ELSEVIER

Energy Policy 33 (2005) 1643–1659

ENERGY POLICY

www.elsevier.com/locate/enpol

An exploration of the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the year 2050

D. Johnston*, R. Lowe, M. Bell

Centre for the Built Environment, Leeds Metropolitan University, Brunswick Terrace, Brunswick Building, Leeds LS2 8BU, UK

Abstract

The aim of this paper is to explore the technological feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the middle of this century. In order to investigate this issue, the paper describes the development of a selectively disaggregated physically based bottom-up energy and CO_2 emission model of the UK housing stock. This model covers both the energy demand and energy supply side and has been used to develop and evaluate three illustrative scenarios for this sector. The results of the scenarios suggest that it may be technically easier, using currently available technology, to achieve CO_2 emission reductions in excess of 80% within the UK housing stock by the middle of this century. However, achieving these sorts of reductions will require strategic shifts in both energy supply and demand side technology.

© 2004 Elsevier Ltd. All rights reserved.

Keywords: Domestic energy use and CO_2 emissions; Physically based model; Climate stabilisation

1. Introduction

The balance of scientific opinion is that changes to the global climate are taking place, primarily due to an increase in anthropogenic CO_2 emissions (IPCC, 2001). Recent analyses suggest that CO_2 emission reductions in excess of 60% are likely to be required across the industrialised countries by the middle of this century, if the atmospheric CO_2 concentration is to be stabilised at current levels, and the effects of climate change are to be mitigated (Royal Commission on Environmental Pollution, 2000; IPCC, 2001; DTI, 2003). In response to this problem, the majority of the world's governments met at the World Climate Conference in Kyoto, where agreement was reached on a legally binding international protocol, designed to cut emissions of the six main greenhouse gases which cause climate change (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6). This Protocol commits developed countries to reduce their overall emissions of these greenhouse gases by an average of 5.2% based on 1990 levels, between 2008 and 2012. The scale of the reductions agreed varies between the countries, with the European Union, the USA and Japan contributing 8%, 7% and 6% respectively (DETR, 2000). The UK's contribution to the European target is a reduction in emissions of greenhouse gases of 12.5% (DETR, 2000). However, the UK Government is convinced that it could and should go beyond the reduction targets that were agreed at Kyoto. Consequently, the UK Government has set a separate domestic goal of reducing CO_2 emissions to 20% below 1990 levels by the year 2010 (DETR, 2000), and has recently stated in its Energy White Paper (DTI, 2003) that one of its energy policy goals is to put the UK on a path to achieving a 60% reduction in CO_2 emissions by about 2050, as recommended by the Royal Commission on Environmental Pollution (Royal Commission on Environmental Pollution, 2000).

In the UK, as in most industrialised countries, the domestic sector contributes substantially to national CO_2 emissions and is directly responsible for just under 30% of the UK's total CO_2 emissions (DEFRA, 2001). While the UK housing stock is characterised by long physical lifetimes and slow stock turnover, energy use within this sector has been growing relatively slowly in comparison to other sectors of the UK economy (for example, the transport sector), while CO_2 emissions have actually been declining for some years. Given that

---

*Corresponding author. Tel.: +44-113-2832600; fax: +44-113-2833190.

E-mail address: d.johnston@leedsmet.ac.uk (D. Johnston).

0301-4215/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2004.02.003

the CO_2 emissions from the transport and non-domestic buildings sectors are rising and expected to continue to rise for many years, it would seem unlikely that the UK will be able to achieve large overall reductions in national CO_2 emissions without the savings in the domestic sector being at least as large as those that are likely to be required in the economy as a whole.

2. A physically based energy and carbon dioxide emission model of the UK housing stock

In order to explore whether it is technically feasible to achieve such reductions in the CO_2 emissions of the UK housing stock by the middle of this century, a selectively disaggregated physically based bottom-up energy and CO_2 emission model of the UK housing stock has been developed. The model not only develops work previously undertaken within this area by Shorrock et al. (2001) using BREHOMES,[1] it also represents the most recent detailed attempt to date to project the delivered energy use and CO_2 emissions attributable to the UK housing stock so far into the future—other studies have been truncated in the first or second decade of this century. The model is also one of the first to have been developed to explore the implications of deep rather than marginal cuts in UK CO_2 emissions.

The model has been constructed around two separate but inter-related components: a data module, which contains information on various energy-related characteristics of the UK housing stock; and a BREDEM-based[2] energy and CO_2 emission calculation module (see Fig. 1). Transparency within the model has been preserved by adopting a parsimonious approach to detail. Thus, the data module has adopted a selectively disaggregated approach,[3] a major feature of which is the use of just two 'notional' dwelling types,[4] which are deemed to be representative of pre- and post-1996[5] construction, respectively. The use of two 'notional' dwelling types is justified on two accounts. First of all, data on and projected trends in insulation ownership, the use of lights and appliances and stock replacement cycles, are only available at the level of the whole housing stock (see, for example, Shorrock and Dunster, 1997). Secondly, at the whole stock level, the impact of dwelling type on energy use and CO_2 emissions is small,[6] in comparison with the impact of the thermal characteristics of the building fabric and system efficiencies. Therefore, in the long-term, what is important is the average performance of a wall, a roof, a space heating system and a lighting system across the stock, rather than the individual differences in geometry, thermal performance and energy use of the various individual dwelling types.

The model is then used to construct a number of detailed illustrative scenarios of the UK housing stock for each 'notional' dwelling type. Relevant scenario-specific information relating to each of the scenarios, on factors such as the number of households, dwelling size, thermal and ventilation characteristics of the building envelope, type and seasonal efficiency of the space and hot water heating systems, information on lights, appliances and cooking, occupancy details and the effects of global warming,[7] is then fed into the calculation module. The calculation module uses the information held in the data module to calculate the delivered energy use and CO_2 emissions attributable to each 'notional' dwelling type, for the particular year in question. This process is undertaken from the base case year 1996, up to and including the year 2050.[8] Finally, information on the total number of 'notional' dwellings is then used to scale the delivered energy use and CO_2 emissions up to the level of the whole UK housing stock.

A more detailed description of the developed model can be found within Johnston (2003).

---

[1] BREHOMES is the Building Research Establishment's Housing Model for Energy Studies.

[2] The BREDEM-based energy and CO_2 emission model is based upon a modified version of the Building Research Establishment's Domestic Energy Model Version 9.60.

[3] This approach has enabled the model structure and the data collection to be biased towards those sectors that dominate domestic energy use and CO_2 emissions and those sectors where energy efficiency measures are likely to be implemented.

[4] In this context, dwelling types refer to a very broad range of dwellings, rather than dwellings of a particular size, form, tenure or age-related category. This represents a rather different approach to modelling than is sometimes taken in this field. The BREHOMES model, for example, incorporates a stock model with over a 1000 dwelling variants (see Shorrock et al., 2001).

[5] 1996 is the base case year used within the model. This year was chosen since it is the most recent year where a fairly comprehensive breakdown of the various factors that are likely to influence UK housing stock energy use and CO_2 emissions are available.

[6] For extreme dwelling types, we acknowledge that there is a large difference in space heating energy consumption. Nevertheless, for the purposes of this paper, we have taken the view that shifts in the mix of dwelling types within the housing stock as a whole, are likely to be significantly less than shifts due to improved energy performance in new build and existing housing. This position is based not least on the observation that some 60% of the housing stock of 2050 has already been built.

[7] The effects of global warming have been modelled by reducing the base temperature of the 'notional' dwellings by the corresponding rise in average annual UK temperature (a temperature rise of approximately 0.88°C by the year 2020 and 1.87°C by the year 2050, as assumed in UKCIP02 (see Hulme et al., 2002). This is broadly consistent with the Medium–High Emissions scenario). This results in a reduction in the number of degree days within the model.

[8] The year 2050 was chosen because this year is commonly referred to in climate stabilisation scenarios.

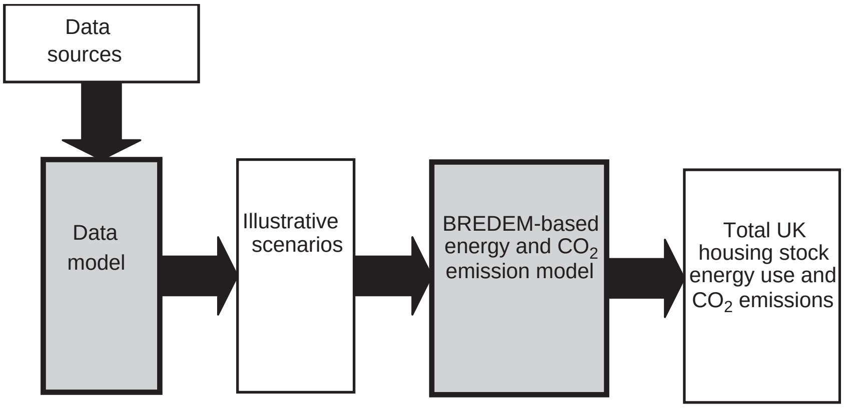

Fig. 1. Structure and form of the energy and CO_2 emission model.

Table 1
The illustrative scenarios

Scenario	Narrative storyline
'Business-as-Usual'	This scenario is based upon the 'Reference Case' scenario developed by Shorrock et al. (2001). It describes a future where concerns about climate change increase on the political agenda and there is a perception that there are plentiful sources of energy. No substantive changes are made to current UK trends in energy efficiency policy, and no additional policy measures are introduced beyond those that are already in place, those that have already been defined with a known implementation date, or those that represent a continuation of current trends. Therefore, the emphasis of UK energy efficiency policy continues to be on encouraging competitive markets. This competition not only leads to low energy prices, which encourages consumers to consume more energy, but it also restricts the scope for cost effective investment in energy efficient measures. In terms of the energy supply sector, electricity generation continues to be primarily based upon the consumption of fossil fuels. However, over the scenario period there is a progressive shift away from more carbon-intensive fuels, such as coal and oil, towards natural gas coupled with a modest increase in the use of renewables. The net effect is a continuation of current trends in building fabric performance, end-use efficiencies and the carbon intensity of electricity generation.
'Demand Side'	This scenario is based upon the 'Business-as-Usual' scenario, but describes a future where evidence continues to emerge on the likely impact of climate change, leading to more stringent legally binding EU CO_2 emission reduction targets. There is also a shift in the perception of the technical feasibility of achieving much greater levels of energy efficiency within the demand side of the domestic sector. This arises from the success of a number of high profile energy demonstration projects, undertaken both in the UK and in other EU member states. This leads to EU collaboration and pooling of best practice on energy efficient housing. Energy efficiency efforts are subsequently concentrated on the energy demand side of the domestic sector. These efforts are 'technology-led'—the current straitjacket imposed by the need to demonstrate the micro-economic case for all marginal changes to practice is relaxed in favour of a strong drive to achieve significant improvements in efficiency. However, no changes are expected to occur to the energy supply sector beyond those identified within the 'Business-as-Usual' scenario.
'Integrated'	This scenario represents the integration of both the energy supply and the demand side of the UK housing stock. It is based upon the 'Demand Side' scenario, but describes a future where dramatic new scientific evidence of the impact of climate change emerges, which indicates that much more ambitious reductions in global CO_2 emissions will be required if the long-term effects of climate change are to be avoided. This new evidence leads to a series of high level political agreements, initially in the EU but by 2010 involving a political *volte face* in the US, to effect much deeper cuts in CO_2 emissions by 2050. Energy supply problems also begin to emerge, due to political instability in Eastern Europe and Central Asia. This leads to a clear political perception of the need to increase the diversity and reduce the carbon intensity of the UK's energy supply, in order to guarantee future security, as North Sea oil and gas resources begin to diminish. An immediate response is triggered in the electricity generation industry, resulting in a concentration of energy efficiency efforts within this sector. This in turn leads to the widespread use of renewables and carbon efficient fossil generation technologies, such as gas-fired combined cycle and advanced fuel cells.

3. The illustrative scenarios

The model has been used to construct and evaluate three illustrative scenarios for the UK housing stock: a 'Business-as-Usual'; a 'Demand Side'; and an 'Integrated' scenario. The narrative storylines associated with each of these scenarios are detailed within Table 1. Central to all of the scenarios are a number of core assumptions. These are that economic growth continues, standards of living continue to rise, and there is a

Table 2
'Business-as-Usual' scenario assumptions

	'Business-as-Usual' scenario
Building fabric	80% of pre-1996 cavity walls insulated by 2050. 10% of uninsulated pre-1996 solid walls insulated by 2050. All pre-1996 glazing replaced at least once by 2050. 10% of pre-1996 dwellings undergo post-construction airtightness work by 2050. Building Regulations wall U-values fall to 0.25 $W/m^2 K$ by 2009, to 0.23 $W/m^2 K$ by 2015, 0.20 $W/m^2 K$ by 2020 and 0.15 $W/m^2 K$ by 2025. Building Regulations window U-values fall to 1.8 $W/m^2 K$ by 2009, 1.5 $W/m^2 K$ by 2015, 1.3 $W/m^2 K$ by 2020 and 1.0 $W/m^2 K$ by 2025. Air leakage rates are introduced into the Building Regulations in 2005 at 10 ac/h @ 50 Pa and fall to 5.0 by 2015, 3.0 by 2020 and 1.0 by 2025.
Mean internal temperature (°C)	Mean internal temperature of pre- and post-1996 dwellings saturate at 21°C by 2040 and 2020, respectively.
Space and water heating systems	All dwellings have a central heating system installed with an average seasonal efficiency of 88% by 2050.
Lights, appliances and cooking	Ownership of the majority of lights, electrical appliances and cooking appliances saturate around 2020. Appliance efficiencies rise over the period 1996–2050.

transition towards a more sustainable and energy efficient UK housing stock. It has also been assumed that all of the measures incorporated within each of the scenarios are based upon currently available technology only, and no attempt has been made to 'second guess' technologies that may be readily available in the future.

4. Scenario assumptions

The assumptions that have been incorporated within the various illustrative scenarios have been developed using information from a variety of external data sources. Where possible, this information has been obtained from relatively uncontentious data sources. Examples of such information include: population projections from the Office for National Statistics (2000); mean household size data from the DETR (1999); details of the state of the existing housing stock from the English House Condition Survey (DETR, 1998); and, projections of the future energy demand of lights and appliances from the Domestic Equipment and Carbon Dioxide Emissions (DECADE) Team at the University of Oxford (see DECADE, 1997; ECI, 2000). In addition, s-curves devised by the BRE have been used to project the likely uptake rate and ownership of various insulation measures (see Shorrock et al., 2001). These curves are described using a logistic function.[9]

Unfortunately,[10] it is impossible to present all of the assumptions associated with the three illustrative scenarios. Nevertheless, Tables 2 and 3 give a flavour of the types of technological measures that are expected to be introduced into the demand side of the UK housing stock within each scenario. The impact of these measures on the specific heat loss, the 24 h mean internal temperature, the weighted average seasonal space heating efficiencies and the electricity consumption attributable to lights and appliances of the 'notional' dwellings, are graphically illustrated in Figs. 2–5.

In terms of the energy supply side, a major simplification that has been incorporated within the model is the assumption that the UK housing stock utilises just two forms of energy, natural gas and electricity, and gas continues to be the predominant heating fuel that is used within the UK housing stock. This approach is justified on the grounds that approximately 90% of all of the energy delivered to the UK housing stock in the base case year 1996, was in the form of either natural gas or electricity (DTI, 2001), and the UK Government envisages that gas will continue to form a large part of the UK's energy mix throughout the first part of this century (DTI, 2003). In the case of natural gas, it has been assumed that no reduction occurs to the carbon intensity over the period 1996–2050 (see Fig. 6). In principle, reductions could be achieved if a significant component of biogas were to be introduced into the UK gas supply. However, it was felt that such an assumption was not appropriate for the illustrative scenarios.

---

[9] This function takes the following form, $L\% = S\%\{1 - \exp(-k(t - t_0)^2)\}$, where $L\%$ is the ownership level in any particular year, $S\%$ is the eventual saturation level, t is the year, t_0 is the year when the product or measure was first introduced and k is a constant that describes the rate of uptake.

[10] However, almost endless detail can be found within Johnston (2003).

Table 3
'Demand Side' and 'Integrated' scenario assumptions

	'Demand Side' and 'Integrated' scenarios
Building fabric	All pre-1996 cavity walls insulated by 2050. All pre-1996 uninsulated solid walls insulated by 2050. All pre-1996 glazing replaced at least once by 2050. 30% of pre-1996 dwellings undergo post-construction airtightness work by 2050. Building Regulations wall U-values fall to 0.25 W/m^2 K by 2005 and 0.15 W/m^2 K by 2010. Building Regulations window U-values fall to 1.5 W/m^2 K by 2005 and 1.0 W/m^2 K by 2010. Air leakage rates are introduced into the Building Regulations in 2005 at 10 ac/h @ 50 Pa and fall to 5.0 by 2007 and 1.0 by 2010.
Mean internal temperature (°C)	Mean internal temperature of pre- and post-1996 dwellings saturate at 21°C by 2040 and 2020, respectively.
Space and water heating systems	All dwellings have a central heating system installed which is fuelled by a gas-fired condensing boiler (seasonal efficiency of 91%) or an electrically driven heat pump (seasonal efficiency of 230%).
Lights, appliances and cooking	Ownership of the majority of lights, electrical appliances and cooking appliances saturate around 2020. Appliance efficiencies rise over the period 1996–2050, resulting in higher efficiencies than experienced within the 'Business-as-Usual' scenario.

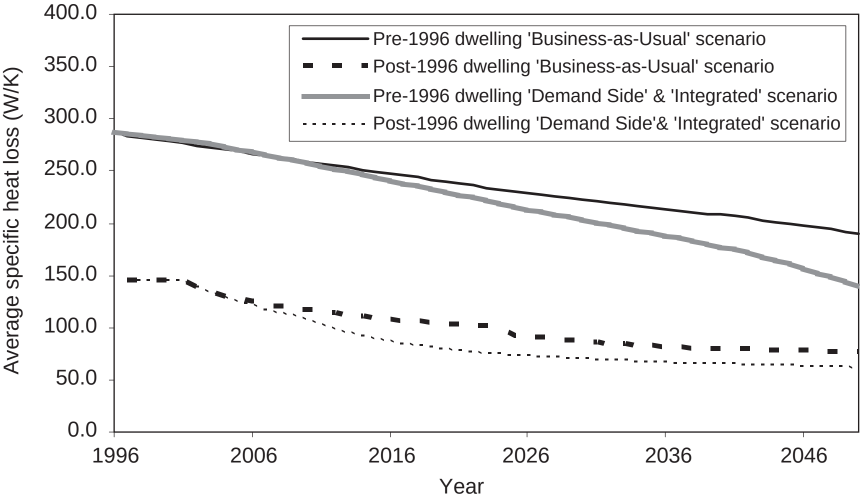

Fig. 2. Total specific heat loss of the 'notional' dwellings under the illustrative scenarios.

With respect to electricity, changes to the fuel mix and improvements in generation efficiency have resulted in a dramatic reduction in the carbon intensity of electricity over the last 50 years or so (see Fig. 6). Although it is likely that the carbon intensity of electricity will rise at the beginning of the 21st century, as first of all Magnox and then AGR nuclear power stations are decommissioned, and no new nuclear power stations are built, many technical options exist that are capable of reducing the carbon intensity of electricity generation throughout the 21st century. Examples of such technologies include: advanced combined cycle gas turbines (CCGTs); integrated gasification combined cycle (IGCC) systems; gas-fired CHP plants; renewable energy technologies; nuclear power; advanced fuel cell technology; and decarbonisation technologies. Therefore, given the existence—indeed the proliferation—of the technical options that are available, the ever increasing political awareness of the problem of climate change, and the likelihood of a strategic shift towards the increased use of renewables[11] and small-scale distributed energy sources in the UK (DTI, 2003), it seems very likely that the historical trends in the carbon intensity of electricity that are illustrated in Fig. 6, will

---

[11] The UK Government's aim is that renewables should supply 10% of UK electricity by 2010 and 20% by 2020 (DTI, 2003). Work undertaken by Marsh et al. (2003) suggests that by 2050, renewables will need to supply 30–40% of the UK's electricity generation to achieve the 60% CO_2 emission reduction target referred to within the Energy White Paper.

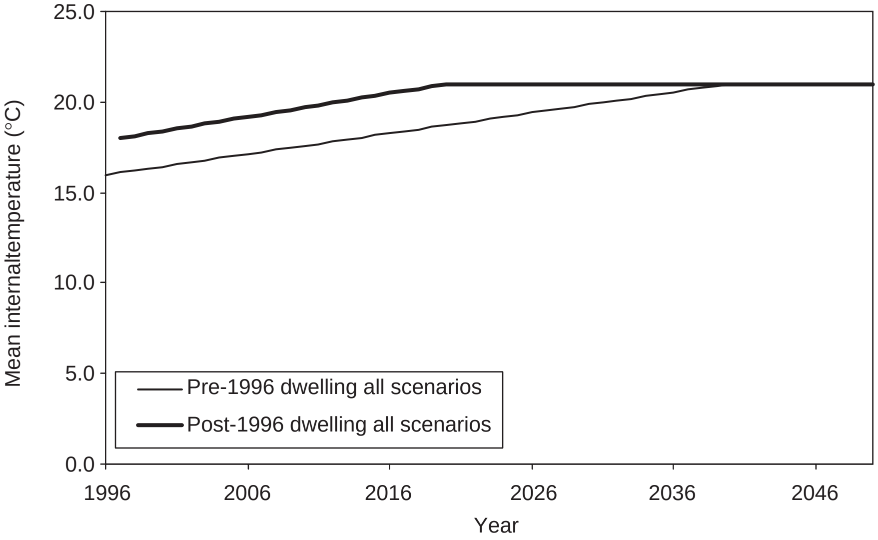

Fig. 3. Twenty-four hour mean internal temperatures of the 'notional' dwellings under the illustrative scenarios.

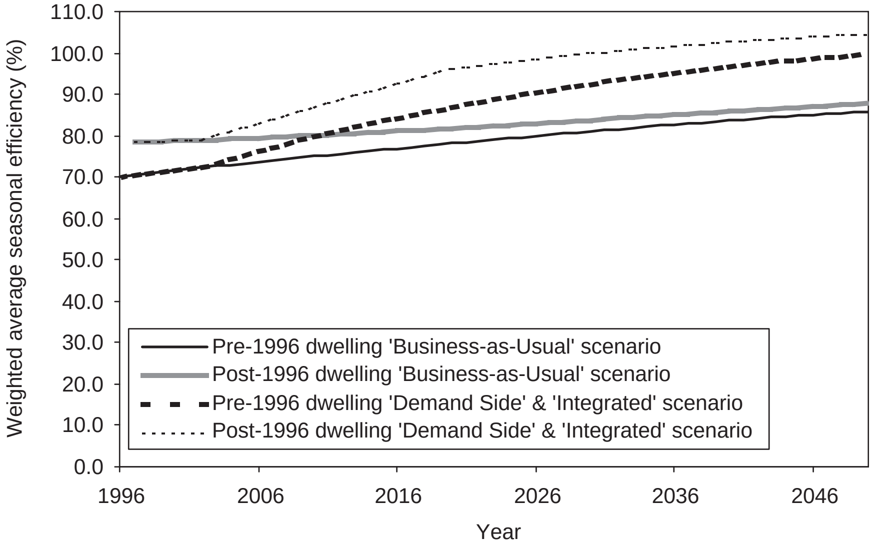

Fig. 4. Weighted average seasonal efficiencies of the 'notional' dwellings space heating systems under the illustrative scenarios. For the purpose of this graph, no distinction has been made between the efficiency of gas boilers and the coefficient of performance of heat pumps. The presence of significant numbers of heat pumps in the 'Demand Side' and 'Integrated' scenarios therefore leads to weighted average space heating efficiencies in excess of 100%.

continue in the medium- to long-term. Consequently, it has been assumed that the carbon intensity of electricity generation reduces over the period 1996–2050, within all of the illustrative scenarios (see Fig. 6). In the 'Business-as-Usual' and 'Demand Side' scenario, the carbon intensity of electricity is projected to reduce to 92 kg CO_2/GJ by 2050, whilst in the 'Integrated' scenario the carbon intensity is projected to reduce to 51 kg CO_2/GJ by 2050, the same intensity as natural gas. These assumptions are important, because the changes that have occurred to the electricity generation sector over the last 50 years or so, have been, and are likely to continue to be (see DTI, 2003), at least as important as those changes that have taken place in various end-use systems, such as dwellings.

A summary of the illustrative scenarios can be found in Tables 4–6.

5. Results

The delivered energy use and CO_2 emissions attributable to each of the illustrative scenarios are illustrated graphically in Figs. 7–10 and are summarised in Tables 7–11. The figures illustrate that relative to the base case year 1996, the delivered energy use and CO_2 emissions

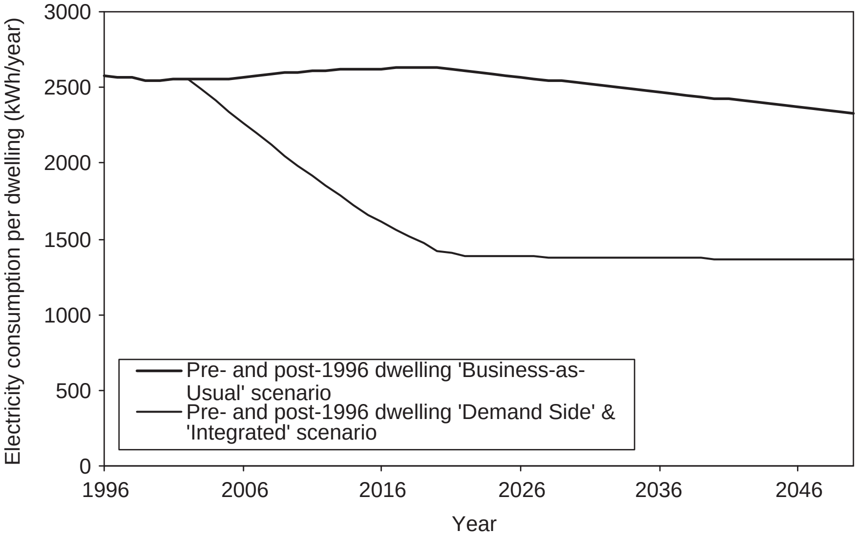

Fig. 5. Total lights and appliance electricity consumption of the ‘notional’ dwellings under the illustrative scenarios.

Table 4
Summary of the ‘Business-as-Usual’ scenario

‘Business-as-Usual’ scenario	Pre-1996 1996	Pre-1996 2050	Post-1996 1997	Post-1996 2050
Households				
Total number of UK households (million)	24.010	22.246	0.304	9.198
Mean household size	2.4	2.0	2.4	2.0
Dwelling size				
Floor area[a] (m^2)	85.0	80.0	76.0	76.0
Volume (m^3)	212.5	200.0	174.8	174.8
Building fabric				
Wall *U*-value ($W/m^2 K$)	1.40	0.96	0.45	0.24
Ground floor *U*-value ($W/m^2 K$)	0.67	0.62	0.45	0.20
Roof *U*-value ($W/m^2 K$)	0.50	0.43	0.25	0.14
Glazing *U*-value ($W/m^2 K$)	4.04	1.62	3.30	1.61
Door *U*-value ($W/m^2 K$)	3.70	1.51	3.30	1.61
Air leakage rate (ac/h @ 50 Pa)	13.1	12.4	11.7	5.4
Total dwelling heat loss (W/K)	287.8	190.2	144.9	76.3
Mean internal temperature				
24 h mean internal temperature (°C)	16.0	21.0	18.0	21.0
Space and water heating systems				
Efficiency of primary space heating system (%)	69.9	85.9	78.6	87.9
Efficiency of secondary space heating system (%)	60.0	77.5	68.2	81.1
Efficiency of water heating system (%)	74.6	87.6	78.8	87.6
Lights, appliances and cooking (per dwelling)				
Lighting consumption per (kWh/year)	703.6	841.0	709.3	841.0
Cold appliance consumption (kWh/year)	727.4	300.6	725.2	300.6
Wet appliance consumption (kWh/year)	472.9	261.8	471.4	261.8
Consumer electronics consumption (kWh/year)	436.7	719.1	431.0	719.1
Miscellaneous appliances consumption (kWh/year)	232.0	208.8	231.6	208.8
Gas cooking consumption (kWh/year)	347.4	277.0	342.6	277.0
Electric cooking consumption (kWh/year)	529.5	480.6	528.4	480.6
Carbon intensities				
Gas (kg CO_2/GJ)	51.0	51.0	51.0	51.0
Electricity (kg CO_2/GJ)	137.6	91.7	124.9	91.7

[a] Assumed that the average useable floor area of the pre-1996 ‘notional’ dwelling reduces as older, larger dwellings are gradually demolished.

Table 5
Summary of the 'Demand Side' scenario

'Demand Side' scenario	Pre-1996 1996	Pre-1996 2050	Post-1996 1997	Post-1996 2050
Households				
Total number of UK households (million)	24.010	20.583	0.000	10.861
Mean household size	2.4	2.0	2.4	2.0
Dwelling size				
Floor area[a] (m^2)	85.0	80.0	76.0	76.0
Volume (m^3)	212.5	200.0	174.8	174.8
Building fabric				
Wall *U*-value (W/m^2K)	1.40	0.52	0.45	0.20
Ground floor *U*-value (W/m^2K)	0.67	0.56	0.45	0.15
Roof *U*-value (W/m^2K)	0.50	0.20	0.25	0.12
Glazing *U*-value (W/m^2K)	4.04	1.51	3.30	1.34
Door *U*-value (W/m^2K)	3.70	0.96	3.30	0.97
Air leakage rate (ac/h @ 50 Pa)	13.1	11.0	11.7	3.5
Total dwelling heat loss (W/K)	287.8	140.5	144.9	61.4
Mean internal temperature				
24 h mean internal temperature (°C)	16.0	21.0	18.0	21.0
Space and water heating systems				
Efficiency of primary space heating system (%)	69.9	99.7	78.6	104.6
Efficiency of secondary space heating system (%)	60.0	86.5	68.2	86.5
Efficiency of water heating system (%)	74.6	103.3	78.8	103.4
Lights, appliances and cooking (per dwelling)				
Lighting consumption per (kWh/year)	703.6	336.0	709.3	336.0
Cold appliance consumption (kWh/year)	727.4	135.8	725.2	135.8
Wet appliance consumption (kWh/year)	472.9	280.1	471.4	280.1
Consumer electronics consumption (kWh/year)	436.7	423.8	431.0	423.8
Miscellaneous appliances consumption (kWh/year)	232.0	184.2	231.6	184.2
Gas cooking consumption (kWh/year)	347.4	277.0	342.6	277.0
Electric cooking consumption (kWh/year)	529.5	393.4	528.4	393.4
Carbon intensities				
Gas (kg CO_2/GJ)	51.0	51.0	51.0	51.0
Electricity (kg CO_2/GJ)	137.6	91.7	124.9	91.7

[a] Assumed that the average useable floor area of the pre-1996 'notional' dwelling reduces as older, larger dwellings are gradually demolished.

attributable to all three scenarios are projected to reduce over the period 1996–2050. All of these reductions are expected to occur despite: a 31% increase in the total number of UK households (equivalent to approximately 7.4 million additional households by 2050); a substantial increase in, and the eventual saturation of, mean internal temperatures; and a substantial increase in the ownership and usage of central heating systems and various electrical appliances.

In terms of delivered energy use, Fig. 7 illustrates that under all of the scenarios, delivered energy use is expected to reduce steadily over the period 1996–2040, as the thermal and ventilation performance of the building envelope improves and appliances become more efficient. Then, from 2040 onwards, total delivered energy use begins to reduce at a much greater rate, as mean internal temperatures saturate and the total number of UK households begins to decline. Consequently, by the middle of this century, energy reductions of around 21% (430 PJ per year) are projected to occur within the 'Business-as-Usual' scenario. However, if the rate at which fabric and end-use efficiency measures are currently being implemented into the UK housing stock are increased to the levels identified within the 'Demand Side' scenario, then delivered energy reductions of around 50% (1003 PJ per year) are possible for this sector.

With respect to CO_2 emissions, the performance of the electricity supply sector introduces a further layer of complexity. The projected overall reduction in the carbon intensity of electricity generation, together with a gradual decline in the delivered energy use of the UK housing stock, result in a reduction in CO_2 emissions under all of the scenarios (see Fig. 9). If current trends in fabric, end-use efficiency measures and the carbon intensity of electricity generation continue, CO_2 emis-

Table 6
Summary of the 'Integrated' scenario

'Integrated' scenario	Pre-1996 1996	Pre-1996 2050	Post-1996 1997	Post-1996 2050
Households				
Total number of UK households (million)	24.010	20.583	0.000	10.861
Mean household size	2.4	2.0	2.4	2.0
Dwelling size				
Floor area[a] (m^2)	85.0	80.0	76.0	76.0
Volume (m^3)	212.5	200.0	174.8	174.8
Building fabric				
Wall *U*-value ($W/m^2 K$)	1.40	0.52	0.45	0.20
Ground floor *U*-value ($W/m^2 K$)	0.67	0.56	0.45	0.15
Roof *U*-value ($W/m^2 K$)	0.50	0.20	0.25	0.12
Glazing *U*-value ($W/m^2 K$)	4.04	1.51	3.30	1.34
Door *U*-value ($W/m^2 K$)	3.70	0.96	3.30	0.97
Air leakage rate (ac/h @ 50 Pa)	13.1	11.0	11.7	3.5
Total dwelling heat loss (W/K)	287.8	140.5	144.9	61.4
Mean internal temperature				
24 h mean internal temperature (°C)	16.0	21.0	18.0	21.0
Space and water heating systems				
Efficiency of primary space heating system (%)	69.9	99.7	78.6	104.6
Efficiency of secondary space heating system (%)	60.0	86.5	68.2	86.5
Efficiency of water heating system (%)	74.6	103.3	78.8	103.4
Lights, appliances and cooking (per dwelling)				
Lighting consumption per (kWh/year)	703.6	336.0	709.3	336.0
Cold appliance consumption (kWh/year)	727.4	135.8	725.2	135.8
Wet appliance consumption (kWh/year)	472.9	280.1	471.4	280.1
Consumer electronics consumption (kWh/year)	436.7	423.8	431.0	423.8
Miscellaneous appliances consumption (kWh/year)	232.0	184.2	231.6	184.2
Gas cooking consumption (kWh/year)	347.4	277.0	342.6	277.0
Electric cooking consumption (kWh/year)	529.5	393.4	528.4	393.4
Carbon intensities				
Gas (kg CO_2/GJ)	51.0	51.0	51.0	51.0
Electricity (kg CO_2/GJ)	137.6	51.0	124.9	51.0

[a] Assumed that the average useable floor area of the pre-1996 'notional' dwelling reduces as older, larger dwellings are gradually demolished.

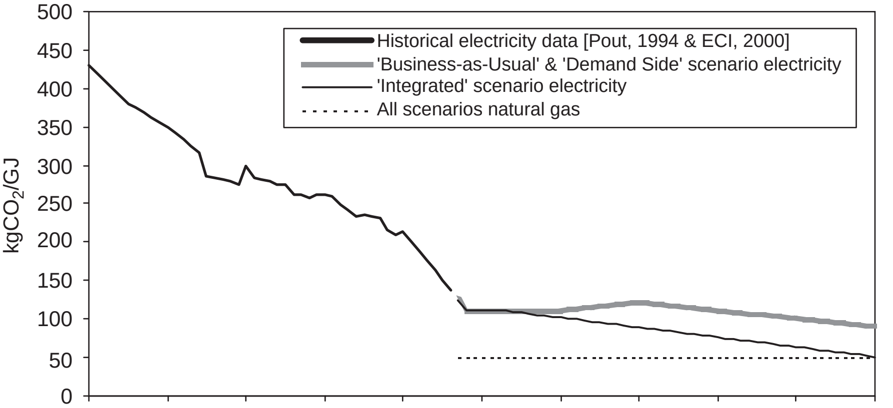

Fig. 6. Carbon intensity of natural gas and electricity.

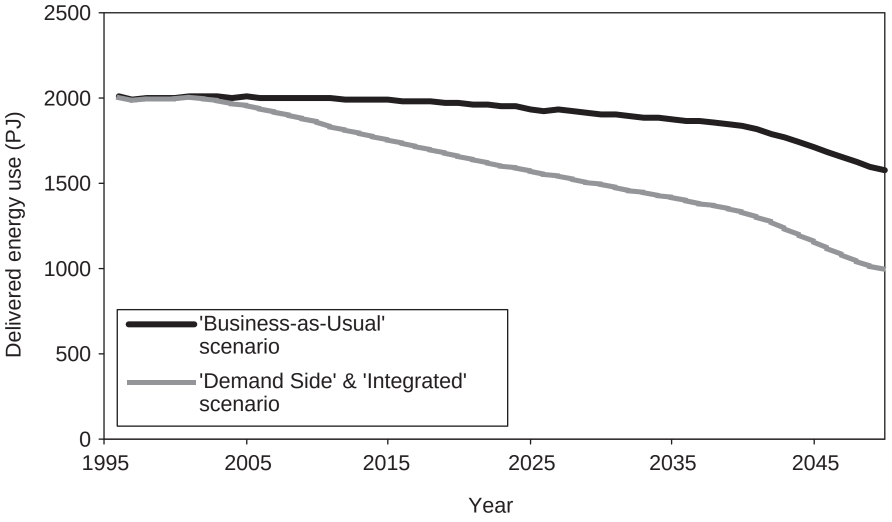

Fig. 7. Total delivered energy use attributable to the developed scenarios over the period 1996–2050.

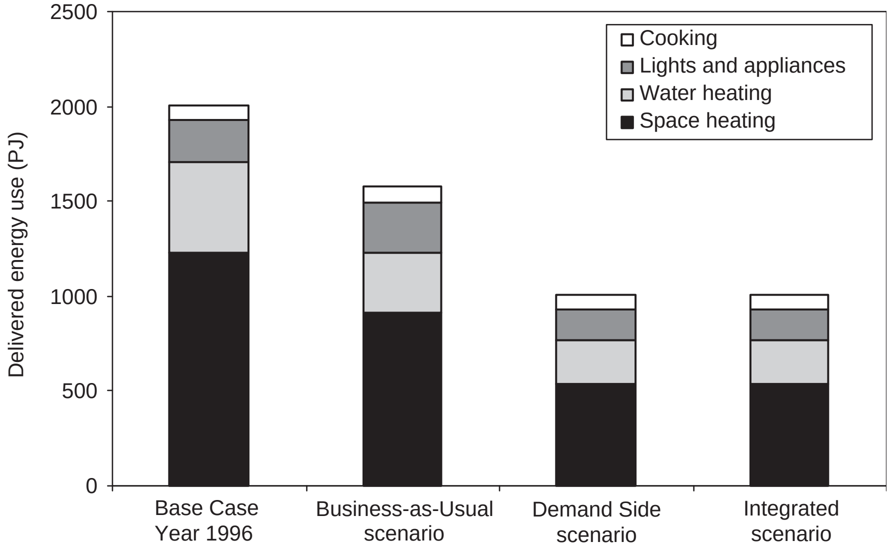

Fig. 8. Total delivered energy use attributable to the developed scenarios.

sions are expected to be 33% lower (equivalent to around 48 million tonnes of CO_2 per year) in 2050 than they were in the base case year 1996. If the uptake rate of a number of the technological measures that are contained within the 'Business-as-Usual' scenario are increased to the levels identified within the 'Demand Side' scenario, and a number of currently available technological measures are also implemented into the UK housing stock (for instance, heat pumps), then the CO_2 emissions attributable to the UK housing stock could be reduced by a further 25% or 37 million tonnes of CO_2 per year by 2050. In addition, Figs. 9 and 10 also illustrate that a further 7% reduction in CO_2 emissions (equivalent to approximately 10 million tonnes of CO_2 per year), could be achieved by the middle of this century if various measures are also applied to the electricity generation side of the energy supply sector.

The CO_2 emission trajectories attributable to all three scenarios have also been compared against the UK's Kyoto target, the UK Government's domestic target of a 20% reduction in CO_2 emissions by the year 2010, and the Royal Commission on Environmental Pollution's (RCEP) target of a 60% reduction in CO_2 emissions by the year 2050[12] (see Fig. 9). Relative to the 1990 baseline[13] CO_2 emission rate of around 155 million tonnes of CO_2 per year, the results of this comparison suggest that although all of the scenarios are expected to achieve the UK's Kyoto target, the UK Government's domestic target is unlikely to be achieved unless the current rate of uptake of energy efficiency measures is

---

[12] The RCEP target uses 1998 as a baseline.

[13] The year 1990 has been used as a baseline as it is commonly referred to in climate change scenarios.

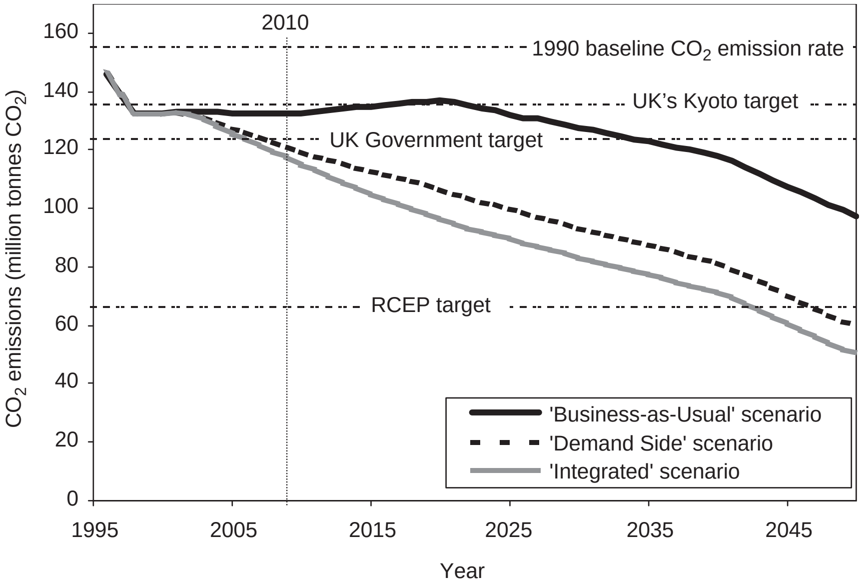

Fig. 9. CO_2 emissions attributable to the developed scenarios over the period 1996–2050.

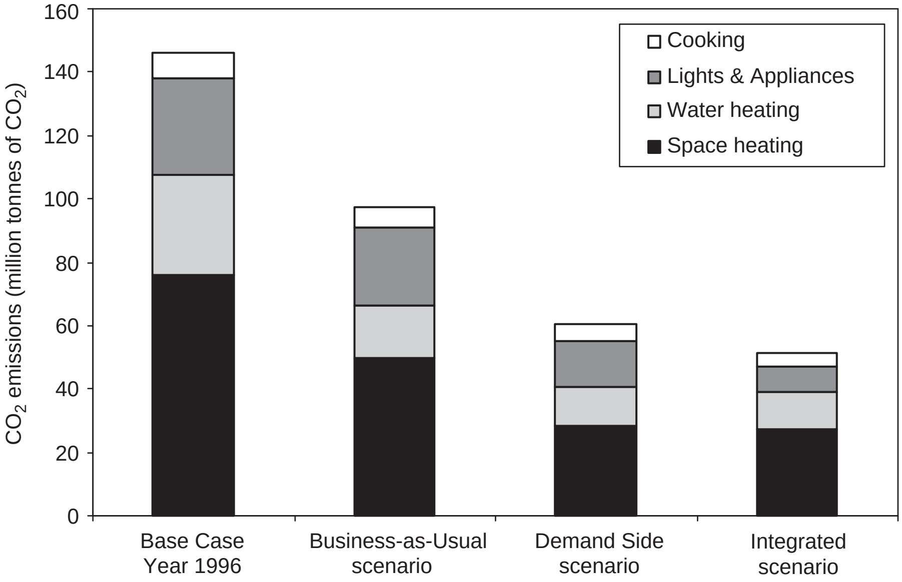

Fig. 10. Total CO_2 emissions attributable to the developed scenarios.

Table 7
Change in delivered energy use by end-use under the 'Business-as-Usual' scenario, relative to 1996

	Change in delivered energy use (PJ)	Change in delivered energy use (%)
Space heating	−318.3	−25.9
Water heating	−164.8	−34.4
Lights and appliances	+43.0	+19.4
Cooking	+10.0	+13.2
Total	−430.3	−21.4

Table 8
Reduction in CO_2 emissions by end-use under the 'Business-as-Usual' scenario, relative to 1996

	Reduction in CO_2 emissions (million tonnes of CO_2)	Reduction in CO_2 emissions (%)
Space heating	26.3	34.6
Water heating	14.6	46.2
Lights and appliances	6.3	20.6
Cooking	1.2	15.4
Total	48.4	33.2

Table 9
Change in delivered energy use by end-use under the 'Demand Side' and 'Integrated' scenarios, relative to 1996

	Change in delivered energy use (PJ)	Change in delivered energy use (%)
Space heating	−695.1	−56.6
Water heating	−242.0	−50.5
Lights and appliances	−65.6	−29.5
Cooking	+0.1	+0.1
Total	−1002.7	−50.0

Table 10
Reduction in CO_2 emissions by end-use under the 'Demand Side' scenario, relative to 1996

	Reduction in CO_2 emissions (million tonnes of CO_2)	Reduction in CO_2 emissions (%)
Space heating	47.7	62.8
Water heating	19.2	60.8
Lights and appliances	16.2	52.9
Cooking	2.1	26.9
Total	85.2	58.4

Table 11
Reduction in CO_2 emissions by end-use under the 'Integrated' scenario, relative to 1996

	Reduction in CO_2 emissions (million tonnes of CO_2)	Reduction in CO_2 emissions (%)
Space heating	48.7	64.2
Water heating	19.5	61.7
Lights and appliances	22.6	73.9
Cooking	3.9	50.0
Total	94.7	64.9

increased to the levels identified within the 'Demand Side' and the 'Integrated' scenarios. More importantly, the results also suggest that the much larger reductions in CO_2 emissions that are likely to be required to stabilise the atmospheric CO_2 concentration and mitigate the effects of climate change, can only be achieved if the technological measures identified within the 'Demand Side' and the 'Integrated' scenario are implemented into the UK housing stock. Relative to the 1990 baseline CO_2 emission rate, these scenarios are projected to achieve a reduction in emissions of approximately 61% and 67% respectively, by 2050. However, achieving these sorts of reductions will require the implementation of technological measures that go substantially beyond those that would be expected on the basis of current trends.

Figs. 8 and 10 also illustrate that space heating will still be the most important end-use category in terms of delivered energy use and CO_2 emissions by the year 2050, in all of the scenarios. A closer analysis of the results indicates that the majority (approximately 90%) of the delivered energy use and CO_2 emissions associated with space heating in the year 2050 is attributable to the pre-1996 'notional' dwellings (see Figs. 11 and 12). The reason why these dwellings have such high space heating energy use and CO_2 emissions can be attributed to their relatively high heat losses, particularly when they are compared to the corresponding post-1996 'notional' dwellings (see Fig. 13), as well as their much larger number. Almost two-thirds of the heat losses associated with the pre-1996 'notional' dwellings are expected to be attributable to the external walls and the ventilation of the 20th century cavity walled stock. The reasons for this are that the thermal performance of the cavity walled stock tends to be restricted by the width of the cavity,[14] and under current conditions, cavity walled masonry dwellings tend to be leakier than solid walled properties (Stephen, 2000).

A number of variant versions of the 'Integrated' scenario have also been modelled to explore the technological feasibility of achieving CO_2 emission reductions greater than 67%, by the middle of this century. These scenarios are as follows:

- *ITPa scenario*—As the 'Integrated' scenario, but assumes that by 2050, all of the pre-1996 cavity walled dwellings have their walls thermally upgraded to the same standard as the solid walled stock, i.e. they all have a U-value of $0.25\,W/m^2\,K$.
- *ITPb scenario*—As the ITPa scenario, but assumes that by 2050, all pre-1996 dwellings also undergo post-construction airtightness work to reduce their mean air leakage to 6 ac/h @ 50 Pa (consistent with a maximum for any given dwelling of 10 ac/h @ 50 Pa). These dwellings are still assumed to be naturally ventilated with intermittent mechanical extract.
- *ITPc scenario*—As the ITPb scenario, but assumes that by 2050, all dwellings that contain a central

---

[14] This assumes that the thermal performance of cavity walled dwellings is improved by injecting insulation material into the wall cavity, as is currently the case, rather than internally or externally insulating these dwellings.

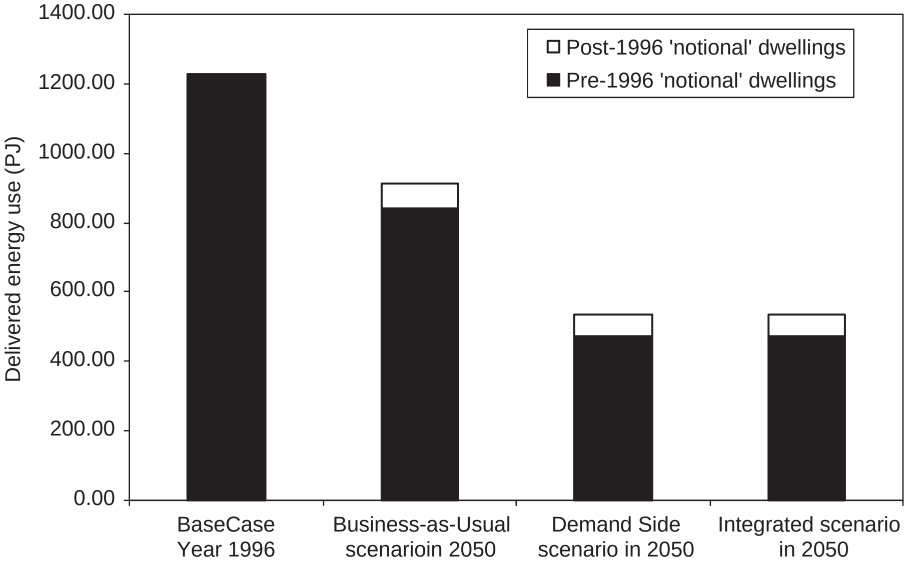

Fig. 11. Delivered energy use attributable to space heating within each of the developed scenarios.

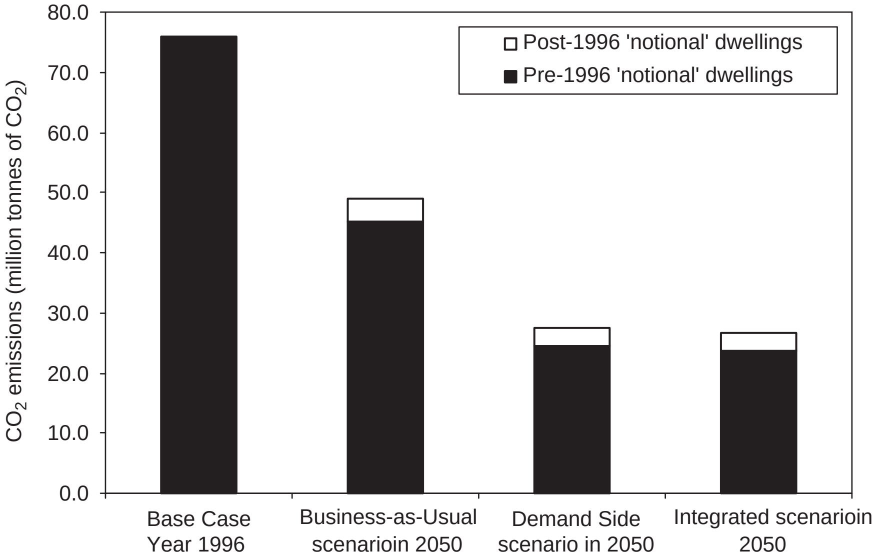

Fig. 12. CO_2 emissions attributable to space heating within each of the developed scenarios.

heating system will have a heat pump installed with a seasonal coefficient of performance (COP) of 2.3.[15]

The results of the variant versions of the 'Integrated' scenario illustrate that it is technically feasible to achieve CO_2 emission reductions of more than 67% (see Fig. 14 and Tables 12 and 13). Such reductions can be achieved in a number of ways. First of all, if measures are undertaken to improve the thermal performance of the pre-1996 cavity walled stock, then CO_2 emission reductions of around 70% could be achieved by 2050. Secondly, if post-construction airtightness work is also undertaken on all of the pre-1996 stock, CO_2 emissions could be reduced by a further 2 percentage points. Finally, if the uptake rate of heat pumps is also substantially increased, then CO_2 emission reductions of approximately 83% could be achieved by 2050, even with the modest COP assumed here. This represents CO_2 emission reductions of some 24 million tonnes of CO_2 per year, compared with the 'Integrated' scenario.

Although substantial CO_2 emission reductions can be achieved under the ITPc scenario, it will require a strategic shift away from the direct use of natural gas as a heating fuel within the UK housing stock, to using electricity. Such a shift will have an important impact

---

[15] This COP is based upon work undertaken by Grigg and McCall (1988).

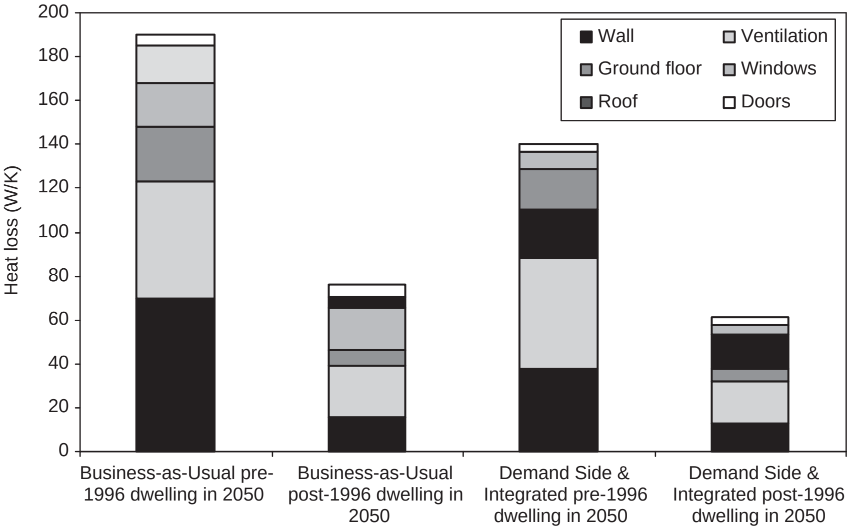

Fig. 13. Heat loss of the 'notional' dwellings in the year 2050.

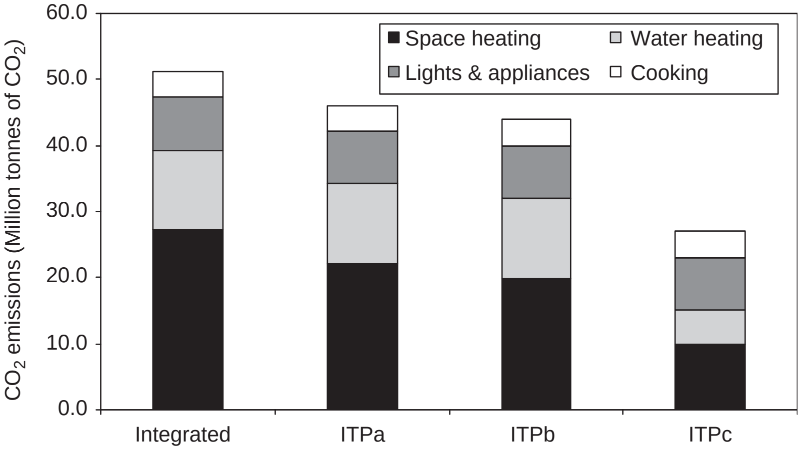

Fig. 14. CO_2 emissions attributable to the variant versions of the 'Integrated' scenario in 2050.

Table 12
CO_2 emissions attributable to the variant scenarios in 2050

	CO_2 emissions (million tonnes/year)				
	Space	Water	Lights and appliances	Cooking	Total
ITPa	22.1	12.1	8.0	3.9	46.1
ITPb	19.9	12.1	8.0	3.9	43.9
ITPc	9.9	5.2	8.0	3.9	27.0

Table 13
Reduction in CO_2 emissions attributable to the variant scenarios, relative to the 1990 baseline

	Reduction in CO_2 emissions (million tonnes of CO_2)	Reduction in CO_2 emissions (%)
ITPa	109.2	70.3
ITPb	111.4	71.7
ITPc	128.3	82.6

upon the total demand for natural gas within the UK housing stock. In order to determine the scale of this impact, the total gas consumption of the ITPc scenario has been compared with the corresponding figures for the 'Business-as-Usual', 'Demand Side' and 'Integrated' scenarios (see Fig. 15). The results suggest that if the proportion of electricity generated using gas-fired CCGTs is assumed to be around 40% in 2050 under all of the scenarios,[16] then total gas consumption could

---

[16] This implies that any reductions in the carbon intensity of electricity are achieved by reducing the proportion of electricity that is generated using coal and/or oil, and increasing the proportion of electricity that is generated using renewables and/or nuclear power.

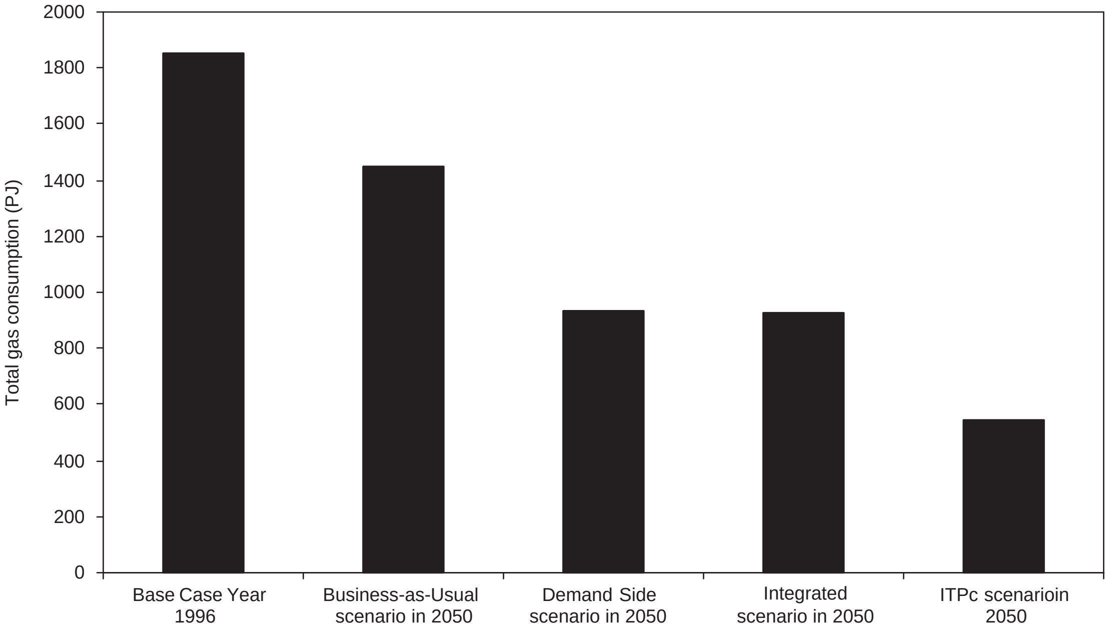

Fig. 15. Total gas consumption attributable to a number of the developed scenarios.

be reduced by more than 60% in 2050, even if there is a large-scale shift towards using electrically driven heat pumps, rather than gas-fired condensing boilers. Indeed, even with conservative assumptions about heat pump COPs, all electric heat pump scenarios will use less gas by 2050 than scenarios based on gas-fired condensing boilers.[17]

It is important to realise that the variant versions of the 'Integrated' scenario illustrate only a handful of ways in which the UK housing stock could achieve CO_2 emissions that are greater than 67%. Various other technological options are available that are likely to achieve much greater CO_2 emission reductions. For instance, such reductions could be achieved if a considerable proportion of the 20th century cavity walled stock was demolished and replaced with new super-insulated and airtight dwellings. Considered as a whole, the variant scenarios clearly illustrate that achieving CO_2 emission reductions greater than about 80% will be technically demanding. However, this study leaves a number of important questions unanswered. For instance, understanding the consequences of this switch for the electricity system, in terms of simultaneous maximum demand and transmission requirements.

6. Conclusions

The overall conclusion from this work is that by the middle of this century it is technically possible, using currently available technology, to achieve the sorts of reductions in the CO_2 emissions from the UK housing stock that are likely to be required to stabilise the atmospheric CO_2 concentration and mitigate the effects of climate change. These reductions appear feasible despite a substantial increase in the total number of UK households, an increase in thermal comfort standards and a significant increase in the standards of service that occupants are likely to expect. However, achieving these reductions will be technically demanding, and will require the uptake and application of a range of technological measures that go substantially beyond those that would be expected on the basis of current trends. There appear to be no easy, trouble-free technological options for the UK housing stock.

The results obtained from the illustrative scenarios suggest the following:

- Relative to the 1990 baseline CO_2 emission rate, the following emission reductions are projected to occur by 2050:
  - A 37% reduction under the 'Business-as-Usual' scenario, by assuming a continuation of current trends in fabric and end-use efficiency measures and the carbon intensity of electricity generation.
  - A 61% reduction under the 'Demand Side' scenario, by applying additional demand side measures to the 'Business-as-Usual' scenario.

---

[17] Electric heat pumps will reduce the demand for gas for heating if $C_G/\eta_{GAS} \geqslant C_{EL}/COP$, where C_G = carbon intensity of gas, C_{EL} = carbon intensity of electricity, η_{GAS} = seasonal efficiency of gas-fired condensing boilers and COP = seasonal efficiency of electric heat pumps.

  - A 67% reduction under the 'Integrated' scenario, by applying a number of electricity generation measures to the energy supply side of the 'Demand Side' scenario.
  - A reduction in excess of 80% is technically feasible given existing technology, if a significant proportion of gas-fired space heating systems are replaced by electrically driven heat pumps. However, this represents a strategic shift in the application of both demand side and supply side technologies. This will have significant implications for UK energy policy.
- It looks as though the UK Government's domestic target of a 20% reduction in CO_2 emissions by the year 2010 will be difficult to achieve, regardless of what eventually happens in 2050. The time lags associated both with the housing stock and the energy supply system are too long to allow a reversal of existing trends within such a short time.
- The RCEP target and UK energy policy goal of a 60% reduction in CO_2 emissions by the year 2050 can technically be achieved. However, this is likely to require a significant increase in the rate at which fabric and end-use efficiency measures are currently being implemented into the UK housing stock.

The illustrative scenarios have also thrown up a number of results that may be counter-intuitive. These are as follows:

- All of the scenarios suggest that space heating will remain the most important determinant of CO_2 emissions in 2050, and will account for more CO_2 emissions than almost all of the other end-uses of energy put together. This is expected to occur despite considerable reductions in dwelling heat loss and a significant improvement in space heating efficiencies.
- All of the scenarios suggest that the 20th century cavity walled stock, rather than the pre-1996 solid walled stock, will be the poorest performing category of the housing stock by 2050.[18]
- Provided that a significant proportion of existing solid walled dwellings can be externally insulated (for instance, see The Carbon Trust, 2003), very large reductions in CO_2 emissions can be achieved without recourse to the large-scale demolition of various sectors of the housing stock, or by assuming that significant changes will have to be made to the ownership and usage of various demand side technologies.
- The largest reductions in CO_2 emissions are likely to be achieved by making a strategic shift away from the direct use of natural gas as a heating fuel within the UK housing stock, and moving towards a combination of technologies such as heat pumps, supported by a low carbon electricity supply system.
- All electric heat pump scenarios will tend to use less gas by 2050 than scenarios based upon the use of gas-fired condensing boilers, even with conservative assumptions about heat pump COPs. This is despite the fact that the electricity supply system is assumed to derive 40% of its output from natural gas in 2050.

References

DECADE, 1997. 2MtC—two million tonnes of carbon. Energy and Environment Programme, Environmental Change Unit, University of Oxford, Oxford.

DEFRA, 2001. Digest of Environmental Statistics. Department for Environment, Food and Rural Affairs, London, HMSO.

DETR, 1998. English house condition survey 1996. Department of the Environment, Transport and the Regions, HMSO, London.

DETR, 1999. Projections of households in England to 2021: 1996-based estimates of the numbers of households for regions. Department of the Environment, Transport and the Regions, HMSO, London.

DETR, 2000. Climate change: The UK programme—summary. Department of the Environment, Transport and the Regions, HMSO, London.

DTI, 2001. Digest of United Kingdom energy statistics. Department of Trade and Industry, HMSO, London.

DTI, 2003. Energy white paper: our energy future—creating a low carbon economy. Department for Trade and Industry, The Stationary Office, London.

ECI, 2000. Lower carbon futures for European households. Environmental Change Institute, University of Oxford, Oxford.

Grigg, P., McCall, M., 1988. Domestic heat pumps: performance and economics. Building Research Establishment Report BR 126. Building Research Establishment, Garston, Watford.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassell, D., Boorman, P., McDonald, R., Hill, S., 2002. Climate change scenarios for the United Kingdom: the UKCIP02 scientific report. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

IPCC, 2001. Climate change 2001: the scientific basis. Technical Summary, Intergovernmental Panel on Climate Change, Geneva.

Johnston, D., 2003. A physically based energy and carbon dioxide emission model of the UK housing stock. Ph.D. Thesis, Leeds Metropolitan University.

Marsh, G., Taylor, P., Anderson, D., Leach, M., Gross, R., 2003. Options for a low carbon future—phase 2. Future Energy Solutions from AEA Technology, Harwell, Oxfordshire.

Office for National Statistics, 2000. National Population Projections: 1998-based. Prepared by the Government Actuary in consultation with the Registrars General, Series PP2 no. 22. A publication of the Government Statistical Service, HMSO, London.

---

[18] This is based upon the assumption that over the next 50 years, effort is concentrated on improving the thermal performance of the poorest performing walls, i.e. uninsulated solid walls and uninsulated cavity walls. Although it is technically possible to improve the thermal performance of previously insulated cavity walls by adding extra internal or external insulation, this option has not been considered. The reason for this, is that the improvements that could be achieved by doing this are marginal in comparison to those that can be achieved by insulating those walls that are currently uninsulated.

Royal Commission on Environmental Pollution, 2000. Twenty Second Report. Energy—the changing climate. Royal Commission on Environmental Pollution, HMSO, London.

Shorrock, L.D., Dunster, J.E., 1997. The physically based model BREHOMES and its use in deriving scenarios for the energy use and carbon dioxide emissions of the UK housing stock. Energy Policy 25 (12), 1027–1037.

Shorrock, L.D., Henderson, J., Utley, J.L., Walters, G.A., 2001. Carbon emission reductions from energy efficiency improvements to the UK housing stock. BRE Report 435, Building Research Establishment, Garston, Watford.

Stephen, R., 2000. Airtightness in UK dwellings. BRE Information Paper IP 1/00, January 2000. Building Research Establishment, Garston, Watford.

The Carbon Trust, 2003. The Carbon Trust Accelerates Research & Development into Energy Efficient Buildings. Available from: http://www.thecarbontrust.co.uk/thecarbontrust/press + centre/press + releases/Defaut.htm (Accessed November 3rd, 2003).