A detailed analysis of the historical role of energy efficiency in reducing carbon emissions from the UK housing stock

Les Shorrock
Building Research Establishment Ltd.
Garston, Watford, WD25 9XX
United Kingdom
shorrockl@bre.co.uk

Keywords
carbon emissions, decomposition, household growth, levels of service, insulation improvements, heating efficiency improvements, the seventies, the eighties, the nineties

Abstract
In the United Kingdom efforts to reduce energy use, and hence carbon emissions, which have become the main motivating factor more recently, began in the early 1970s amid concerns about the security of energy supplies prompted by the oil crisis. This paper examines the success of those efforts for the largest energy-use sector in the United Kingdom; the housing stock, or *domestic sector*. It uses a decomposition analysis to establish the effect of individual factors.

The analysis reveals that the 11.9 MtC/year reduction in carbon emissions between 1970 and 2001 can be explained by (a) increases due to household growth and rising levels of service, outweighed by (b) reductions related to improved thermal insulation, improved heating efficiency, changes in electricity generation, the changing fuel mix and variations in external temperatures. The results indicate that without the energy efficiency improvements that have been introduced since 1970 carbon emissions from this sector would have increased.

The changes have also been examined within three individual decades; the seventies, the eighties and the nineties. The patterns seen in these results suggest that continued reductions of carbon emissions will be more difficult to achieve in the first decade of the 21st century unless efforts to accelerate energy efficiency improvements are significantly stepped up from the rates seen in the nineties.

Methodology
The decomposition analysis presented in this paper is an update and extension of a previously published analysis covering the period 1990 to 2000 (Shorrock 2000). This was undertaken when the data for many of the years during that period were unavailable and it had always been intended to revise and update the analysis when the relevant information was to hand. The approach used differs from the more usual index-based methodologies (see, for example, Greening et al 1997), instead presenting the decomposition in terms of absolute carbon emissions. It has been found that this approach provides greater transparency and makes the analysis more useful to policy makers.

All the relevant data to 2001 have now been assembled and extensively analysed and will be published, before this paper appears, in a BRE Report early in 2003 (Utley and Shorrock 2003). This report (the Domestic Energy Fact File) will present detailed year-by-year information on the changes between 1970 and 2001 in the energy use and energy efficiency characteristics of the housing stock. This paper makes extensive use of the information that will appear in this forthcoming report. In particular, it relies on an equation that will appear in the report which describes the energy use of the domestic sector, allowing the contributions of individual factors to be identified. The equation, which describes the energy use of the average dwelling and is based on regression analyses together with detailed energy balance calculations, is as follows:

$$Q = 97.81 + (2.12 \times [Year - 1970]) - (3.30 \times T_e) - (0.26 \times \Delta H) - (1.49 \times \Delta E\%)$$

Equation (1)

where T_e is the mean winter external temperature (°C), ΔH is the improvement in the average dwelling heat loss (in W/°C) since 1970, ΔE% is the improvement in average heating efficiency since 1970, and the result is expressed in Gigajoules per year. The T_e term describes the fluctuations in energy use that are to be expected from variations in the mean winter external temperature, the ΔH term covers the effect of the numerous improvements that have been made to building envelope insulation since 1970, whilst the ΔE% term accounts for efficiency improvements that have occurred due to the installation of more efficient heating systems over the same period. A term increasing by 2.12 GJ per year relative to 1970 is also included to capture the increasing levels of service being demanded by households (i.e. higher temperatures, more domestic hot water, increased lighting and more appliances).

Multiplying the equation by the number of households provides an estimate of the total housing stock energy use. Figure 1 shows how these estimates compare with the actual energy use of the housing stock from which it can be seen that the agreement is very good, particularly for years after about 1980. Prior to this there are some larger discrepancies, but even the largest of these only amounts to about 7%. It is not hard to understand why the energy use in the early years is difficult to replicate given, for example, the fact that the heating expectations at either end of the period in question were very different. In 1970 only 31% of homes had central heating and very little of this was based on natural gas, but by 2001 about 90% of homes had central heating and most of this was based on natural gas. The effects of such radical changes will clearly be difficult to fully capture with a *level of service* term that is simply taken to be linearly related to the year.

In fact, in the previous version of the analysis the level of service term was related to central heating ownership to attempt to better cover the widely disparate standards at either end of the period (which at that time only went as far as 1996). This worked well up to 1996 but subsequent energy use figures for the domestic sector have shown that the following gradual saturation that it implied has not in fact happened. Energy use actually continued to rise at a similar rate to that in earlier years, and capturing this behaviour properly required the use of a level of service term linearly related to the year.

Multiplying the equation again by the average carbon emission factor for the year in question results in an estimate of the overall carbon emissions of the domestic sector. In fact, these estimates have been made to agree exactly with the actual carbon emissions by slightly adjusting the average carbon emission factor to compensate for the small errors in the energy use predictions illustrated in Figure 1. Doing this helps with the subsequent decomposition analysis because it ensures that the individual components always add to the correct overall carbon emission.

Changes in the carbon emission between one year and the next can be attributed to changes to the energy use of the average dwelling (which can be further decomposed into the separate terms of equation (1)), changes to the number of households, and changes to the average carbon emission factor (which can also be further decomposed as will be seen later). Considering two adjacent years 0 and 1, it is obvious that the difference in carbon emissions can be written:

$$C_{change} = (C_1 \times N_1 \times Q_1) - (C_0 \times N_0 \times Q_0)$$

Equation (2)

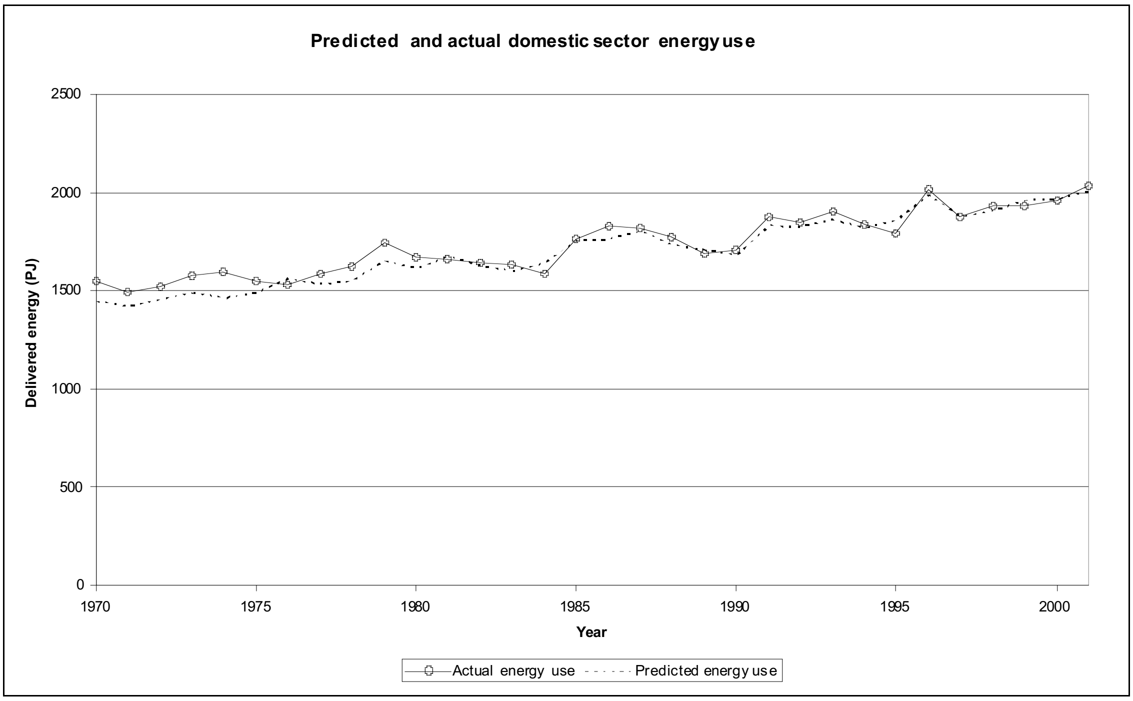

Figure 1. *Actual domestic sector energy use compared with the predictions of equation (1).*

Where C_i represents the carbon emission factor, N_i represents the number of households and Q_i represents the average dwelling energy use. This equation can be expanded in various ways to separately consider the changes in these three factors. By writing ΔC in place of C_1-C_0, and similarly for ΔN and ΔQ, it is relatively easy to show that there are six possible variations of the equation. These are:

$$C_{change} = (N_1 \times Q_1 \times \Delta C) + (C_0 \times Q_1 \times \Delta N) + (C_0 \times N_0 \times \Delta Q)$$

$$C_{change} = (N_1 \times Q_1 \times \Delta C) + (C_0 \times Q_0 \times \Delta N) + (C_0 \times N_1 \times \Delta Q)$$

$$C_{change} = (N_0 \times Q_0 \times \Delta C) + (C_1 \times Q_0 \times \Delta N) + (C_1 \times N_1 \times \Delta Q)$$

$$C_{change} = (N_0 \times Q_0 \times \Delta C) + (C_1 \times Q_1 \times \Delta N) + (C_1 \times N_0 \times \Delta Q)$$

$$C_{change} = (N_0 \times Q_1 \times \Delta C) + (C_1 \times Q_1 \times \Delta N) + (C_0 \times N_0 \times \Delta Q)$$

$$C_{change} = (N_1 \times Q_0 \times \Delta C) + (C_0 \times Q_0 \times \Delta N) + (C_1 \times N_1 \times \Delta Q)$$

Equations (3) to (8)

Each of these equations will give exactly the same overall result but the values of the individual terms will vary slightly. They each represent an approximation of the full integral between year 0 and year 1 (the full integral is, of course, not possible because this would require data at more than just the year-ends and this is not available). The best possible estimate of the correct allocation between the individual terms (i.e. that which would be given by the full integral, if it were possible) is provided by averaging the results given by all six equations and this has been done for the results presented in this paper.

To undertake the calculation of carbon emission changes using the above equations we need to know how the average carbon emission factor, the number of households and the average energy use per household are changing with time. The average carbon emission factor depends on the fuel mix (which is known from national energy statistics) and on the emission factors for individual fuels (which can also be determined from national energy statistics). The number of households is well characterised in official statistics. The average energy use per household depends on a number of factors as already indicated by equation (1).

At this point it is worth noting that the factors used in equation (1) focus on elements that primarily affect space heating - because these are relatively easy to characterise and they are undoubtedly the principle factors influencing overall domestic energy use (space heating accounts for around 60% of domestic energy use in the United Kingdom). However, the equation describes the total energy use of the stock, not just the space heating component, as illustrated by Figure 1. Consequently, the effects of other non-space-heating-related energy efficiency measures are implicitly included. This means that the heat loss and heating efficiency improvements that will be derived in the following, although undoubtedly dominated by these factors, probably also implicitly include some effects due to other energy efficiency measures that cannot readily be characterised in a quantitative manner as required for this type of analysis.

Equations (3) to (8) and equation (1), together with information on fuel mix, average emission factors, household numbers, external temperature, average dwelling heat loss and average heating efficiency (all of which can be obtained from the forthcoming BRE Report (Utley and Shorrock 2003)) provide all of the elements that are required to examine the allocation of domestic sector carbon emission changes.

Results

Table 1 shows the result of averaging the year by year predictions of equations (3) to (8) for the carbon emission changes between years. Summing the figures it shows that the total reduction to carbon emissions between 1970 and 2001 was 11.92 MtC. This is made up of increases of 13.65 MtC and 36.97 MtC (due, respectively, to the increase in the number of households and improving levels of service) and reductions of 1.74 MtC, 17.57 MtC, 17.06 MtC, 14.08 MtC and 12.10 MtC (due, respectively, to changes in the external temperature, improved insulation, improved heating efficiency, changes to the Electricity Supply Industry (ESI) and other carbon factor changes). Note that the available data allow the changes in the average carbon emission factor to be split into that due to the ESI and that due to other effects and so this has been done. These other effects are best thought of as structural changes since they are related to the altering mix of fuels used by the domestic sector. They can also be considered to contain any residuals of the calculation.

Table 1 also shows the variation around the average that is observed in each of the terms through using the individual equations. Generally, these only amount to about 1.5% or less, except in the case of external temperature where the 5.5% figure reflects the relatively small effect that this plays in comparison to the other terms.

Table 2 shows the same information as Table 1 but presents the carbon changes cumulatively. The figures in Table 2 can be used to easily determine the carbon emission changes between any two years simply by noting the difference between the cumulative figures for the respective years. Figures thus calculated relating to each of the three decades (i.e. the seventies, the eighties and the nineties) are included at the bottom of Table 2. The change between 2000 and 2001 is also included for the sake of completeness but it is obviously unwise to read too much into these figures given that they relate to a change within a single year and so they will be very sensitive to the inevitable statistical uncertainties in the source data. The implications of the figures for the different decades will be discussed later.

Table 1. Changes in domestic sector carbon emissions between years.

Between years	Components of carbon emission change (MtC)							Total
	Household growth	Level of service	External temperature	Building envelope heat loss	Heating system efficiency	ESI	Other C factor changes	
1970-1971	0.67	1.41	-2.09	-0.35	-0.59	-0.79	-1.64	-3.38
1971-1972	0.56	1.38	0.72	-0.51	-0.83	-0.38	-0.62	0.32
1972-1973	0.49	1.38	0.57	-0.69	-0.62	-0.23	0.16	1.06
1973-1974	0.49	1.39	-1.33	-0.86	-0.66	-1.09	0.82	-1.24
1974-1975	0.53	1.36	0.74	-0.84	-0.90	0.21	-3.33	-2.24
1975-1976	0.55	1.27	1.12	-0.91	0.24	-0.43	-4.18	-2.34
1976-1977	0.55	1.24	-1.48	-0.96	-0.28	-0.07	1.96	0.96
1977-1978	0.47	1.27	0.26	-0.94	-0.46	-0.70	-0.58	-0.69
1978-1979	0.42	1.27	2.69	-0.79	-0.63	0.76	-0.39	3.34
1979-1980	0.44	1.26	-1.41	-1.10	-0.33	-0.07	-1.35	-2.55
1980-1981	0.38	1.22	1.23	-0.91	-0.18	-0.08	-2.68	-1.02
1981-1982	0.33	1.19	-1.20	-0.93	-0.72	-0.95	0.60	-1.68
1982-1983	0.42	1.19	-0.71	-0.84	-0.75	-0.51	0.43	-0.77
1983-1984	0.49	1.16	0.69	-0.42	-0.92	-0.89	-2.29	-2.18
1984-1985	0.51	1.15	1.78	-0.26	-0.23	0.27	1.04	4.26
1985-1986	0.52	1.19	-0.80	-0.58	-0.16	-0.36	1.51	1.32
1986-1987	0.50	1.20	0.62	-0.52	-0.74	-0.20	-1.29	-0.42
1987-1988	0.49	1.19	-2.38	-0.33	-0.79	-1.07	0.87	-2.02
1988-1989	0.44	1.18	-1.31	-0.31	-0.63	-0.66	-1.12	-2.40
1989-1990	0.42	1.19	-1.32	-0.35	-0.57	0.22	1.20	0.78
1990-1991	0.51	1.19	2.91	-0.36	-0.61	-1.00	-0.72	1.94
1991-1992	0.39	1.17	-0.15	-0.87	-0.65	-0.97	-0.27	-1.35
1992-1993	0.42	1.13	-0.03	-0.17	-0.57	-1.86	-0.28	-1.36
1993-1994	0.45	1.11	-1.78	-0.15	-0.52	-0.78	0.19	-1.49
1994-1995	0.40	1.08	0.47	-0.47	-0.62	-0.39	-2.13	-1.66
1995-1996	0.31	1.05	1.98	-0.27	-0.46	-1.38	0.99	2.21
1996-1997	0.33	1.03	-2.59	-0.33	-0.74	-1.67	0.17	-3.80
1997-1998	0.32	1.03	-0.35	-0.08	-0.24	-0.17	0.78	1.30
1998-1999	0.35	1.02	0.56	-0.08	-0.81	-0.10	-1.47	-0.51
1999-2000	0.24	1.02	0.03	-0.67	-0.50	-0.13	0.47	0.46
2000-2001	0.25	1.06	0.82	-0.76	-0.59	1.42	1.02	3.22
1970-2001	13.65	36.97	-1.74	-17.57	-17.06	-14.08	-12.10	-11.92
+/-	0.15	0.54	0.09	0.25	0.26	0.13	0.11	
+/- as %	1.1%	1.5%	5.4%	1.4%	1.5%	0.9%	0.9%	

The results for 1970 to 2001 are illustrated more clearly in Figure 2. The chart at the top of this figure shows the cumulative effect of factors leading to an increase in carbon emissions. It indicates that by 2001 emissions could have been about 50.6 MtC higher than the 1970 level, in the absence of improvements to offset these increases. The centre chart illustrates the effect of the improvements and shows that they lead to a reduction of about 62.5 MtC. Note that external temperature appears in both charts because in a few years it increases energy use and carbon emissions relative to 1970, but in most years it reduces these (1970 being colder than most of the years that followed, with just a few exceptions).

The bottom chart shows the net effect of the factors that increase emissions and those that decrease emissions, indicating an overall reduction of about 11.9 MtC. The right hand axis indicates the actual carbon emissions in each year. The changes in these exactly match the pattern derived from the decomposition analysis, as noted earlier.

It is important to note that although the analysis has separated out the effect of seven factors on the carbon emission changes the results should only be used to identify the relative importance of those factors in the overall changes, and not to try and identify the specific contribution of a single factor. Thus, although one can readily conclude from the results that without the energy efficiency improvements that have been introduced since 1970 carbon emissions from the domestic sector would have increased, it is not possible to say with any confidence what the carbon emissions would then have been.

The reason for this is that the different factors are not independent of each other. For example, a part of the improvement in energy efficiency is directly due to the growth in the number of households (i.e. new homes being built to higher standards). Similarly, a part of the level of service increase is related to the improvements in energy efficiency which in turn automatically imply that higher comfort standards will be achieved.

Figure 2 indicates the relative importance of the different factors over the whole period 1970 to 2001. However, it is also of interest to see whether those relative importance rankings have changed over time. The figures required to make this assessment are contained at the bottom of Table 2 for each of the three decades. Figure 3 illustrates these results more clearly. Note that, strictly speaking, data for 1969 are

Table 2. Cumulative effect of changing carbon emissions.

To year ending	Components of carbon emission change (MtC)							
	Household growth	Level of service	External temperature	Building envelope heat loss	Heating system efficiency	ESI	Other C factor changes	Total
1970								
1971	0.67	1.41	-2.09	-0.35	-0.59	-0.79	-1.64	-3.38
1972	1.23	2.80	-1.37	-0.86	-1.42	-1.17	-2.25	-3.06
1973	1.72	4.18	-0.80	-1.55	-2.04	-1.41	-2.10	-2.00
1974	2.21	5.57	-2.13	-2.41	-2.70	-2.50	-1.28	-3.24
1975	2.74	6.93	-1.39	-3.26	-3.60	-2.29	-4.61	-5.49
1976	3.29	8.19	-0.28	-4.17	-3.36	-2.72	-8.78	-7.83
1977	3.84	9.44	-1.76	-5.12	-3.64	-2.79	-6.82	-6.86
1978	4.31	10.71	-1.50	-6.07	-4.11	-3.49	-7.40	-7.55
1979	4.73	11.97	1.19	-6.85	-4.74	-2.73	-7.79	-4.21
1980	5.17	13.24	-0.21	-7.95	-5.07	-2.80	-9.13	-6.76
1981	5.55	14.46	1.02	-8.86	-5.25	-2.88	-11.81	-7.78
1982	5.88	15.64	-0.18	-9.78	-5.98	-3.83	-11.21	-9.46
1983	6.30	16.84	-0.89	-10.63	-6.72	-4.35	-10.78	-10.23
1984	6.80	18.00	-0.20	-11.05	-7.65	-5.24	-13.07	-12.41
1985	7.30	19.14	1.58	-11.30	-7.87	-4.97	-12.03	-8.14
1986	7.82	20.34	0.78	-11.88	-8.03	-5.33	-10.52	-6.83
1987	8.32	21.54	1.40	-12.40	-8.77	-5.53	-11.81	-7.25
1988	8.81	22.73	-0.98	-12.73	-9.56	-6.60	-10.94	-9.27
1989	9.25	23.91	-2.29	-13.03	-10.18	-7.26	-12.06	-11.67
1990	9.67	25.09	-3.61	-13.38	-10.75	-7.05	-10.86	-10.89
1991	10.18	26.29	-0.70	-13.74	-11.36	-8.05	-11.57	-8.95
1992	10.58	27.46	-0.85	-14.61	-12.01	-9.02	-11.84	-10.30
1993	11.00	28.59	-0.88	-14.78	-12.58	-10.88	-12.12	-11.66
1994	11.45	29.70	-2.66	-14.93	-13.10	-11.66	-11.93	-13.15
1995	11.86	30.77	-2.19	-15.40	-13.73	-12.06	-14.06	-14.80
1996	12.16	31.82	-0.21	-15.66	-14.18	-13.44	-13.07	-12.59
1997	12.49	32.85	-2.80	-15.99	-14.93	-15.11	-12.91	-16.39
1998	12.81	33.88	-3.14	-16.06	-15.17	-15.28	-12.13	-15.09
1999	13.16	34.90	-2.59	-16.14	-15.97	-15.37	-13.59	-15.60
2000	13.40	35.92	-2.56	-16.81	-16.47	-15.50	-13.12	-15.14
2001	13.65	36.97	-1.74	-17.57	-17.06	-14.08	-12.10	-11.92
1970-1980	5.17	13.24	-0.21	-7.95	-5.07	-2.80	-9.13	-6.76
1980-1990	4.51	11.86	-3.40	-5.44	-5.68	-4.25	-1.73	-4.13
1990-2000	3.73	10.82	1.05	-3.42	-5.72	-8.45	-2.26	-4.26
2000-2001	0.25	1.06	0.82	-0.76	-0.59	1.42	1.02	3.22

needed in order to quantify changes that occurred in 1970, and hence in the seventies. Unfortunately, such data are not available, at least not in the level of detail that is required for this analysis. Thus, for the purposes of this paper, the *seventies* is taken to mean the ten-year period to the end of 1980, and similarly the *eighties* end in 1990 and the *nineties* in 2000.

Figure 3 shows that in the seventies the most important factor reducing carbon emissions was the structural changes in domestic energy use (as the use of natural gas increased rapidly whilst the use of solid fuel and town gas fell). Insulation improvements were important in this decade with heating system efficiency improvements also helping to secure carbon emission reductions against rapidly increasing levels of service and increasing numbers of households.

In the eighties heating system efficiency improvements, followed closely by insulation improvements (although at a lower level than in the seventies), were the most important factors. Structural changes continued but less rapidly than in the seventies as changes to the Electricity Supply Industry became more important. These succeeded in offsetting increases due to household growth and increased levels of service (although these were slowing relative to the seventies). Note that external temperature accounts for a relatively large change in emissions in this decade but this is simply due to the fact that the end year of 1990 happened to be the warmest year on record.

In the nineties changes to the Electricity Supply Industry became the most important factor affecting carbon emissions from the domestic sector (as electricity generation by gas-fired plant rapidly substituted for coal-fired plant). Heating system efficiency improvements continued at a similar level to the previous decade but insulation improvements slowed somewhat. This was undoubtedly due to the fact that the insulation measure that had been so important in earlier decades (loft insulation) was beginning to saturate and this was not fully superseded by the next important insulation measure (cavity wall insulation) until much later in the decade. Overall, a similar reduction to emissions was achieved in the nineties as in the eighties, helped again by

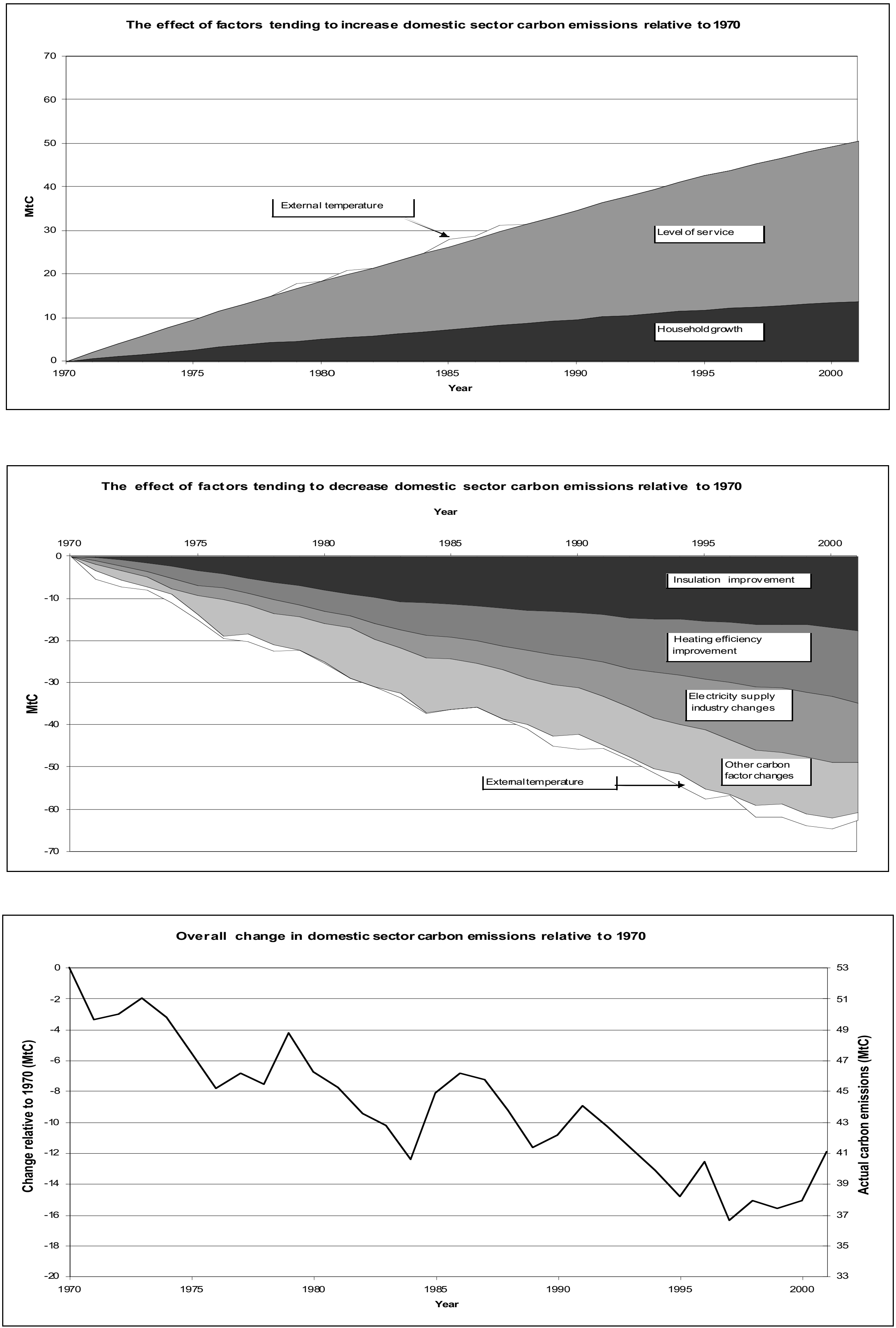

Figure 2. *Carbon emission changes and the factors contributing to these from 1970 to 2001.*

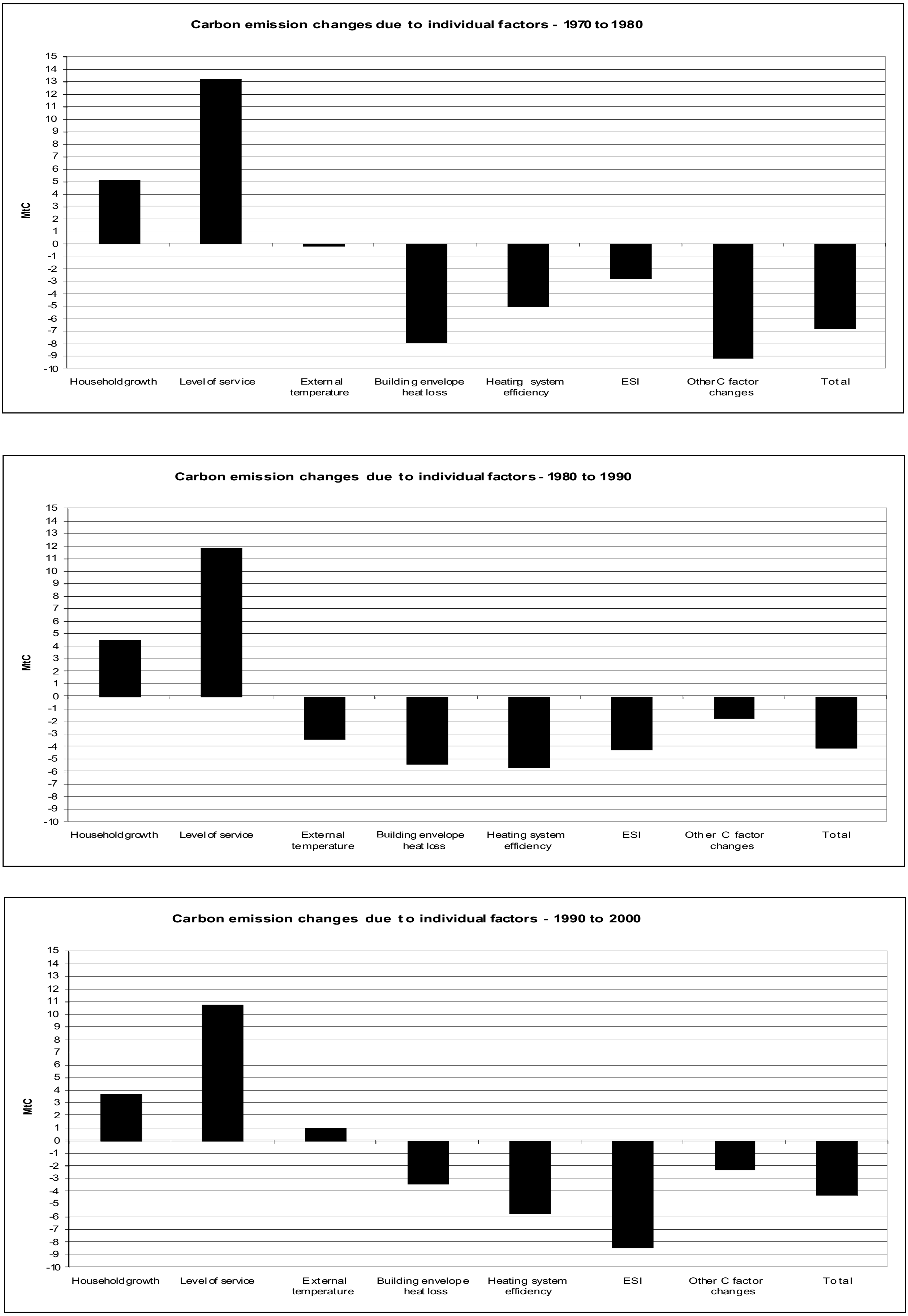

Figure 3. *The relative importance of individual factors in reducing carbon emissions in the 70s, 80s and 90s.*

the continuing slowing of increases due to household growth and increased levels of service.

It is interesting that the emissions in 2001 increased significantly relative to 2000, largely because of a reversal in the carbon emission factor for electricity coupled with a fuel mix change that also led to an increase in emissions. Obviously, one cannot read too much into the figures for a single year but the figures at the bottom of Table 2 do suggest that it will be difficult to continue reducing domestic sector carbon emissions in the first decade of the 21st century. The strong reductions in emissions due to Electricity Supply Industry changes that have been in train during the nineties are probably coming to an end if the 2001 figures are anything to go by, so it will be important to significantly accelerate the introduction of energy efficiency improvements in the new decade, and indeed this is the aim of various initiatives that have recently been introduced by the Government and Devolved Administrations of the United Kingdom (such as the significant tightening of the Building Regulations that was introduced in 2002).

Conclusions

This paper has examined the changes to carbon emissions in the United Kingdom domestic sector between 1970 and 2001. The results have shown that the net reduction of 11.9 MtC can be explained by the effect of factors that have tended to increase emissions, outweighed by the effect of factors that have tended to reduce emissions. Factors tending to increase the emissions relative to 1970 include the number of households (accounting for 13.65 MtC) and the level of service being demanded by households (36.97 MtC). Factors tending to reduce the emissions relative to 1970 include improved insulation standards (17.57 MtC), improved heating system efficiency (17.06 MtC), changes to the Electricity Supply Industry (ESI) (14.08 MtC) and changes to emission factors due to the altering fuel mix of the domestic sector (12.10 MtC). Higher external temperatures were also responsible for a small reduction relative to 1970 (1.74 MtC).

The results indicate that without the energy efficiency improvements that have been introduced since 1970 carbon emissions from this sector would have increased. Equally, however, the changes in electricity generation were also essential in securing an overall reduction in carbon emissions from this sector. It is the combination of the factors that led to the significant net reduction. This emphasises the importance of the continuing efforts to improve the energy efficiency of households in the United Kingdom. Indeed, consideration of the results for the different decades also reinforces this conclusion. In the nineties a large part of the improvement was accounted for by changes to the Electricity Supply Industry, which do not look likely to continue to the same extent in the early part of the 21st century. The importance of the individual factors has thus changed with time in such a way that implies that future carbon emission reductions will inevitably have to rely more on energy efficiency improvements than was the case in the nineties.

Acknowledgements

The work described in this paper forms part of the UK Government's Climate Change Programme and was supported by the Global Atmosphere Division of the Department for Environment Food and Rural Affairs (DEFRA). The data and model underlying the work are developed and maintained with support from the Sustainable Energy Policy Division of DEFRA through a contract managed by the Energy Saving Trust.

References

Comparison of six decomposition methods; application to aggregate energy intensity for manufacturing in ten OECD countries. L A Greening, W B Davis, L J Schipper and M P Krushch.

Energy Economics. Vol 19 (3) pp375-390. 1997.

Domestic Energy Fact File. J I Utley and L D Shorrock. BRE Report. Publication anticipated in March/April 2003.

Identifying the individual components of United Kingdom domestic sector carbon emission changes between 1990 and 2000. L D Shorrock. Energy Policy. Vol. 28 pp193-200. 2000.