temperate climates appear to choose internal temperatures consistent with light levels of clothing whenever cost and income allow.

[6]The revolution in technology and cost of controls, sensors and data processing that took place between 1970 and 2000 was an additional factor in making automatic central heating simple and cheap.

[7]There are separate regulations for England and Wales, Scotland, and Northern Ireland. England and Wales accounts for approximately 88% of the UK population. The regulations referred to in this paper are those for England and Wales. For brevity, these will be referred as 'the Building Regulations'.

[8]The presentation of analyses for just two dwelling types may appear to indicate an over simple approach to the problem. The justification for this is that the flat represents the most difficult dwelling type to deal with. Achievable savings on delivered space and water heating are likely to be larger in any other dwelling type. The presentation of the second dwelling type is therefore generous, and any further analysis would be gratuitous.

[9]This represents a conservative interpretation of the statement by the UK government that: 'It seems likely that the level of performance improvement that will be sought at each review [of the Building Regulations following the 2006 review] will be in the order of 20–30%' (ODPM, 2004, Section 6, p. 8).

[10]Which will in turn have been offset by an increase in energy use in restaurants and in the production and retailing of prepared meals.

[11]The key factor here is that the flat has approximately 1 m^2 of exposed surface area per m^2 of floor area, while the semidetached house has more than twice as much.

[12]SAP 2005 does not, however, account for the effect of household income or energy price on use of demand for energy.

[13]The author recently replaced a nine-year-old, first-generation condensing boiler which suffered from advanced internal corrosion.

[14]There are many examples where sealed units have failed after as little as five years. Most of these are, however, due to a failure to apply obvious and well-understood principles of window design.

[15]For example, the difference between trade prices of condensing and non-condensing boilers is of the order of £100, but the full cost of buying and installing a new boiler is of the order of £1000. The marginal cost of improving the efficiency of a new gas boiler from around 80% to around 90% is, therefore, an order of magnitude less than the fixed cost of buying and installing a new gas boiler.

[16]The author recently externally insulated part of his own house. The cost of the insulant (150 mm of expanded polystyrene, giving a U-value in the region of 0.25 W/m^2K) was around 10% of the total cost of the job. The cost-effectiveness of external wall insulation has been recognized in the latest revision of the Building Regulations for England and Wales (ODPM, 2006), which require this to be done where solid walls are being externally repaired or renovated. While it remains to be seen how vigorously it is enforced, this provision is potentially of strategic importance to the task of managing energy use and CO_2 emissions from the existing stock.

[17]Unless it is done using polyurethane foamed *in situ*. However, almost all retrofitted cavity insulation consists of blown fibre.

[18]The balance of performance may shift even further in favour of solid-walled dwellings, if one includes heat losses associated with cavity party walls in houses built since the 1970s. Measurements made by Siviour (1994) suggest that party walls constructed in cavity masonry may have U-values as high as 0.6 W/m^2K, roughly equal to the U-values of insulated cavity wall and more than twice the U-values of insulated solid external wall. This heat loss mechanism is not present in solid-walled houses.

[19]This arises because of the higher proportion of detached and semidetached dwellings in the cavity wall stock. An additional factor that has only recently surfaced is that cavity party walls in terraced and semidetached houses built since the 1970s may have significant U-values associated with them (Lowe *et al.*, in press).

[20]The first UK example of combined heat and power using a fuel cell has recently been built at Woking (Judd *et al.*, 2005). This system has an electrical output rating of just under 200 kW, an electrical generation efficiency rate of 34% (gross calorific value), and a power-to-heat ratio in the region of 0.6. One of the most interesting features of fuel cells is that, unlike heat engines, they are scalable without significant loss of efficiency.

[21]One of the effects of decarbonizing heat supply is to reduce the environmental benefit from thermal insulation. However, it is technically possible to decarbonize any sector of energy demand, including the manufacture of thermal insulation.

[22]It would be easy to read this statement as supporting one or other particular electricity generation technology, but, as a re-reading of the relevant sections of this paper will show, the analysis is non-partisan. A very wide range of existing and emerging technologies is capable of supporting the substantial decarbonization of the grid. Possible combinations include the following: (1) gas-fired combined cycle plus renewables (in equal proportions this would deliver a carbon intensity in the region of 0.2 kg (CO_2)/kWh, but note that Barrett (2006) suggests that much higher renewables fractions are technically feasible); (2) gas-fired combined cycle plus coal with carbon capture and storage; and (3) nuclear plus either gas-fired combined cycle or coal with carbon capture and storage. It is likely that for the next decade or so UK grid electricity will become more carbon intensive, as nuclear power stations are decommissioned. The absence of a strategy for electricity supply over the last decade means these power stations will be replaced by more carbon-intensive alternatives. But by 2050 most of the existing electricity-generating infrastructure will need to be either replaced or extensively refurbished. Given the lead-time of more than four decades, and in the face of so many different opportunities for achieving what appears, from the analysis presented in this paper, to be a strategically essential objective, the author would

be surprised if it were not achieved. Note that the debate around the advantages and disadvantages of embedded as opposed to grid-based generation of electricity is of secondary importance to the goal of reducing CO_2 emissions.

[23]In the author's opinion, this is the most important general conclusion from this paper. The possible economic behaviour of multistage energy-conversion systems was explored by Lowe (2003).

[24]Demolition and new build also results in significant energy and CO_2 investment in infrastructure. The largest such investments probably take place where construction takes place on greenfield sites. Indications are that these investments are of the same order as the embodied energy costs of dwellings alone (Schiller, 2007). Other inconsistencies in the case for demolition emerge. The dwellings that will be the most difficult to insulate are likely to be those with the highest heritage value, but these would be unlikely to be demolished except under the most extreme circumstances. Existing housing, particularly the oldest housing, is compact and has co-evolved with public transport systems and other systems, which in many cases are still operational. There is no indication that new developments will have anything like the compactness and organic relationship to services. There is also no indication that current design and planning practice can capture the intimacy and human scale of most remaining pre-First World War housing.