Least-cost greenhouse planning

Supply curves for global warming abatement

Tim Jackson

The paper presents a methodology for comparing the cost-effectiveness of different technical options for the abatement of greenhouse gas emissions. The methodology also allows a determination of the extent to which each technology can contribute to abatement by a specified date. The primary focus of the paper concerns carbon dioxide (CO_2) emissions. The analysis concludes that of seventeen different abatement options examined, the nuclear option is the most expensive, except for the marginal CO_2 savings achieved from advanced coal technology. A combination of energy efficiency measures and high efficiency gas-fired generation can achieve CO_2 savings approaching 285 million tonnes per year by year 2005. This represents a saving of 46.5% over existing emissions from the stationary sector (ie excluding transport). If the analysis is extended to include the effect of methane emissions from fossil fuel cycles, the advantages of energy efficiency and the renewable generating sources is improved.

Keywords: Global warming; Energy-efficiency; Cost-effectiveness

Global warming presents policymakers with a unique, and somewhat alarming challenge. Despite international acceptance of the findings of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC)[1] on the scope and scale of climate change, the uncertainties identified by the group leave a wide margin for uncertainty. Uncertainties over feedback mechanisms (for instance due to the reflectivity of clouds or the unlocking of methane from melting arctic tundra), over the relative interaction of sources and sinks, and over the timing of climate change due to the lag effect of the oceans for instance, all render exact predictions of temperature rises by certain dates impossible. Policymaking under conditions of such uncertainty is at best uncomfortable.

The primary decision facing governments and policymakers at the moment is whether to take preventive measures against the possibility of future global warming or whether to do nothing now and take adaptive ones when and if the need arises. Adaptive ones (it is argued) may save unnecessary capital expenditure and institutional restructuring now. On the other hand adaptive options will essentially be limited to the (costly) construction of defences against sea-level rise in low-lying regions at some future date, resettlement of threatened habitats and so on.

Preventive measures aim to lessen the probability of future temperature rises by attempting to abate the emission of greenhouse gases (carbon dioxide, methane, nitrous oxide, ozone, CFCs and hydrocarbons) from anthropogenic sources. Concern over this approach centres on the fear that it could be costly, disruptive and possibly (depending on the degree of existing 'commitment' to global warming) ineffectual.

Preventive measures and adaptive measures are of course not mutually exclusive. It is noteworthy, however, than in many societies these different types of measure would be implemented by different institutional bodies, with possibly differing economic infrastructures and policymaking frameworks: since the energy sector contributes some 60% towards the greenhouse effect (globally), energy utilities and infrastructures would be significantly affected by the need to implement preventive strategies; on the other hand, adaptive measures as a matter of national defence would be likely to be undertaken by civil defence or construction bodies of one kind or another.

Given the potential severity and disruptive nature of global warming, and the possible lagtime between emission abatement and its effect on the climate, the

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most prudent choice, even for an only moderately risk-averse society, is undoubtedly to favour preventive action at the earliest opportunity. Climate change could have very significant long-term effects on water management, on food production, and on national and international security. Prevention under these circumstances, is far better than cure. In fact, many of the energy policy options which are suitable for the abatement of global warming also provide other environmental advantages such as the elimination (or reduction) of acid pollution, particle emissions, or nuclear waste, and the elimination of the need to site costly and intrusive power plants in increasingly stressed environments.

Paper commitments to this sort of preventive strategy have already been made. Most of these commitments focus on carbon dioxide (CO_2) emissions which are believed to contribute around 50% of the warming effect of the greenhouse gases. In November 1988, for instance, the Toronto Conference on the Changing Atmosphere[2] agreed in principle to a 20% reduction in CO_2 emissions by the year 2005. The NGO statement from the Climate and Development Congress in Hamburg[3] called on industrialized nations to commit themselves to reducing their emissions by 30% by the year 2000 and by 60% by the year 2015 (based on 1986 levels).

Unilateral reduction targets have yet to be set, however, at the national level. The Dutch government has called for a stabilization of CO_2 emissions at 1989/90 levels by the turn of the century.[4] The UK government has set a target date of 2005 for stabilization of CO_2 emissions. The USA is resisting the pressure to set any targets at all. There are many reasons for this reticence to act.[5] Modelling the international political climate is probably more complicated even than modelling the atmosphere. It seems likely however that a concerted multilateral approach to the problem will become a major concern at the United Nations Conference on Environment and Development in 1992.

The starting point for this paper is that at least some preventive measures are advisable in order to control and abate global warming.

It seems logical, once the preventive position is adopted, to assume that one would wish to pursue such a strategy in the most cost-effective manner.[6] That is, one would identify the most cost-effective options for greenhouse abatement, and implement them first, and so on. Of course this apparently simple methodological principle covers a multitude of complexities, which must be addressed. These are associated to some extent with uncertainties in the scientific knowledge base and to some extent with the irregularities and peculiarities internalized within the economic, institutional and social infrastructures of individual societies.

On the other hand the advantages of pursuing such a cost-effective approach are significant, not only in narrow economic terms but also in terms of long-term, global, environmental aims.

National goals for preventing global warming are likely to require substantial investment. To proceed without paying attention to cost-effectiveness would be to lay oneself open to future difficulties in the funding either of additional preventive strategies (as may be required) or indeed of adaptive strategies, should the preventive measures fail to provide full protection against the effects of climate change.

A significant array of other environmental problems, some of which may have synergistic interactions with climate change effects such as sea-level rise, are also likely to require substantial investment commitments throughout the next 20 or 30 years.[7] Although returns on some of these investments may be high, availability of capital may become an increasing concern even for the richer industrialized nations before the end of the twenty-first century.

When one considers, in addition, the global impact of many environmental problems, it becomes clear that unilateral action at the national level is not going to be sufficient to ensure that global environmental goals are achieved or indeed that national environmental protection is assured. Particular concerns hinge around the development of the poorer nations. If these countries are not to be condemned to continuing poverty throughout the next century, they must be able to respond to their own development needs. If they are to do this without incurring the sort of environmental damage which has been incurred during the development of the presently-industrialized nations, then they will require both technological and financial assistance, to overcome crippling debt problems, to invest in clean and energy-efficient technologies and to develop resource-efficient, sustainable economies.

Economic and technical aid from the developed to the developing world is going to be crucial in achieving this. If it is not achieved, then the effects will be felt, in environmental terms, not only within those countries, but globally.

In a very real sense, therefore, poor economic management, even within the well-off nations of the industrialized world, is going to have long-term global implications for the environment.

The aim of this paper is therefore to set out a conceptual framework for the cost-effective allocation of resources to global warming abatement measures. In the following sections, I first elaborate the methodological basis of such an approach as applicable to the abatement of CO_2 emissions in the UK. I examine briefly how these results should be extended to include the effects of other greenhouse gases, and abatement options. This leads to the development of a rather general methodology for least-cost greenhouse planning. Finally, I discuss some of the economic, social and scientific factors relevant to the question of developing policy options appropriate to a cost-effective greenhouse abatement strategy.

Least-cost CO_2 abatement

CO_2 emission abatement from the energy sector can be achieved through four different types of technological measures:[8]

- reducing fossil fuel usage by improving supply-side efficiency;
- reducing fossil fuel usage by using non-fossil sources of supply;
- replacing high carbon fuels such as coal with low carbon fuels such as natural gas;
- reducing demand by end-use efficiency.

On the supply side, this paper looks at combined heat and power (CHP) (large-scale, industrial and small-scale) at gas-fired combined-cycle gas turbines, at renewables, and at nuclear power; and at the replacement of electric heating with gas heating. On the end-use side, I have carried out a comparison of efficiency measures, disaggregated by ten sectoral end-uses including space and water heating efficiency improvements, and improvements in lighting and appliance efficiency.

The methodology I have chosen to use for the cost-effectiveness comparison follows closely the methodology of the 'least-cost integrated planning approach' to meeting energy demand, now familiar from many applications in North America.[9] Least-cost planning is essentially very simple. It assumes that the demand for a particular service can be met in a variety of possible ways. Each of these ways of meeting the demand for the service will have certain potential for meeting that demand (constrained by the availability of natural resources and certain institutional factors) at a certain cost. A simple ranking system then prioritizes the various measures in terms of their cost-effectiveness.

What characterizes this approach to energy planning is the incorporation of both supply-side and demand-side options as *bona fide* methods of meeting the demand for energy services. This integrated approach institutionalizes the implementation of electricity-efficiency (for instance) as a legitimate way for utilities to meet the demand for energy services. Whereas, traditionally, utility planning has tended to take electricity demand as read and to address the problem of meeting that demand by constructing supply-side options, the least-cost integrated approach accepts that, where demand-side measures deliver the same service at less cost than the supply-side option, utility planning should implement those measures first.

The basic tool of the approach is a 'supply curve' which compares directly, and using the same economic criteria, the costs of implementing the various options (both supply-side and demand-side), and their potential in meeting the demand for energy services.

The idea is to extend this methodology to CO_2 abatement technologies. The extension is not entirely straightforward for the following reason. Whereas the objective of a supply curve is to compare the different options for supplying energy, given a particular demand, and assess the most cost-effective way of doing this, the objective here is to adopt the most cost-effective way of reducing CO_2 emissions. A reduction of CO_2 emissions over a finite time period can only be measured against some projected base case for emissions over the period. Likewise the cost of abatement is meaningful only as the marginal cost associated with carrying out abatement options over and above the cost that would have been incurred anyway by the reference or base case.

With this proviso in mind, it is possible to extend the least-cost planning method in the following way. Each of the demand-side options has a potential to save a certain amount of delivered energy by a certain date. Associated with those savings in fuel is a saving in CO_2 release. Similarly, each supply-side option has the potential to save a certain amount of CO_2 emissions with respect to the base case. Dividing the cost of the measure in terms of £/GJ by the CO_2 savings in terms of tonnes of CO_2 per GJ (t/GJ), one arrives at a savings cost in pounds per tonne of CO_2 (£/tonne). One can then construct a CO_2 abatement supply curve or 'savings curve' as shown in Figure 1.

The height of the blocks in Figure 1 represents the cost in £/tonne of CO_2 saved by the measure and the width of the block represents the potential contribution to saving CO_2 that the associated measure can achieve by the specified date.[10] The savings curve then provides a direct comparison of the different abatement options in terms of their relative cost-effectiveness and their potential for reducing CO_2

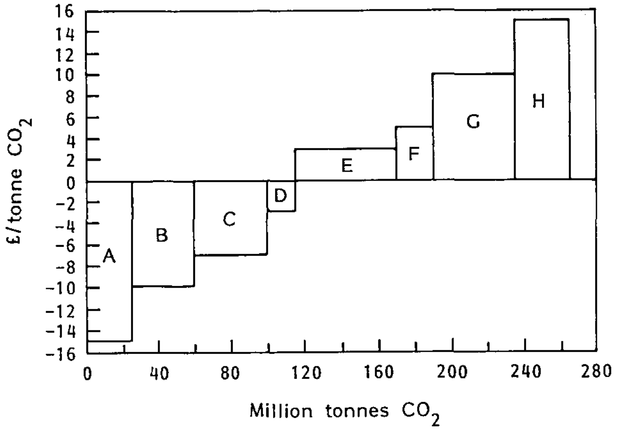

Figure 1. Illustrative savings curve for CO_2-abatement options, 2005.

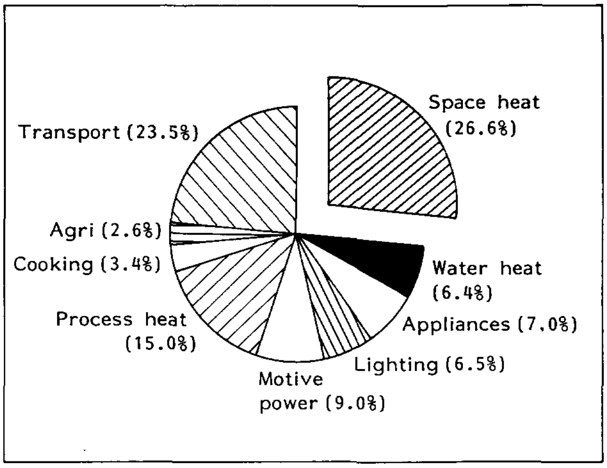

Figure 2. Estimated CO_2 emissions by end-use, 1987.

emissions. Some of the costs may be negative because some of the measures are less expensive than the base case: abatement may actually save you money.

Once a particular target for CO_2 reduction has been chosen it is possible by using the 'savings curve' to see which abatement strategies would best be implemented in order to achieve that target in the most cost-effective manner. In Figure 1, for instance, if the desired target requires a reduction in CO_2 emissions of say 120 million tonnes (mt), then the most cost-effective route to achieve those reductions would be to implement options A–D. If the target reduction was 240 mt, then options E–G would also be implemented and so on.

Given suitable and sufficiently detailed supply curves for supply-side and demand-side technologies for each of the stationary UK sectors (domestic, commercial and public, and industrial), and a breakdown of the end-uses in terms of delivered fuel types, it would be relatively straightforward to calculate the potential for CO_2 savings associated with each measure and the cost of those savings on a disaggregated basis.

However, detailed supply curves of this nature are not yet available in the UK – apart from some early work on cost comparisons between technologies for supplying and saving energy.[11] This early work needs some updating now, but provides a valuable illustrative basis for the cost-effectiveness of energy-saving technologies. Many examples exist of detailed supply curves in other countries but their relevance to the case of the UK must be considered to be limited.

For the purposes of this study considerable use has been made of three extensive reports on energy use and energy efficiency in the three stationary sectors (domestic, industrial and services) carried out for the Energy Efficiency Office (EEO) by the Energy Technology Support Unit at Harwell.[12] Estimates of electricity demand were taken from the Central Electricity Generating Board's (CEGB's) estimates[13] (appropriately adjusted to take account of Scotland and Northern Ireland).

From these sources I have derived, first of all the reference or base case CO_2 emissions scenario for the period up to the year 2005.[14] The total estimated emissions for 2005 are 691 mt, as opposed to a calculated 554 mt for the year 1987.[15] Estimated emissions are broken down by end-use in Figures 2 and 3.

It is to be noted that transport plays an increasingly important role in CO_2 emissions so that by 2005, it represents the single largest end-use contributing to CO_2 emissions. Despite this fact, and largely because of its origins, this study concentrates on emissions from the stationary sectors, and nothing furth-

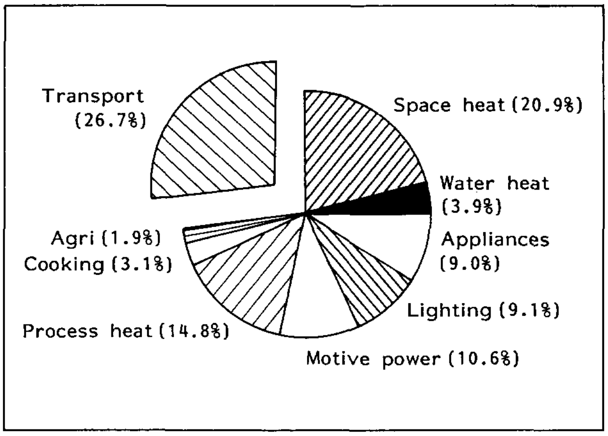

Figure 3. Estimated CO_2 emissions by end-use, base case (2005).

er will be said about emissions from the transport sector in this paper. This is not in any way to relegate transport emissions in importance. It is purely a limitation of the study.

The base case scenario incorporates certain assumptions about supply. These have largely been taken from the fuel mix predictions of the EEO reports. For electricity supply, I have assumed a base case scenario in which the need for new capacity is supplied by conventional coal-fired power stations.[16] Abatement technologies will be measured against this reference both in terms of the amount of CO_2 they save and also in terms of their cost.

The next step was to use the potential savings from and costs for energy efficiency identified in the reports to calculate potential CO_2 savings from each end-use efficiency measure. Costs for demand-side options have been calculated by taking the cost-effectiveness criteria used in the EEO reports and using additional information on technology lifetime to estimate raw capital costs.

Availability of raw cost data might well indicate a greater potential for energy efficiency, cost-effective in terms of the present analysis, but not captured in the narrow cost-effectiveness criteria adopted in the EEO reports. This represents a methodological conservatism inherent in the assumptions of this study about the potential for energy efficiency.

In order to be able to compare the different options on a 'level-playing-field' basis, capital costs have been annuitized at a 10% discount rate. Appropriate fuel savings have been taken into account. Costs are largely assumed to be on a 'natural replacement' basis, and where accelerated replacement occurs, it has been assumed that this is taken into account via the EEO cost-effectiveness criterion.

Costs and potential for the electricity supply options, such as renewable energies, CHP, combined cycle plant and nuclear power, have in the main been drawn from evidence supplied to the Hinkley Point Inquiry by various authors.[17]

In this way I have built up a savings curve (Figure 4) of the form illustrated in Figure 1. The potential contributions (ie the widths of the various blocks) are the contributions at the given costs that might under various conditions be implemented by the year 2005. If another date were chosen for the analysis, the broad conclusions of the comparison would remain unchanged, but the potential for implementation would be greater or less depending on whether the date were after or before the year 2005. The data on which Figure 4 is based are provided in Table 1 (Appendix).

What is striking in Figure 4 is that, out of 17 options considered, nuclear power is more expensive than anything except advanced coal technology where the marginal CO_2 savings are rather small. In fact it is possible to save around 275 mt of CO_2 without adopting the nuclear power option. If one looks at overall CO_2 emissions from transport and the stationary sectors, this saving is in excess of that required by the Toronto target of 20%, even without considering savings possible in the transport sector. If one looks at the stationary sectors (excluding transport) in isolation, the potential CO_2 savings (without using the nuclear power option) amount to a 46.5% reduction on existing emission levels.

It is also noteworthy that several of the options, including particularly those associated with end-use efficiency improvements, have an overall negative cost, by comparison with the base case. In other words, saving CO_2 does always mean vast expenditure. Sometimes you can save CO_2 and make money. The crucial point is not to spend money on the wrong thing to start with.

The effect of methane emissions from fossil fuel usage

When discussing the energy policy implications of the greenhouse effect, attention has largely focused on CO_2 emissions. Since these contribute over 50% of the greenhouse effect, this is not surprising. There are however other greenhouse gases which arise to a greater or lesser extent as a result of anthropogenic energy production. Of these, the most significant is undoubtedly methane (CH_4).

A number of recent studies[18] advocate the replacement of high carbon fuels such as coal with lower carbon fuels such as natural gas, in order to reduce the emission of greenhouse gases. Indeed the supply curve illustrated in Figure 2 above includes several supply-side options involving natural gas.

While this obviously makes sense from the point of view of CO_2 emissions, potential problems arise as a result of the CH_4 content of natural gas, and the propensity for leakage from the gas distribution system. A recent paper in this *Energy Policy*[19] estimates that leakage from the UK distribution mains lies in the range 1.9%–10.8%. The significance of leakage rates towards the higher end of this range arises because CH_4 is considerably more effective as a greenhouse gas than CO_2.

In order to capture the relative effectiveness of the different greenhouse gases, an index known as the global warming potential (GWP) relative to CO_2 has been adopted.[20] The GWP reflects a combination of

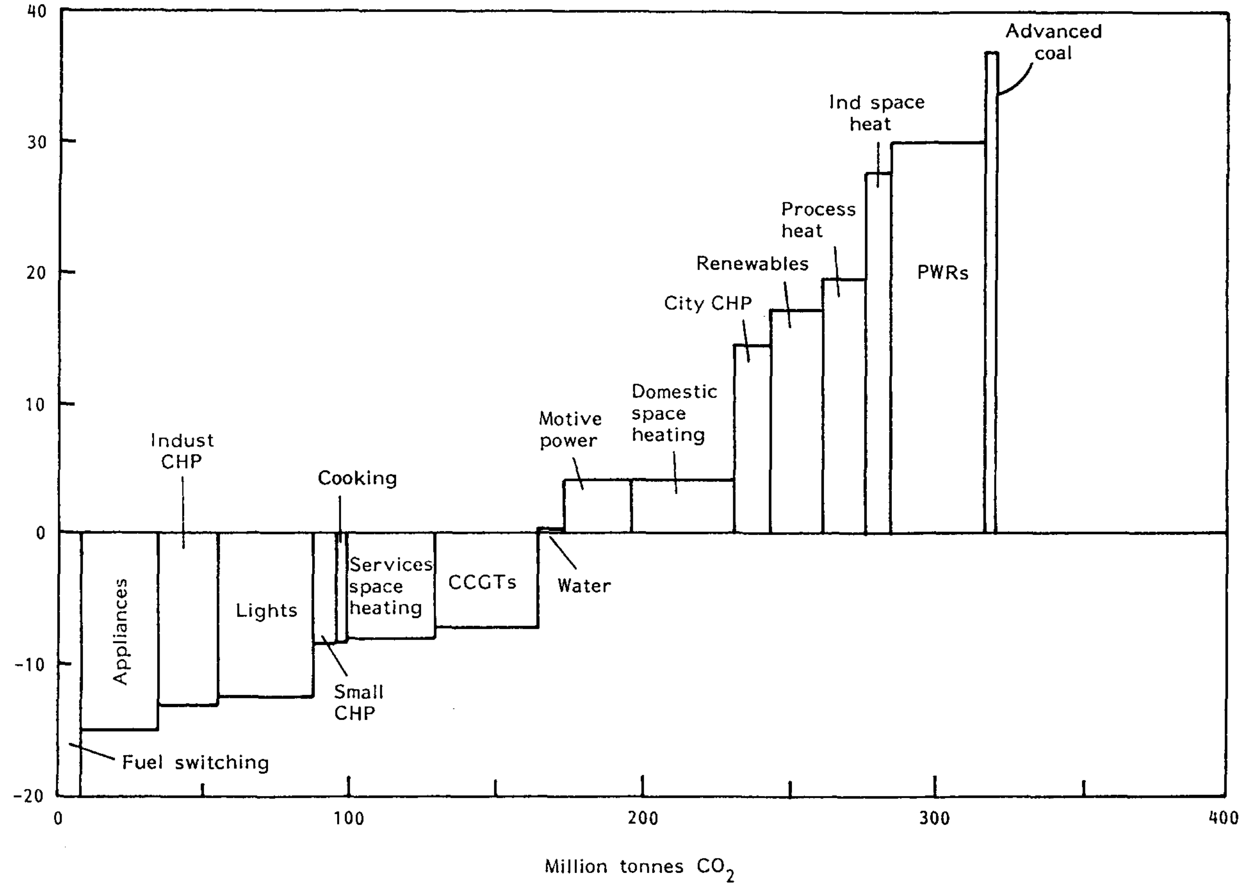

Figure 4. Savings curve for CO_2-abatement options (10% discount rate).

factors including the radiative forcing of the various gases relative to CO_2, and the 'atmospheric lifetime' of the gases in the atmosphere. CH_4 has a radiative forcing which is some 80 times greater than CO_2. On the other hand, its lifetime is of the order of 10–15 years. The atmospheric lifetime of CO_2, by contrast, is around 200 years. The problem in determining the GWP of CH_4 is the allocation of an appropriate time horizon over which the comparison should be made. At different time horizons, the GWP of CH_4 is different. Over a shorter time horizon, because of the short atmospheric lifetime of CH_4 relative to CO_2, the GWP is rather high.[21] Over a longer time horizon the GWP diminishes.[22]

The appropriate time horizon over which to consider the relative warming effect is not immediately obvious. Using the shorter horizon will tend to lead to policy decisions which abate short-term warming at the expense of longer-term warming. Using a longer horizon will mean abatement strategies take effect over a longer period.

Generally speaking it is probably unwise to base policy decisions on predicted short-term effects at the risk of endangering long-term warming abatement. The only circumstances in which one could envisage favouring the shorter term, would be where it could be shown that the associated short-term warming effect might exceed critical rates of change, and thus give rise to uncontrollable 'feedback' effects. On the basis of current knowledge, it is difficult to predict such 'rate of change' effects. There are no indications at present, however, that significant warming *impacts* will actually occur within the next 20 years. This is not to suggest that greenhouse gas *emissions* are not critical in the next 20 years. But only that their critical impacts are likely to lie on a longer time-scale. For the purposes of the analysis that I wish to carry out here I have therefore used 100-year time horizon, over which the GWP of CH_4 (on a weight-for-weight basis) is 21.

The second difficulty inherent in attempting to include the effects of CH_4 leakage into the cost-effectiveness assessment of greenhouse abatement options is the uncertainty surrounding leakage. This has been discussed in considerable detail elsewhere.[23] The problem is to determine what

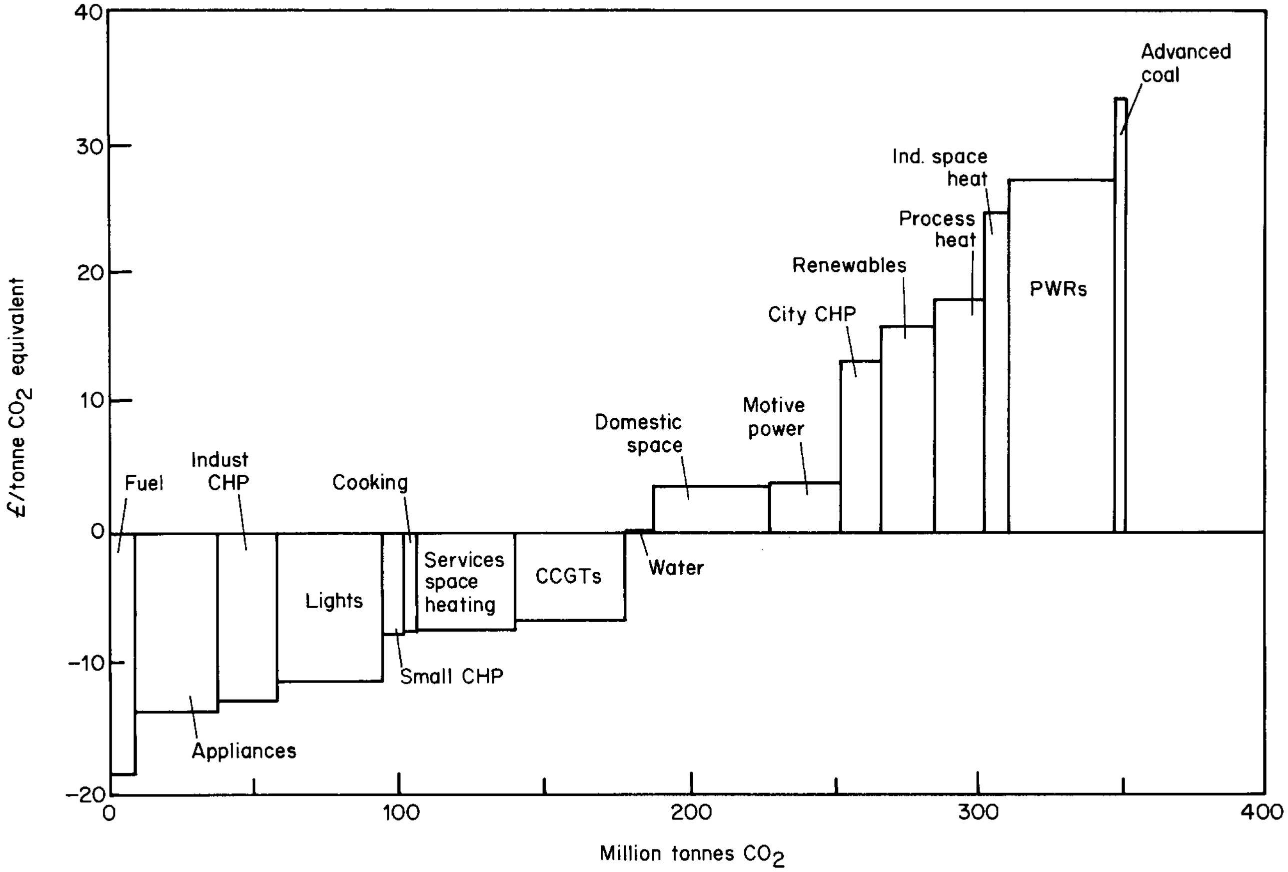

Figure 5. CO_2-equivalent savings curve (low leakage).

marginal leakage is attributable to any marginal increase in supply. The rather high leakage attributable to the existing distribution system which was designed for operation using a different gas may not be representative of leakage rates for marginal new supply. A lower leakage rate (of say 1% or 2%) may be appropriate for dedicated supply pipelines to combined-cycle gas turbines or large-scale combined heat and power plants, for instance. On the other hand, average lifetime leakage rates in a complex distribution system could be substantially higher.

There is also the question of CH_4 emissions from the other fuel industries, particularly from coal mining, on which reliable data are currently rather sketchy.

In order to get a rough idea of the possible effect of CH_4 leakage on the cost-effectiveness prioritization of abatement options illustrated in Figure 2, I have taken three scenarios for gas leakage: low, medium and high. In the low case, I assume a leakage rate of 2% for the existing system and 1% for new plant. In the medium case, I assume a 5.3% leakage rate for the existing system, a 2% leakage rate for new large-scale plant (assumed to have dedicated pipelines) such as city-wide CHP and combined-cycle gas turbines, and a 4% leakage rate for smaller-scale supplies (small CHP, industrial CHP and fuel switching). In the high case, I assume 10.8% leakage for the existing system, 3% for new large-scale supplies and 8% for smaller ones.[24] The results of this analysis are illustrated in Figures 5, 6 and 7, and shown in tabular form in Tables 2, 3 and 4 of the Appendix. In all three graphs, CH_4 emissions from other fuels (coal and gas) are accounted for according to official estimates.[25]

It is notable that on all three graphs the overall potential savings are at least as high as those given in Figure 4. Although the gas-fired options are not so favourable in the medium and high cases, this is more than made up for, because the energy efficiency options also save on CH_4 leakage by displacing the need for gas supply. This effect is reinforced by the avoided emissions of CH_4 from the other fuels, and supplemented by the increased effectiveness of some of the supply-side options, once CH_4 emissions from coal are taken into account.

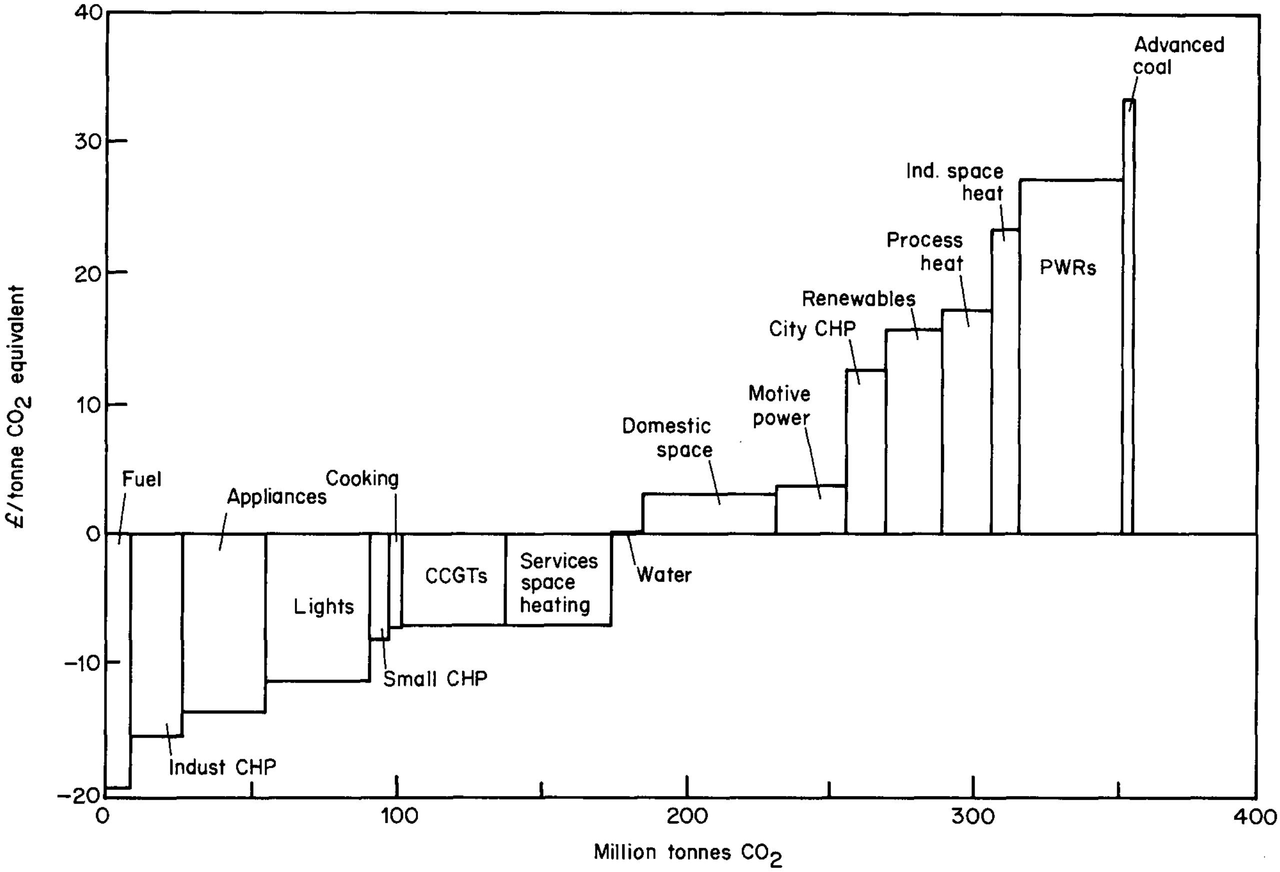

Figure 6. CO_2-equivalent savings curve (medium leakage).

Least-cost greenhouse abatement

The concept of a relative global warming potential (GWP) opens the way for a comprehensive cost-effectiveness analysis of greenhouse abatement options. Since the effect of each greenhouse gas in the atmosphere can be described in terms of the effect of CO_2 in the atmosphere, it is possible to construct a single savings curve to incorporate all abatement options for all of the greenhouse gases. Such a curve would show tonnes of CO_2 equivalent (CDE) on the horizontal axis. The vertical axis would still be the cost of each option, but now it would be expressed as cost per tonne of CDE saved.

To take a simple example, we could look at the cost-effectiveness of re-piping parts of the gas distribution network as a greenhouse abatement strategy. Suppose that the marginal annuitized lifetime cost of relaying older pipes were £5.00 per metre,[26] and that the total length of such pipes is 150 000 km. Suppose in addition that the gas leakage rate is 10 t of CH_4 km/y. Then this is about 200 t CDE per km/y (assuming a GWP of 21 for CH_4), and the total potential savings could be 30 million t/y of CO_2 equivalent, at a total cost of 750 million, or a unit cost of £25/t CDE.

This simple analysis using order-of-magnitude figures reveals that this is a rather costly greenhouse abatement option, by comparison with the options illustrated in Figure 4 but has a significant potential for reducing greenhouse gas emissions. It serves to illustrate, moreover, the principle whereby direct comparison of the cost-effectiveness of different options for reducing emissions of all of the greenhouse gases can be made on an equitable basis. Clearly, the analysis can be extended to incorporate other CH_4 sources, such as landfill sites, organic residues and agriculture, and indeed emissions of other greenhouse gases such as nitrogen oxides and CFCs.

Concluding remarks

The work described in this paper has been carried out using well-established assessments, largely from

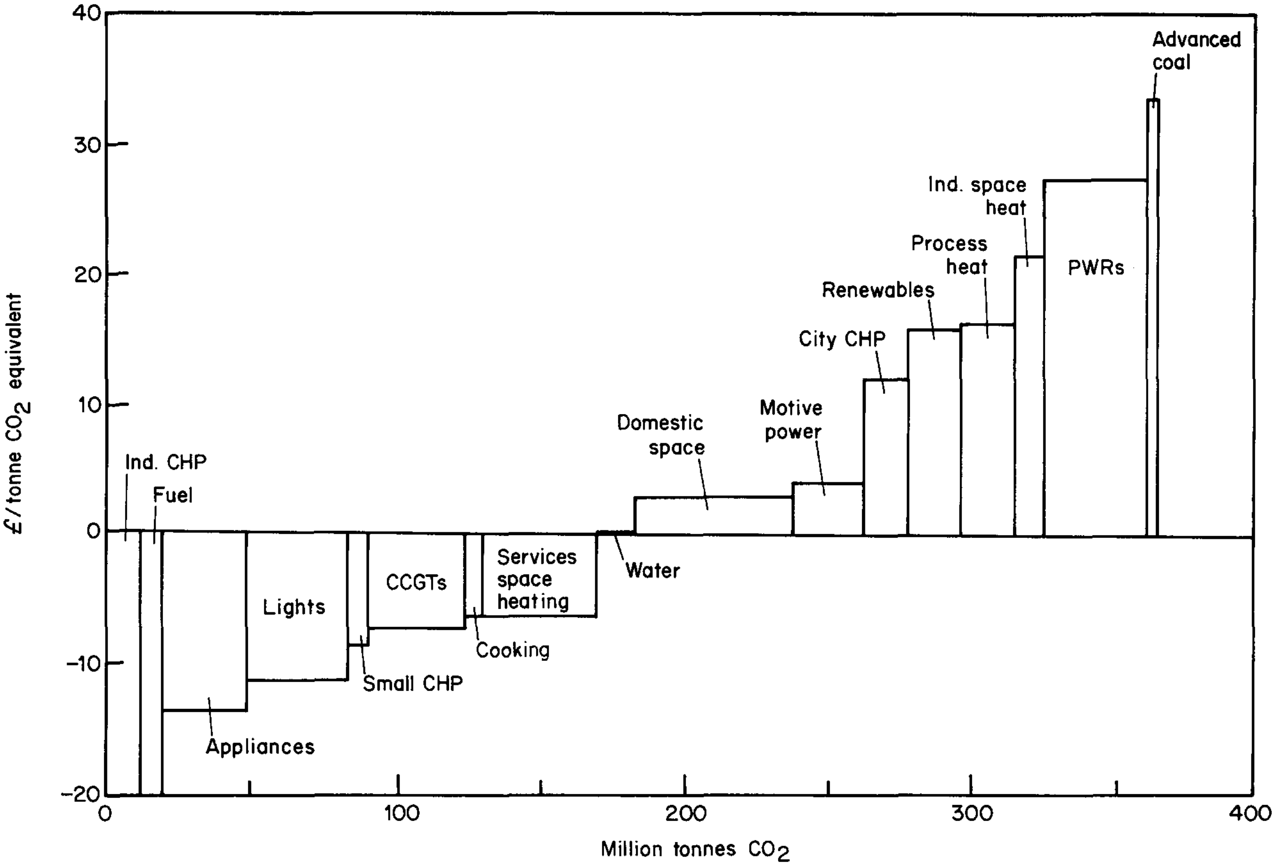

Figure 7. CO_2-equivalent savings curve (high leakage).

government departments, of the costs and potentials for the various measures. No assumptions of technological advance or improved economies of scale in energy efficiency measures have been made. In the event that such improvements become viable, as they surely must do, the analysis made here would weigh even more greatly in favour of the conservation options.

The analysis carried out here has been coarse-grained in another sense which is unfavourable to the energy-efficiency options. Assessments of the potential have been made on the basis of estimates of cost-effectiveness appropriate to largely private sector investments. Strictly speaking, this usage is to put the cart before the horse. The proper way of proceeding would be to assess the *technical* potential against cost, *without regard for cost-effectiveness*. A marginal savings cost curve could then be produced which included increasing potential from each conservation option as a function of cost. Judgements of cost-effectiveness (in terms of resource allocation) should then be made on the basis of the marginal savings cost curve so produced. Such a progression could only improve the assessment of the demand-side options.

Despite the limitations of the analysis, the methodology described here seems to present a useful way of prioritizing investments in greenhouse abatement. It indicates immediately that the construction of nuclear power stations represents a serious misallocation of resources in any *bona fide* attempt to ameliorate global warming. Generally speaking, demand-side measures are to be preferred, and such measures offer significant potential for CO_2 (or CO_2 equivalent) reduction.

Throughout the analysis, I have assumed that the same fixed discount rate applies to all technologies. In practice it is well-known that private sector discount rates are generally higher than public sector rates. Individual investor rates may be higher than utility rates, and social discount rates are widely variant, depending on wealth, class, social habits, expectations and outlook. It is largely these variances in effective discount rate which have been responsible for the relatively slow uptake of energy-efficient technologies in the market.

For the purposes of this study, in which I am assessing the efficient allocation of economic resources to achieve a common social, environmental goal, the appropriate comparison is evidently under financial conditions which reflect as far as possible the cost to national resources, rather than the fragmented interests and financial criteria of many different lobbies.

Having identified the most cost-effective measures on this equitable basis, it is then a matter of policy and institutional infrastructure to ensure that these optimal strategies are chosen. It may be that in order to achieve the optimal stratgegy some changes in infrastructure, policy and regulation, will be necessary. At the moment it is not easy to predict what those changes might entail. Intervention in the market is likely to be necessary to ensure that the optimal strategies identified under the assumptions of equatible investment criteria as I have outlined above are implemented. Such intervention could take a number of different forms including the imposition of carbon taxes, efficiency subsidies, investment incentives, appliance labelling, building standards, or regulatory constraints.[27] How best to decide which particular form such intervention should take is a matter for ongoing work and considerable debate.[28]

Some of the work presented in this paper was originally carried out on behalf of Friends of the Earth UK and presented as evidence (FoE 10) to the Hinkley Point Inquiry in June 1989. At that time I was working for Earth Resources Research, and I am grateful for the guidance and support of Mark Barrett and Malcolm Fergusson during that period. I acknowledge also a debt of gratitude to Simon Roberts of Friends of the Earth, and to all those whose comments were invaluable in refining earlier drafts of the work including: Brenda Boardman, Stewart Boyle, Ian Brown, Michael Harper, Gerald Leach, and Lord Silsoe. All the mistakes are mine.

[1] Working Group 1, IPCC, *Policy Makers Summary*, Bracknell, UK, 1990.

[2] *The Changing Atmosphere: Implications for Global Security*, Conference Statement, Toronto, Canada, June 1988.

[3] *Escaping the Heat Trap – an NGO Statement of Policies to Prevent Climate Change*, Climate and Development Congress, Hamburg, November 1988.

[4] Ministry of Housing, Physical Planning and Environment, *Highlights of the Dutch National Environment Policy Plan*, The Hague, the Netherlands, 1989.

[5] For a fuller discussion see M. Grubb, *The Greenhouse Effect: Negotiating Targets*, Royal Institute of International Affairs, London, UK, 1989.

[6] Many observers have explicitly called for such an approach. See for example: B. Keepin and G. Kats, 'Greenhouse warming: comparative analysis of nuclear and efficiency abatement strategies', *Energy Policy*, Vol 16, No 6, December 1988, pp 538–561; B. Dale, 'Abatement of greenhouse gases in the UK', ETSU paper to the OECD experts seminar in Paris, November 1989; E. Barbier and D. Pearce, 'Thinking economically about climate change', *Energy Policy*, Vol 18, No 1, January/February 1990; pp 11–18; D. Lashof and D. Ahuja, 'Relative global warming potentials of greenhouse gas emissions', *Nature*, Vol 344, 1990, pp 529–531.

[7] The clean-up of sites already contaminated with toxic waste is one example; the prevention of further pollution from toxic wastes still being generated is another.

[8] It should also be mentioned that demand can be reduced by lifestyle changes, in other words by reducing the demand for energy services, as well as by supplying the demand more efficiently. The present paper does not investigate this possibility, however. It assumes that the demand for services is met. The economic growth rates assumed for the analysis lie towards the middle of the range of those assumed within the EEO reports.

[9] See, for instance, Rocky Mountain Institute, *Advanced Electricity Saving Technologies and the South Texas Project*, Colorado, CO, USA, 1986; The Alliance to Save Energy, *Designing and Evaluating Demand Side Management Rebate Programs: Analytical Tools and Case Study Application*, Washington DC, USA, 1988; Ontario Ministry of Energy, *Electricity Conservation: Supply Curves for Ontario*, Ottawa, Canada, 1987.

[10] Strictly speaking a fully dynamic modelling exercise could reveal some subtleties that will not emerge from the 'snap-shot year' approach adopted here. One of the limitations which should properly be taken into account in a fully dynamic model, is that the costs associated with each aggregated abatement option have been assumed to be constant. In fact, it is likely, particularly for end-use options, that each technology 'block' in the supply curve, will have a profile which is non-rectilinear. A more sophisticated analysis might reveal a 'blurring' of the dividing lines between the different abatement options, and provide a kind of 'mix-and-match' picture of cost-effectiveness: there might be different tranches of energy-efficient lighting for instance at different costs, some more expensive, some less expensive than certain energy-efficient appliances, say. Generally speaking, for energy efficiency, I have attempted to overcome this limitation by adopting a cost for each technology which is the highest estimated cost for that particular penetration of the technology. The problem is less acute for supply-side technologies.

[11] D. Olivier *et al*, *Energy Efficient Futures*, Earth Resources Research, London, UK, 1983.

[12] *Energy Use and Energy Efficiency in UK Manufacturing Industry up to the Year 2000*, Vol 3, in the Energy Efficiency Series (EEO3), Energy Efficiency Office, HMSO, London, UK, 1984; *Energy Use and Energy Efficiency in UK Commercial and Public Buildings up to the Year 2000*, Vol 6 in the Energy Efficiency Series (EEO6), Energy Efficiency Office, HMSO, London, UK, 1988; *Energy Use and Energy Efficiency in the UK Domestic Sector up to the Year 2010*, draft report to be published.

[13] *Medium and Long-term Load Estimates: Methodology and Forecasts*, CEGB, London, UK, April 1988.

[14] This year has been chosen as being roughly in line with targets for reduction and stabilization of emissions commonly discussed.

[15] This estimate is slightly lower than some others, because it is based on delivered fuel and excludes fuel consumed within the fuel supply industries.

[16] Since this represents a likely 'worst-case' from the point of view of CO_2 emissions.

[17] T. Jackson, *The Technical and Economic Comparison of Non-Fossil Fuelled Electricity Supply Options*, COLA 13 (Evidence to the Hinkley Point Inquiry on behalf of the Coalition of Opposing Local Authorities, Somerset, 1988); A. Morrow, *Plant Requirement and Selection*, COLA 6 and 7; see also *Prospects for Advanced Coal Technology*, Energy Paper 56, Department of Energy, HMSO, London, UK, 1988.

[18] See for instance a number of papers in *Energy Policy Implications of the Greenhouse Effect: Memoranda of Evidence*, House of Commons Energy Committee, HMSO, London, UK, February 1989; see also G. Leach and Z. Nowak, *Cutting Carbon Dioxide Emissions from Poland and the United Kingdom*, Stockholm Environment Institute, Stockholm, Sweden, 1990; and *Carbon Emission Control Strategies: Case Studies in International Cooperation*, World Wildlife Fund and the Conservation Foundation,

Maryland, USA, 1990.

[19] C. Mitchell, J. Sweet and T. Jackson, 'A study of leakage from the UK natural gas distribution system', *Energy Policy*, Vol 18, No 9, November 1990, pp 809–818.

[20] See, for example, Lashof and Ahuja, *op cit*, Ref 6.

[21] The IPCC estimate is 63 over a 20-year time horizon.

[22] The IPCC estimate is 21 over a 100-year time horizon and 9 over a 500-year time horizon.

[23] See Mitchell, Sweet and Jackson, *op cit*, Ref 19.

[24] The leakage rates for new small-scale supplies in the medium and high cases are slightly lower than the medium and high estimates in Mitchell, Sweet and Jackson, *op cit*, Ref 19. This is because we are considering marginal leakage from new supplies rather than existing leakage on the system.

[25] *Ibid.*

[26] As an illustrative cost, this is likely to be a significant underestimate.

[27] Some examples of appropriate policy initiatives are detailed in T. Jackson and S. Roberts, *Getting out of the Greenhouse*, Friends of the Earth, London, UK, 1989.

[28] It is perhaps worth remarking that social concerns may need to play some part in constraining policy options based on pure cost-effectiveness. Macro-economic implications of this microeconomic analysis include potentially damaging impacts on the coal-mining industry and communities. A broader policymaking framework would need to take account of these.

Appendix

Table 1. Data for Figure 4: CO_2-equivalent abatement (no CH_4 leakage).

Abatement option	**Cost-effective potential (PJ)**	**CO_2 savings (mt)**	**Marginal cost (£/t)**
Fuel-switching	40.50	8.07	−19.87
Appliances	104.24	25.97	−14.89
Industrial CHP	70.96	20.80	−13.02
Lighting	131.34	32.72	−12.38
Small-scale CHP	31.54	6.89	−8.43
Cooking	37.69	4.05	−8.18
Services space heating	337.39	31.63	−8.02
Gas turbines	236.52	35.28	−7.08
Water heating	123.86	8.63	0.08
Industrial motive power	92.00	22.92	4.07
Domestic space heating	562.72	34.69	4.18
City-wide CHP	61.50	12.17	14.49
Renewables	69.38	17.29	17.21
Process heat	328.77	15.44	19.68
Industrial space heating	111.11	7.77	27.79
Nuclear	133.40	33.24	30.01
Advanced coal technology	102.49	3.19	36.73

Table 2. Data for Figure 5: CO_2-equivalent abatement (CH_4 leakage: low case).

Abatement option	**Cost-effective potential (PJ)**	**CO_2 savings (mt)**	**Marginal cost (£/t)**
Fuel-switching	40.50	8.73	−18.36
Appliances	104.24	28.43	−13.60
Industrial CHP	70.96	20.96	−12.92
Lighting	131.34	35.82	−11.31
Small-scale CHP	31.54	7.42	−7.83
Cooking	37.69	4.32	−7.67
Services space heating	337.39	34.16	−7.42
Gas turbines	236.52	37.46	−6.67
Water heating	123.86	9.79	0.07
Domestic space heating	562.72	40.32	3.60
Industrial motive power	92.00	25.09	3.72
City-wide CHP	61.50	13.43	13.12
Renewables	69.38	18.92	15.73
Process heat	328.77	16.85	18.03
Industrial space heating	111.11	8.74	24.72
Nuclear	133.40	36.38	27.42
Advanced coal technology	102.49	3.49	33.56

Table 3. Data for Figure 6: CO_2-equivalent abatement (CH_4 leakage: medium case).

Abatement option	Cost-effective potential (PJ)	CO_2 savings (mt)	Marginal cost (£/t)
Fuel-switching	40.50	8.29	−19.34
Industrial CHP	70.96	17.55	−15.43
Appliances	104.24	28.43	−13.60
Lighting	131.34	35.82	−11.31
Small-scale CHP	31.54	7.19	−8.08
Cooking	37.69	4.62	−7.17
Gas turbines	236.52	35.74	−6.99
Services space heating	337.39	36.43	−6.96
Water heating	123.86	10.90	0.06
Domestic space heating	562.72	45.77	3.17
Industrial motive power	92.00	25.09	3.72
City-wide CHP	61.50	13.82	12.75
Renewables	69.38	18.92	15.73
Process heat	328.77	17.55	17.31
Industrial space heating	111.11	9.22	23.44
Nuclear	133.40	36.38	27.42
Advanced coal technology	102.49	3.49	33.56

Table 4. Data for Figure 7: CO_2-equivalent abatement (CH_4 leakage: high case).

Abatement option	Cost-effective potential (PJ)	CO_2 savings (mt)	Marginal cost (£/t)
Industrial CHP	70.96	11.87	−22.80
Fuel-switching	40.50	7.70	−20.82
Appliances	104.24	28.43	−13.60
Lighting	131.34	35.82	−11.31
Small-scale CHP	31.54	6.80	−8.54
Gas turbines	236.52	34.02	−7.34
Cooking	37.69	5.12	−6.47
Services space heating	337.39	40.20	−6.31
Water heating	123.86	12.75	0.05
Domestic space heating	562.72	54.87	2.65
Industrial motive power	92.00	25.09	3.72
City-wide CHP	61.50	14.79	11.91
Renewables	69.38	18.92	15.73
Process heat	328.77	18.71	16.23
Industrial space heating	111.11	10.01	21.57
Nuclear	133.40	36.38	27.42
Advanced coal technology	102.49	3.49	33.56