A Reference Scenario for Energy Use and CO_2 Emissions by the Residential Sector in the United Kingdom

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A 'bottom-up' methodology has been developed for estimating energy consumption and CO_2 emissions in the United Kingdom residential sector, using a physically based model of energy demand. It brings together data from a variety of sources on the physical factors determining energy demand, and reconciles estimated energy requirements with the historical fuel delivery aggregates given in the Digest of UK Energy Statistics. It has been used previously to explain past demand for energy in the sector in terms of trends in the physically determining factors, including the growth in the use of central heating and improvements to insulation.

This paper illustrates the methodology by calculating CO_2 emissions for a reference scenario. This scenario estimates residential sector energy consumption and CO_2 emissions on the assumption that the physically determining factors included in the model continue to follow present trends. This takes account of ownership and other factors, allowing for saturation effects where appropriate. It does not constitute a forecast of UK residential sector emissions but allows the impact of technical, social and policy factors to be investigated by making appropriate alterations to the scenario assumptions.

Introduction

The residential[1] sector is estimated to account for 28% of all delivered energy in the United Kingdom, and a similar proportion of energy-related emissions of greenhouse gases to the atmosphere. It has also been estimated that carbon dioxide emissions could be reduced by 25% by making improvements to energy efficiency that are currently considered to be cost-effective, most having a simple payback period of less than 7 years. (Henderson and Shorrock 1990) Those improvements are of particular interest to policy makers because they may present an opportunity for reducing emissions at no net cost.

The 25% reduction in emissions of carbon dioxide referred to in the previous paragraph was estimated to be the result of applying the improvements immediately, with the demand for energy services remaining at current levels. Although that is an interesting result in itself, it does not relate to an outcome that could be achieved in practice. That would depend upon the rate of uptake of energy efficiency technologies, trends in internal temperature, appliance ownership, social factors including population and household size and economic factors such as fuel price and household income. The bottom-up methodology takes account of the interaction of many of those factors that determine energy demand. The reference scenario illustrates the methodology by estimating the outcome of a continuation of present trends. It is therefore a starting point for estimating the effect of policies designed to increase the rate at which energy efficiency technologies are applied; it should not be considered as a forecast of future UK residential sector energy consumption or CO_2 emissions.

Building a Reference Scenario

Why Bottom-up?

Households buy energy to provide a range of services, but the consumption of energy does not, by itself, necessarily result in any benefit to the consumer. Some uses of energy are considered by households to be necessary, while others are for luxury purposes. Moreover, some energy services can be provided by a range of fuels, while others need electricity. Also, many services provided by the use of energy are subject to saturation effects: they are not beneficial beyond a certain level. For example, additional space heating ceases to be a benefit when a comfortable temperature is exceeded. It can be misleading, therefore, to consider all residential energy demand, or even the demand for a particular fuel, as a single variable.

The disparate nature of the services that households derive from the use of energy has led us to adopt a "bottom-up" approach to building the reference scenario. As it is based on consideration of individual end-uses, this approach enables saturation effects to be accounted for adequately.

Also policy options often relate to particular kinds of energy efficiency improvements or particular end-uses; a bottom-up model is valuable for estimating their effects and their interactions with other measures. Accordingly, we believe that it is an appropriate method for building a 10-20 year reference scenario for the residential sector.

General accounts of the relative merits of bottom-up and top-down models are given elsewhere. (e.g., Stern 1984, Grubb et al 1991)

Available Data Related to Residential Energy

There are several valuable sources of information that relate to energy use in the UK residential sector. Total deliveries of gas, electricity, oil and solid fuels are available from the Digest of United Kingdom Energy Statistics (DUKES) (Department of Energy 1991) in a time series that goes back to before 1950. Good information is also available on the number of dwellings having various forms of insulation and types of heating systems, both surveyed annually since before 1970[2]. Data on the ownership of household electrical appliances are available from several sources, notably the General Household Survey (Office of Population Censuses and Surveys 1991), which is also a good source for household size and composition. The English House Condition Survey (Department of the Environment 1991) is provides information on the extent and duration of heating in dwellings; this is very important because most UK households heat intermittently and, until recently, many dwellings were only partly heated. The UK electricity supply industry has also provided unpublished data that have played an important part in attributing electricity consumption to various end-uses. Much of the available data have been collated and published by the Building Research Establishment (Shorrock et al 1992).

Methodology

Our approach to bottom-up modelling is based on charting the historical development of factors that affect demand for energy services and the efficiency with which those services can be produced. Demand for delivered energy is then estimated using a physical model of energy use and the results aggregated for the entire stock of dwellings. The estimated total energy consumption is then reconciled with aggregate delivery statistics for fuels supplied to the residential sector. This process relies on a disaggregated model of the dwelling stock known as BREHOMES, which has previously been reported. (Henderson and Shorrock 1988)

Ownership Curves. The uptake of particular energy efficiency measures and the market penetration of energy consuming appliances were fitted to S-curves, of the form:

$$L = S\,[1 - \exp(-k(t-t_0)^2)]$$

where: t is the year;
t_0 is the year when the measure was first introduced;
k is a constant that describes the rate of uptake;
S is the eventual saturation level.

(both L and S are percentages of households)

This equation has been found to describe the uptake of most energy efficiency measures and household appliances adequately. The curve parameters for each variable were fitted by visual inspection of past data.

Figures 1 to 4 show examples of the ownership data for appliances and insulation measures, together with the derived curves. Table 1 summarizes the parameters derived for individual cases. The t_0 values are chosen to give the best fit with the data and may not relate well to a definite time when the appliance or measure first became available. The saturation levels have been set at 100% in most cases. There are some cases, however, where more than one appliance can serve the same function. For example, fridge-freezers clearly overlap with both refrigerators and freezers, and the data show ownership of refrigerators declining as they are replaced by fridge-freezers. This can be described by setting a saturation level of 150% for refrigerators, freezers and fridge-freezers together, and 50% each for fridge-freezers and

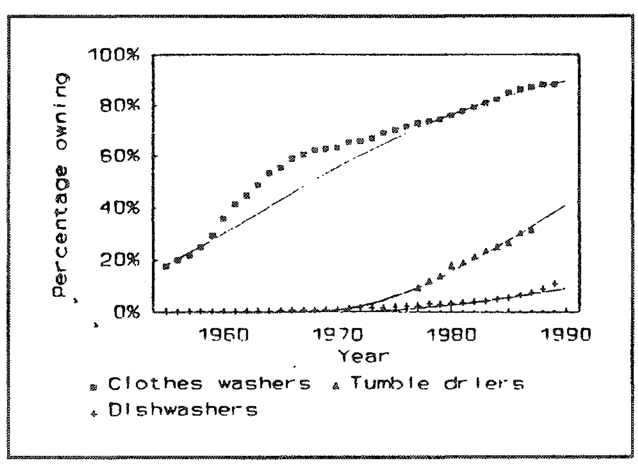

Figure 1. Washing/drying Appliances

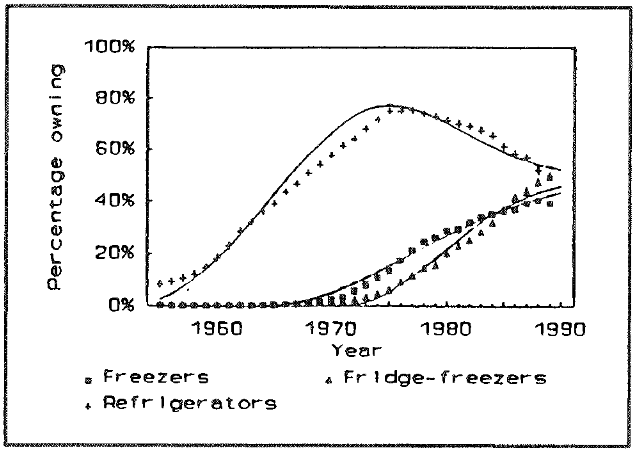

Figure 2. Refrigeration Appliances

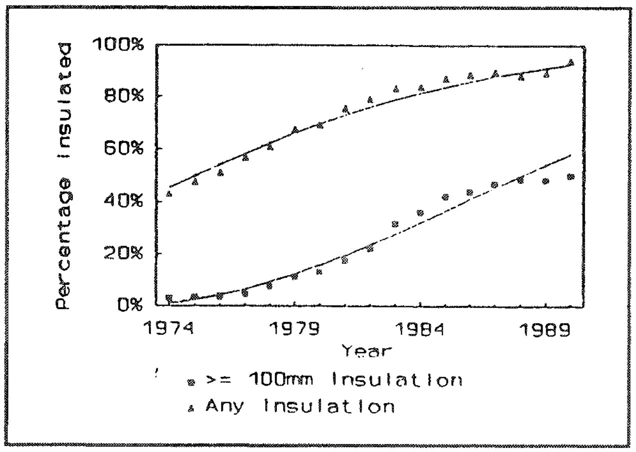

Figure 3. Roof Insulation

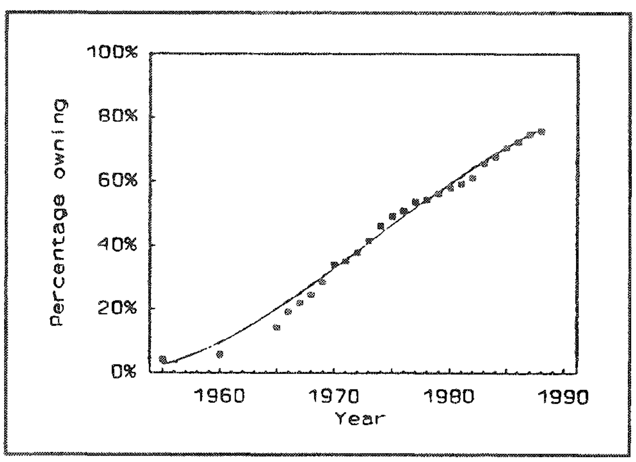

Figure 4. Central Heating

freezers individually. This gives a fairly good fit with the past data and, in practical terms, assumes that each household will have at least some capacity for freezing as well as for refrigeration.

Population and Households. The ownership curves described above need to be combined with projections of household numbers to allow a scenario to be built. Estimates of population up to the year 2031 were obtained from official, published projections (Central Statistical Office 1990). Estimates of household size up to the year 2001 have also been published and they have been extrapolated and combined with population to estimate numbers of households. The assumptions about household size, and the numbers of households derived from population projections through those assumptions, are shown in Table 2.

Heating Standards. A strong trend towards central heating has been the main factor increasing standards of heating for the last three decades, but it is expected to approach saturation during the present decade. Average temperatures have also risen as standards of insulation improved, particularly because of the practice of heating intermittently; a better insulated house cools down more slowly and its average temperature over the periods when the heating is off is therefore higher. It has been estimated that whole-dwelling average temperatures have risen by between 3 and 4 degrees Celsius since 1970, (Shorrock et al 1992).

Temperatures in living rooms during periods of heating do not seem to have increased nearly as much as the whole-house average. Measurements from various sources dating back over several decades suggest that occupants prefer living room temperatures of about 21°C during periods of heating, and the rest of the house to be about 2°C lower. Allowing for improved insulation and full uptake of central heating, this implies that whole-dwelling average temperatures will saturate at about 19°C. Extrapolation of the trend has led us to assume that an average temperature of 18.5°C will be reached by 2005. That would be higher if continuous heating were to displace the intermittent heating preferred at present, but there is no sign of that happening so far, even among affluent households living in well insulated houses.

Efficiency Improvements and Replacement Cycles. The efficiency of household electrical and heating appliances has improved with time, in some cases very considerably. In the past, the rapid growth in numbers of appliances has more than offset any reduction in energy demand arising from increased efficiency for many types of appliance. While this effect may continue for some types of appliance, the benefit of higher efficiency will

Table 1. Parameters Defining Ownership Curves for Appliances and Insulation Measures

Appliance/measure	t_0	k	S%	Comments
Clothes washers	1940	0.0009	100	
Tumble driers	1967	0.0010	100	
Dishwashers	1968	0.0002	100	
Refrigerators	1952	0.0030	150	With fridge-freezers
Fridge freezers	1971	0.0070	50	
Freezers	1964	0.0030	50	
Electric cooking	1929	0.0010	47	Percentage of cooking
Microwave ovens	1980	0.0090	100	
Central heating	1950	0.0010	100	
Condensing boilers	1988	0.0012	100	Percentage of sales
Roof insulation (any)	1959	0.0027	100	
Roof insulation (at least 100 mm)	1972	0.0027	100	
Hot water storage tank insulation	1953	0.0027	100	
Cavity wall insulation	1967	0.0006	80	
Double glazing	1969	0.0008	100	Percentage of all windows

Table 2. Summary of Key Assumptions in Reference Scenario

Population growth	57.9 million in 2005, 59.1 million in 2020
Household population	23.6 million in 2005, 24.9 million in 2020
Household size	2.46 in 2005, 2.37 in 2020 (cf 2.60 in 1990)
Dwelling temperatures	24-hour whole-dwelling average to reach 19°C by 2005
Technology	Commercially available now
Electrical appliances	S-curve projections for appliances with heavy consumption; efficiency improvements through replacement; miscellaneous appliance consumption to grow at 0.8% per year
Cooking	Share of cooking by fuel type to remain as at present (47% electric); microwave cooking to displace 10% of conventional cooking
Space and water heating efficiency	Projection of historical trend for conventional boilers and heaters; 20% of new gas boilers to by of condensing type by 2005
New building rate	To continue at present rate of about 1% of stock per year
Fuel prices and household incomes	No direct input to bottom-up model but the implicit assumption is that household income and energy price will continue to have the same effect on demand for energy services as they have had over the last two decades

tend at some stage to cause actual reductions in demand for appliances that have reached saturation. The trend towards improved efficiency needs to be taken account of with ownership trends to estimate future demand. We must also remember that new forms of appliance may emerge in the future, some of which may add significantly to demand.

Data on the energy consumption of electrical appliances were obtained from a recent study (Department of Energy 1990). Efficiency improvement rates were derived by assuming that appliances with improved efficiency will replace appliances with average efficiency for the existing stock. The level of efficiency for new appliances is derived from the average for those currently sold, improving with time at the historical rate. Replacement rates were obtained by subtracting annual growth in ownership from annual sales. This technique was used for heating, refrigeration, cooking and washing appliances. Other electrical appliance use was grouped together as "miscellaneous" and a growth trend estimated by projecting the historical trend for that category; this results in an estimated rise in demand for that category of 0.8% per year.

Estimating the Overall Demand for Energy

The various trends affecting energy demand were fed into a physically based model to calculate overall demand. The model, known as BREHOMES (Shorrock et al 1991) takes account of the interactions between the various factors. For example, the space heating energy calculation allows for the heat gains arising from other uses of energy in the dwelling. The principal inputs to the model include the uptake of insulation measures and electrical appliances, heating system efficiency, household population, and internal temperature. The principal outputs are estimates of delivered energy required for each end-use, broken down by fuel. The main trend affecting the fuel mix over the past two decades has been the movement away from individual room heating, which was mainly by coal, to central heating, for which natural gas is the dominant fuel. The projected fuel mix for heating is obtained from the central heating S-curve and the assumption that the fuels will retain their present shares of the market for new acquisitions, based on recent sales figures for heating systems. This results in a continuing trend towards gas for heating and away from coal. Electricity currently provides only 5% of space heating, which is projected to grow to 7% by 2005.

The delivered energy requirements are then used to estimate CO_2 emissions, using factors calculated to take account of the primary energy inputs for each form of energy. For fuels consumed directly in the dwelling, this includes energy overheads associated with the extraction, processing and distribution of the fuels. For electricity, it is calculated using the data available from the Digest of United Kingdom Energy Statistics (Department of Energy 1991) to take account of all energy inputs used in generating electricity supplied by the UK national electricity distribution grid. We have not distinguished between different times of day when the electricity is used; coal fired stations currently supply the marginal load across the full range of load conditions, and time-of-day variations are thought to be small on average. (This could well continue when the gas-fired combined-cycle stations that are now being constructed are brought into service, because they are expected to be used for baseload generation.)

Table 2 summarizes the principal assumptions on which the reference scenario is based.

Results

Energy Consumption

Table 3 gives the outputs for energy from the reference scenario at five-yearly intervals up to 2015. The values for 1990, which was an unusually mild year, are adjusted to the temperature in an average year. Actual values for 1970, 1975, 1980 and 1985 are also shown, for comparison. Total energy consumption in the reference scenario falls by 4% by 2005, but electricity consumption rises by about 9%. The results for energy consumption are shown in Figure 5.

Carbon Dioxide Emissions

The carbon dioxide emissions (shown in Table 4) for the year 2005 reduce by about 2% from 1990 levels if the carbon intensity of electricity from the public supply were to remain constant at the 1990 level of 0.76 $kgCO_2/kWh$. If that intensity were to reduce, as seems possible through the current trend towards generation using combined-cycle gas generation, then total carbon dioxide emissions would fall by a further 0.48% for each 1% reduction in carbon intensity. Figure 6 shows the results for carbon dioxide with the emission factor continuing at 1990 level.

Sensitivity of Output to Individual Factors

One of the principal uses of the reference scenario is to test the sensitivity of outcomes to trends in particular factors, especially where those factors could be influenced by policy options. It is also important to estimate the uncertainty that results from assumptions that went into the scenario.

Table 3. UK Residential Sector Energy Consumption

(a) By Fuel Type (in Petajoules)

	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Solid fuel	753	458	350	320	215	186	172	162	154	149
Natural gas	374	622	890	1022	1183	1159	1128	1096	1045	1012
Electricity	277	321	310	318	355	372	379	386	389	395
Oil	141	151	119	103	116	124	125	124	118	114
Total	1545	1552	1669	1762	1869	1841	1803	1767	1705	1670

(b) By End Use (in Petajoules)

	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Space heating	922	924	1028	1079	1142	1118	1078	1030	958	910
Water heating	427	408	381	393	417	409	408	409	411	412
Cooking	109	109	113	115	122	119	118	120	122	124
Appliances	86	112	147	174	188	196	201	207	215	224
Total	1545	1552	1669	1762	1869	1841	1803	1767	1705	1670

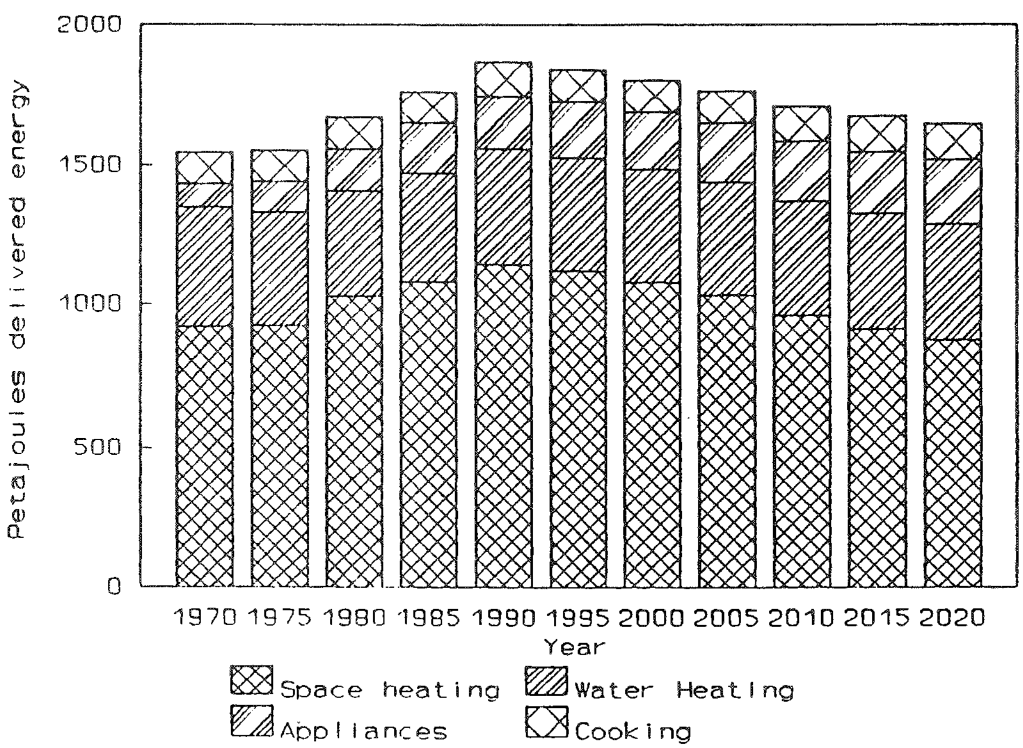

Figure 5. Energy Consumption

Table 4. UK Residential Sector CO_2 Emissions

(a) By fuel, with constant emission factor for electricity beyond 1990 (in millions of tonnes of carbon dioxide)

	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Solid fuel	70	43	33	30	20	18	16	15	14	14
Natural gas	39	37	52	60	69	68	66	64	61	59
Electricity	83	88	82	74	74	78	79	81	81	82
Oil	11	12	9	8	9	10	10	10	9	9
Total	203	180	176	172	172	171	171	169	166	164

(b) By end use, with constant emission factor for electricity beyond 199 (in millions of tonnes of carbon dioxide)

	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
Space heating	105	91	85	82	84	83	81	77	72	68
Water heating	55	46	39	36	36	36	36	36	36	36
Cooking	17	13	13	13	13	13	13	13	13	13
Appliances	26	31	38	41	39	41	42	43	45	47
Total	203	180	176	172	172	171	171	169	166	164

(c) Total if emission factor for electricity decreases uniformly after 1990

	1970	1975	1980	1985	1990	1995	2000	2005	2010	2015
10% by 2005	203	180	176	172	172	170	166	162	155	151
20% by 2005	203	180	176	172	172	167	161	154	146	140

Dwelling Temperatures. The past two decades have seen a marked rise in whole-dwelling average temperatures, largely through increased uptake of central heating. Continued increase due to that particular effect will soon be subject to saturation, but further increases could occur for other reasons. Temperatures are also important because they are the main mechanism through which households can respond in the short term to price increases. A rise of 1°C in whole-dwelling average temperature increases space heating requirements by about 15% and total energy requirements in the residential sector by about 9%. The effect on total carbon dioxide emissions is smaller, at 7%, because only a small proportion of space heating is by electricity. Future temperatures cannot be predicted accurately so this is probably the greatest source of uncertainty for future energy demand in the residential sector.

Heat Loss from Dwellings. Improved insulation has played an important part in restraining space heating energy demand over the past two decades. Various types of insulation applied to existing dwellings, as well as more stringent requirements for new buildings, have contributed to this. The overall effect is best quantified in terms of the power required to raise the temperature of a dwelling by a given amount; this is commonly called specific heat loss (SHL) and measured in W/°C (or BTU/hour/°F). Average dwelling SHL is a good indicator of the extent to which insulation in the dwelling stock has improved and is a key input to the reference scenario.

Space heating energy demand reduces by about 0.6% for each W/°C reduction in SHL while the net effect of the inputs to the reference scenario is to reduce SHL from 285 W/°C in 1990 to 229 W/°C in 2005. Clearly the effect of the insulation improvements in the scenario is very significant and total energy demand in 2005 would be about 6% higher if they were not made, showing the importance of continuing improvement to insulation. This sensitivity factor can also be used to show the relative importance of various forms of insulation and the effect of policies that might affect their rate of application.

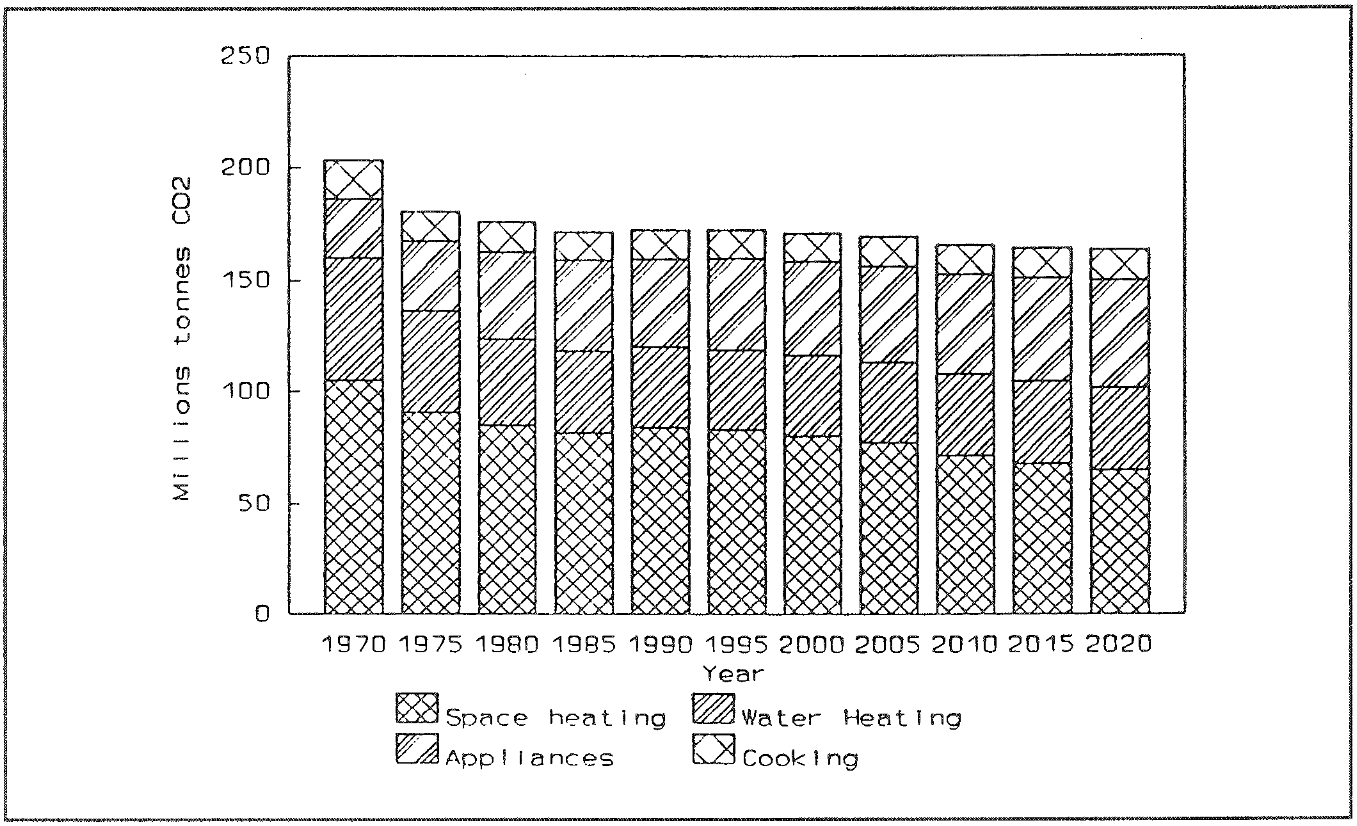

Figure 6. Carbon Dioxide Emissions

Heating System Efficiency. The average efficiency of heating systems is estimated to be 65% in 1990, so each percentage point improvement will reduce demand for space heating by about 1.5%. Over half of all dwellings are heated by wet radiator systems fed by gas fired boilers, most of which could be replaced by much more efficient condensing boilers. Currently the market penetration of gas condensing boilers is low but there is a large potential for replacing the current stock of standard boilers as they come to the end of their useful life. If 25% were replaced by condensing types, we could expect the stock average efficiency to increase 69%; this would have the effect of reducing total residential energy consumption by 4% and CO_2 emissions by 2%.

Electrical Appliances. Electrical appliances and lighting are estimated to account for 12% of total residential energy consumption and 26% of CO_2 emissions by 2005. Growth rates of up to 5% per year for energy use by appliances were apparent in the 1970s but have become much smaller in recent years as certain high consumption appliances have reached saturation levels. There is inevitably uncertainty in estimates of future consumption because of the difficulty of predicting both future ownership levels and efficiency. There is also the possibility that new types of appliance could become popular and add to demand in a way that we cannot envisage at present. It may be noted that the emission levels in the scenario are particularly sensitive to variations in appliance energy use: a 10% increase from the baseline estimate would add just over 1% to total energy consumption and 2.5% to total CO_2 emissions. This also shows the potential for improving appliance efficiency to reduce CO_2 emissions.

Electricity Generation. The reference scenario indicates that, by 2005, electricity will provide 22% of energy delivered to the residential sector and would contribute 48% of CO_2 emissions were the present carbon intensity of generation to continue. A 1% reduction in the carbon intensity of electricity generation would therefore yield a reduction of about 0.48% in total emissions from the residential sector. At present, a large amount of gas-fired generating capacity is under construction and more is planned, often involving private generating companies aiming to break into the recently deregulated market for electricity generation. Sources within the electricity generation industry estimate that there could be 10 to 13 GW of capacity by the year 2000 (Smith 1991), sufficient to reduce the carbon intensity by between 10 and 20%

from 1990 levels. This is one of the most important sources of uncertainty affecting the reference scenario.

Discussion

Price and Income Elasticities

Price and income elasticities were not used directly to construct the reference scenario but this does not mean that they are assumed to be unimportant. The historical data for trends in factors affecting the demand for energy themselves contain influences from economic factors, including both real income growth and fuel price changes. Such effects are not ignored therefore: the projections implicitly assume that the economic influences over the period of the projection will remain the same as they have been over the period from which the trends were derived.

Between 1970 and 1989, the weighted average price of fuels delivered to the residential sector in the UK varied from a low of £6.09/GJ (3.9 UScents/KWh) in 1970, through a high of £7.87/GJ in 1983, to stand at £6.75 in 1989 (in 1989 money values). This represents an average rate of increase of less than 0.6% per year over that period. This degree of stability is because very few households use oil for heating and only a small part of electricity generation is by oil. The UK residential consumer was therefore well isolated from the price fluctuations in the international oil market and the price of natural gas from the North Sea fields remained relatively steady, falling in real terms throughout most of the 1970s. Natural gas now accounts for nearly two thirds of residential energy deliveries and its price therefore of greatest significance. Although no official price forecasts have been published, it seems likely that the trend will be maintained for the next decade at least. Likewise, there is no reason to assume that real income growth will differ greatly from the trends of past two decades. The implicit assumption of a continuation of price and income trends is therefore highly plausible, in the absence of market interventions such as a carbon or energy tax.

Relationship with Econometric Models

The bottom-up model used to construct the reference scenario is clearly not capable of dealing with economic factors in isolation. It could not, for example, be used to estimate how energy consumption would respond to an increase in real fuel prices. Such an estimate would have to consider both short and long term responses. Short term elasticity would arise in practice through households responding to higher prices by reducing consumption of the services provided by the energy they buy. The bottom-up model could be used to estimate how much those services would have to be reduced to achieve a given reduction in consumption. In the longer term, however, households would respond by investing to improve energy efficiency and enable a higher level of energy service to be obtained from each unit of energy bought. The bottom-up model could be used then to quantify the improvements to energy efficiency arising from particular investments. In both cases, the role of the bottom-up model is to explain the relationship between energy services and the quantities of energy required to produce them. Econometric and bottom-up models are therefore complementary tools for policy evaluation rather than rival methods of doing the same task.

The Limitations of the Reference Scenario

By adopting a bottom-up method, we have implicitly claimed to understand the factors that determine the demand for energy services and the efficiency with which they can be delivered. While this may be true for the near future, based on calibrating our model with data from the recent past, it becomes increasingly difficult to substantiate as the time horizon extends. New lifestyles may emerge, perhaps influenced by unforeseen economic factors, leading to different demands for energy services from those we now perceive. Equally, new technologies may be developed that could strongly influence the means of providing energy services and the efficiency with which they can be provided. Changed economic circumstances could also have a strong impact on demand, affecting both demand for energy services and the rate of development of new technology. For longer timescales, it would be necessary to look beyond what is done now and to include mechanisms for dealing with unknown services and technologies.

Conclusions

1. A bottom-up methodology has been established as a basis for projecting energy demand and CO_2 emissions in the UK residential sector.

2. The methodology has been illustrated by developing a reference scenario that assumes present trends in the physical factors determining energy consumption will continue, taking saturation effects into account.

3. The reference scenario is not a forecast, but it provides a starting point for analyzing the impact of changes to the factors affecting energy demand.

4. Improvements in energy efficiency in the dwelling stock are likely to offset increased demand for space heating due to better heating standards as central

heating approaches saturation in the present decade. This could cause energy demand for space heating to fall by 10% by 2005.

5. Continued growth in electrical appliance use is likely to prove a stronger influence than improved appliance efficiency, leading to a 9% increase in electricity demand.

6. Future energy demand and emissions are very sensitive to temperatures in dwellings. Although rise due to increased ownership of central heating will diminish in importance, space heating requirements could still increase considerably through a small general rise in preferred temperatures. An additional rise in average dwelling temperature of 1°C would cause total carbon dioxide emission in 2005 to be about 7% higher than given in Table 3. This shows a continuing need for research on dwelling temperature trends.

7. There are significant opportunities for reducing energy demand and emissions through improvements to insulation and the efficiency of heating systems and household appliances. The defining parameters of the S-curves given in Table 1 for energy efficiency improvement measures, such as wall insulation and condensing boilers, indicate that many cost-effective opportunities will remain unexploited in 2005 if present trends persist.

Acknowledgements

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Endnotes

1. The term "residential" is the same as "domestic" used to define the domestic sector in the Digest of UK Energy Statistics; this includes all energy bought by households except fuel for road transport. "Dwelling" is used to describe a building, or part of a building, occupied by a single household; it includes both houses and apartments. "Household" is used to describe the person or persons occupying a dwelling.

2. These surveys were undertaken by a commercial market research organization for clients, including Government. The results were not published in full, but a summary of the more important results appears in a published report. (Shorrock et al, 1992)

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