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FOSSIL FUELS AND CLIMATE PROTECTION: THE CARBON LOGIC

GREENPEACE INTERNATIONAL

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Fossil Fuels and Climate Protection: The Carbon Logic

Summary

The following document is based upon an extensive technical evaluation published by Greenpeace International entitled *Fossil Fuels and Climate Protection: the Carbon Logic*. The major findings of this report are summarised here. A carbon budget for the period to 2100 has been calculated on the basis of a set of defined ecological targets: to limit the long term (that is, beyond 2100) global temperature rise to 1°C above pre-industrial levels, to limit global sea-level rise to 20 cm above 1990 levels, to reduce the rate of global warming and sea-level rise to below 0.1°C per decade and 20 mm per decade respectively. These targets have been derived on the basis of restricting ecological damage due to global temperature rise to a notional acceptable or manageable level. Based on these calculations, with action to arrest deforestation and to implement replanting of forests, the global budget of fossil fuel consumption can be calculated at 225 billion tonnes of carbon plus or minus 50 per cent. This figure contrasts with estimates of fossil fuel consumption based on a 'business as usual scenario' without regulatory action to control carbon dioxide emissions, which projects emissions of 1400 billion tonnes of carbon to the year 2100.

Clearly, restricting fossil fuel use to this level has far reaching implications for the management and development of the energy industries, and for changes in the use and consumption patterns of fossil fuels. It is concluded that policy should concentrate upon the rapid reduction of carbon dioxide emissions beyond currently favoured policy targets. This can be achieved by a balance of energy conservation and efficiency measures coupled with changes in the use of the energy resource base.

Recommended measures include:

* Phasing out the use of coal, since coal has the highest carbon intensity of the conventional fossil fuels and only a small fraction of known coal reserves can ever be used if emission targets are to be met.

* Transferring subsidies from coal production and use and transfer to renewable energy systems.

* Beginning the phase-out of coal-fired power stations and coal mining.

* Placing significant constraints on the development and exploration of known oil and gas reserves.

* Cancelling plans to expand exploration efforts for oil and gas reserves.

* Ceasing exploration and development of unconventional oil and gas reserves.

* Adopting policies to reduce emissions of carbon dioxide and other greenhouse gases.

Introduction

Human modification of the natural environment is an ancient phenomenon; around 75 per cent of the habitable land on the planet has already been disturbed to some degree by human activities. The Industrial Revolution introduced a period of profound change without parallel in human history. In particular, the increasing use of fossil fuels (coal, oil and natural gas) ushered in an era of intensive industrial activity, in turn creating problems caused by pollution and giving rise to other severe impacts upon natural systems as resources became more intensively exploited. It has become clear with time that impacts of industrial activity extend far beyond the local level to encompass whole regions, and indeed, the whole planet in some cases. It is now known, for example, that persistent chemical pollutants and radioactivity are transported in atmospheric and ocean currents, and are found in areas far remote from their sources. The use of CFCs has resulted in partial destruction of the high level ozone which protects the earth from the effects of damaging ultra violet radiation.

In addition to the manufacture and release of substances with no counterpart in nature, humans have also significantly modified the natural cycling of many substances. Pollution due to the extraction and processing of metals has been recorded since the time of the ancient Greeks, and today human activity is the most important determining factor in the global release of metals. Other natural cycles have been significantly modified by human activity, including the chlorine, sulphur, nitrogen and carbon cycles. Some of these cycles are also being disturbed by deforestation and agricultural practices. The wide-scale burning of fossil fuels for energy supply has directly influenced the carbon and sulphur cycles and has also provided the energy to convert nitrogen and chlorine to other forms, thus also influencing their global cycles.

Greenhouse Gases

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are gases whose natural cycles have been extensively changed by human activity. They all act as 'greenhouse' gases. The atmosphere is relatively transparent to most of the incoming energy from the sun, which heats the surface of the earth. By contrast, energy emitted from the Earth is absorbed by water vapour and the greenhouse gas molecules and retained within the atmosphere. Whilst water vapour is the largest contributor to the effect, this contribution is effectively driven by the effect of other gases in increasing global temperature, which increases water vapour in the atmosphere. The enhancement of the greenhouse effect by human activities is driven by the increase in CO_2, CH_4, N_2O and the addition of industrial gases such as the fluorocarbons, but the contribution of carbon dioxide is of greatest significance. Molecule for molecule, methane and nitrous oxide are more efficient than carbon dioxide at trapping heat energy, but they are present in the atmosphere at very much lower concentrations. The significance of the 'greenhouse' effect for life on Earth has been appreciated since the late 19th century. The trapping of heat by the atmosphere has been very largely responsible for establishing the conditions under which life could actually develop and thrive. Moreover, many of the physical processes which determine climate and weather patterns, such as the circulation of ocean currents and atmosphere, are driven by small temperature differences.

The temperature differences become established as a result of differences in the amount of solar energy reaching the Earth at different latitudes. Carbon dioxide levels in the atmosphere, which were relatively constant until the late 18th century, have increased markedly since the Industrial Revolution as a direct consequence of human activities. From around 280 parts per million volume (ppmv), levels increased by some 30 per cent to reach 358 ppmv in 1994 and over 360 ppmv in 1997. Over half of the 450 billion tonnes of carbon (representing 1647 billion tonnes of carbon dioxide) emitted over the past two centuries remains in the atmosphere. Current emissions are around 7 billion tonnes of carbon a year (25.6 billion tonnes of carbon dioxide.) Atmospheric levels of carbon dioxide will continue to rise unless concerted action is taken to substantially reduce emissions, and thus ultimately stabilise atmospheric carbon dioxide content.

Impacts of Greenhouse Gas Emissions

As the concentration of carbon dioxide in the atmosphere increases, so the amount of heat retained in the lower atmosphere will increases. This, it is predicted, could result in an average warming of the surface of the Earth of between 2.5 °C and 2.9 °C by the year 2100, relative to pre-industrial levels. In historical terms such a change is extremely large, greater in all probability than any following the emergence of the Earth from the last ice age 10,000 years ago. Any increase in temperature of this scale will be accompanied by major climatic changes, although exactly how these global changes will manifest themselves is highly uncertain. It is possible, moreover, that warming could result in changes which will positively reinforce the overall effect. For example, thawing of the tundra regions may release both carbon dioxide and methane into the atmosphere, further increasing the atmospheric concentrations of greenhouse gases further. The role of the oceans as a 'sink' for carbon dioxide is also subject to considerable uncertainty, as are potential impacts on ocean circulation. The ability of the oceans to absorb carbon dioxide could be reduced by changes in ocean circulation, thus reinforcing increased carbon dioxide levels and the subsequent impacts upon regional and global weather and climate patterns.

The most rapid and intense changes are predicted for northern polar regions where the movement of vegetation and climate zones northwards could be equivalent to 1 metre an hour (around 8 kilometres per year), but there are likely to be many changes in temperate and tropical latitudes also. These include expanded desertification, increased frequency of droughts, changes in rainfall and the circulation of the oceans, and a rise in sea level with inundation of island states and productive coastal land. It is likely that there will be changes in the pattern of human and animal diseases too, as vector insects extend their range into higher latitudes and altitudes, resulting in significant loss of life. All are possible and plausible. The influence of shifts in ocean circulation, for example, can be dramatic and damaging as illustrated by documented changes in climate following periodic shifts in the Pacific Ocean circulation (El Niño) recorded in recent years. These changes include substantially increased rainfall in some parts of Latin America and droughts in other parts of the region. Severe droughts have also been observed in southern Africa, Australia and Southeast Asia because of the circulation shift. Indeed, it is possible that the intensity of El Niño events could increase due to the effects of climate change. The fossil record also provides evidence of striking climatic changes in the past associated with relatively small changes in the mean global surface temperature. Gathering current evidence of effects of climate change depends upon eliminating events and trends due to natural variability from the analytical equation. Nonetheless there is evidence that areas of the Arctic have started to warm and of a reduced extent of winter sea ice in Antarctica; both these changes in climate pattern are consistent with a global warming trend.

The question now, therefore, is not one of how to stop climate change due to increases in greenhouse gas concentrations in the atmosphere but of how to prevent dangerous change from occurring. This means ensuring that climate changes are minimised and kept within certain supposedly acceptable limits. This document discusses, in particular, how the emissions of carbon dioxide, the most important of the greenhouse gases, need to be controlled so that there is a reasonable chance that climate can be stabilised at levels which will result in a 'manageable' rate of change. In turn, this implies constraints upon the extraction and use of fossil fuels - that their consumption must be held within a set 'budget'. In short, it is necessary to define a logical set of conditions for the continued use of fossil fuels: The Carbon Logic.

A Carbon Budget and Ecological Targets

In basic terms, the carbon 'budget' is the amount of fossil fuel that can be consumed, taking into account the emission of other greenhouse gases such as methane and nitrous oxide. The budget can be calculated based on a set of defined ecological target conditions. These conditions in turn are designed to limit the magnitude and the rate of climatic change to that which can be tolerated by natural systems. In other words, to accommodate, their ecological limits. The rationale behind this set of ecological conditions and their associated emission scenarios has been extensively discussed and defined in a technical report produced by Greenpeace International. That document, entitled *Fossil Fuels and Climate Protection: the Carbon Logic*, forms the basis for the arguments presented below. The targets represent a much more precautionary approach to global climate change than the 'business as usual' scenario outlined by the Intergovernmental Panel on Climate Change (IPCC). These targets are essentially the same as those proposed by the UN Advisory Group in their conclusions. They represent the minimum constraints necessary and do not in themselves guarantee that there will be no unforeseen changes. Certainly, however, the risk of catastrophic change is likely to be considerably reduced if these targets are adopted.

The Ecological Targets Defined

Specifically, action needs to be taken to limit carbon dioxide emissions so that, as a bare minimum:

a) the long-term global increase in temperature is to be limited to less than 1°C above the pre-industrial global average;

b) the rate of change of global average temperature is to be brought below 0.1°C per decade within a few decades;

c) the long-term rise in sea level above 1990 levels is to be limited to 20 cm or less;

d) the rate of sea-level rise is to be kept below a maximum of 20 mm per decade.

In this context, 'long-term' refers to the period up to and beyond 2100. This may mean that the global mean temperature increase will peak at a higher level than the target before dropping back towards the long-term limit, providing that positive feedbacks do not come into play. For sea-level rise there is a much more significant risk that, even if the target is theoretically able to be met, in reality sea-level could continue to rise due to additional loss of ice from Greenland and Antarctica.

The rationale for this set of ecological targets is broadly as follows. An absolute temperature rise in excess of 1°C may, according to the UN Advisory Group, result in unpredictable changes and high levels of ecosystem damage. Limiting the rate of temperature change to less than 0.1°C per decade would allow most ecosystems to adapt to the various changes that have been forecast. While some damage would still be inevitable, higher rates of change would lead to rapidly increasing risks. Limiting sea-level rise to 20 mm per decade would also, in theory, allow vulnerable ecosystems to adapt to sea-level change to some extent, while the restriction of sea level rise to 20 cm would also protect, to some extent, against ecosystem damage.

There is no guarantee, of course that limiting the future changes to those outlined above will completely avert catastrophic change: the models used to predict climate change are, inevitably, incomplete, and scientific understanding of planetary processes is imperfect. Taken together, these factors result in substantial overall uncertainty. What is certain, however, is that these uncertainties should not be a prescription for inaction. The longer action is delayed the more probable the chance of serious impacts. Conversely, the more extensive the action taken now, the more likely it is that truly catastrophic change can be averted. This is of particular importance given that some current models predict that, whatever the concentration at which carbon dioxide is finally stabilised, the greatest impacts will occur in the first half of the next century. This implies in turn that early action is vital to mitigate the most serious impacts of climate change.

The 'Business-as-Usual' Scenario

The above targets should be seen as representing a notional 'manageable' or 'acceptable' level of impact; in other words, they have a reasonable chance of preventing dangerous climate change. They are not targets for 'no impact' and this makes their comparison with the business-as-usual scenarios calculated by the Intergovernmental Panel on Climate Change (IPCC) highly alarming. The most plausible and realistic of these, the IPCC IS92a scenario, suggests that in the absence of controls carbon dioxide emissions are likely to more than triple from 1990 levels over the next century. They are predicted to reach a cumulative total of around 1400 billion tonnes of carbon due to use of fossil fuels. The likely impact of this is predicted by the IPCC to be a doubling of atmospheric carbon dioxide equivalents sometime between 2030 and 2060. Included in this projection is a calculated CO2 'equivalent' value for the other greenhouse gases. In the IPCC IS92a scenario, the estimated contribution of the other greenhouse gases to overall warming by 2100 is around 24 per cent of that for carbon dioxide, if aerosol emissions are constant. Following other researchers, a similar 'equivalent' figure is used for the purposes of calculation in this document where indicated. For practical purposes, the effect of the other greenhouse gases increased the 1990 carbon dioxide concentration of 355 ppmv to an equivalent concentration of 421 ppmv. At a global level, however, the emission of aerosols to the atmosphere is estimated to reduce warming effects back to a level of 343 ppmv equivalent. The role of aerosols has been ignored in the calculation of the carbon budget to meet long-term temperature and sea-level-rise targets in this document. In the longer term, the influence of aerosols is known to decline much more rapidly (that is, in days and weeks) than that of greenhouse gases (decades to centuries) when their emissions are reduced, hence it is unsafe to use the 'masking' effect of aerosols for policy purposes. Aerosols will however affect the global climate, with their main effects being on the pattern of regional climate change.

The IPCC scenario predicts that absolute carbon dioxide levels will double by 2060, reaching 650-750 ppmv by 2100. The precise change in temperature that will result, and the rate of the change itself, will depend upon a number of factors including, crucially, the sensitivity of the climate.

The sensitivity of the climate is defined as the temperature rise associated with a doubling of carbon dioxide concentrations. The IPCC has estimated the climate sensitivity to lie in the range of 1.5°C-4.5°C with a best-estimate of 2.5°C. However, a higher climate sensitivity of between 3°C and 4°C better fits observed climate changes over the past century. In addition, there is emerging evidence from the fossil record that sensitivity may be in this range. Finally, the most advanced climate models have a sensitivity in the range between 2.1°C and 4.6°C with a median value of 3.7°C. In other words the evidence indicates that the IPCC best-estimate of 2.5°C is too low. Nonetheless it is still used by most governments as a benchmark against which to derive policy measures. It is clear that the assumption of the lower value needs to be urgently revised since impacts at higher values of sensitivity will be greater. Accordingly, since a sensitivity value of 3.5°C is plausible in terms of the scientific evidence, it is considered a prudent minimum value to assume and is used in the calculations outlined here.

Even where the lower value for sensitivity is used, however, IPCC estimates still show that the ecological targets defined above will be exceeded by a very substantial margin. The best-estimate is for a temperature rise between 2.5°C and 2.9°C above the pre-industrial global mean surface temperature by the year 2100. Ultimately, the burning of fossil fuels as projected by the IPCC business-as-usual scenario would commit the globe to a final temperature rise of more than 5°C. Rates of temperature increase, given that estimates of temperature increase from the Industrial Revolution to the present are estimated to be in the range of 0.3-0.6°C, would be in excess of 0.2°C per decade. Over the same period, and for the same emissions and with aerosol emissions constant, sea level could rise between 23 cm and 96 cm (with a best-estimate of 55 cm) and would continue to rise after the year 2100 at a similar rate for many centuries even if carbon dioxide levels were stabilised at that date. Using a higher value of climate sensitivity, the consequences would be even more severe. Other models have shown temperature rises of 3.3°C above pre-industrial levels as a globally averaged figure, with temperatures up to several degrees higher in higher latitudes. The same model suggests that this will threaten the terrestrial vegetation types currently prevalent over 41 per cent of the Earth's land surface. Significantly, this IMAGE model has even lower climate sensitivity than the IPCC best-estimate.

The wide range in the figures estimated for the final temperature increase illustrate the uncertainties inherent in forecasting changes due to increased carbon dioxide

concentrations in the atmosphere and, in particular, the difficulty of incorporating all of the known variables into the analyses. What is clear, however, is that the ecological targets recommended by the UN Advisory Group are likely to be exceeded substantially in the absence of any regulatory action as projected by the IPCC best-estimate. An absolute temperature rise of 2°C compared with pre-industrial levels is regarded as an upper limit beyond which the risks of grave damage to ecosystems and unpredictable responses are expected to increase rapidly. While a maximum sea-level rise of 50 cm above 1990 levels would prevent the complete inundation of some island states, it would result in substantially increased human and ecological impacts from storms. With a temperature rise greater than 2°C, a threshold of major unpredictability in the climate system will be crossed, with a concomitant very high risk of catastrophic consequences.

The Scope for Regulatory Action

Human activity results in the emission of around 7 billion tonnes of carbon annually as carbon dioxide. Of this, in 1990 almost 60 per cent was due to fossil fuel use. For comparative purposes, 1 tonne of carbon equates to 3.7 tonnes of carbon dioxide. The data in Table 1 show the relative importance of the various greenhouse gas sources. From these data, it is apparent that controls upon greenhouse gas emissions can be effected in a number of different sectors with varying degrees of probable ease. The CFCs, HCFCs and related chemicals with a high greenhouse potential are currently being regulated under the terms of the Montreal Protocol, and such emissions can be expected to progressively reduce with time if the Protocol provisions become fully effective and remain so. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluroide (SF_6), all industrially produced gases, are set to increase to significant levels over the next one to two decades unless they are controlled. Agricultural activities also contribute appreciable emissions of greenhouse gases. Undoubtedly changes in agricultural practices, such as reducing the use of inorganic fertilisers, could contribute to emission reductions. Deforestation and land-use changes accounted for some 17 per cent of emissions in 1991. In addition, the loss of forests also reduces the size of the terrestrial carbon dioxide sink. Reversing deforestation, therefore, will not only reduce greenhouse gas emissions but also provide some scope for removing carbon dioxide from the atmosphere.

Table 1 Contribution to 1990 Greenhouse Gas Emissions by Source Category

Total Fossil fuel combustion: electricity, transport, industrial energy and fuel use of which each fuel contributes:	58%
Coal	23%
Oil	23%
Gas	12%
Industrial sources: cement production, adipic acid production (exc. PFCs, HFCs, CFCs and HCFCs)	4%
Agriculture: enteric fermentation, rice paddies. animal waste, cattle and feedlots, cultivated Soils	18%
Deforestation and land use changes	17%
Waste: Domestic and industrial waste, sewage, landfill	3%
	100%

Estimated source of greenhouse gas emissions calculated on the basis of their potential to contribute to global warming over a period of a century. The contribution of gases such as methane and nitrous oxide has been calculated in relation to the greenhouse potential of carbon dioxide.

Clearly, however, the greatest scope for regulatory activity lies within the fossil fuel sector. As noted above, without action to reduce emissions, 1500 billion tonnes of carbon are likely to be released over the next century, of which around 1400 billion tonnes will be due to the use of coal, oil and gas. This represents an addition to atmosphere of between four and ten times the amount of carbon dioxide already added since the first development of the industrialised society. Fossil fuel consumption is a direct and obvious focus for changes in current practice to achieve the mitigation, stabilisation and ultimate reversal of climate change processes.

How Large are Reserves of Fossil Fuels?

A key question in deciding how to address the issue of climate change through regulation of carbon dioxide emissions is the amount of fossil fuels available for burning to provide energy. The IPCC scenarios themselves assume that the share of fossil fuel consumption will change over the next century as increasing reliance is placed upon coal. The precise fuel ratio is of some significance since the different fuels vary in relation to the amount of carbon dioxide that they will emit per unit of energy generated. Coal releases three-quarters as much again carbon per unit of energy generated in comparison to natural gas (that is, 175 per cent), with crude oil releasing one-third as much again. Hence, at any given level of energy consumption, carbon dioxide emissions depend upon the precise proportions of fuels used. For a given production of energy (and assuming that very little natural gas leaks from pipelines), coal is the worst carbon-based fuel and natural gas the best in terms of carbon dioxide emissions.

The IPCC business-as-usual scenario assumes that by 2050 coal will be responsible for 60 per cent of total carbon dioxide emissions with oil responsible for 20 per cent and gas emitting 20 per cent. This compares with the current proportion of around 40 per cent for oil and 40 per cent for coal with the balance made up by natural gas. The projections for the next century are similar to the proportion of fuels in use from the Industrial Revolution through to 1990, where coal dominated as a fuel. Certainly, a return to coal burning is a strong possibility since coal has the largest proven reserves. Are reserves big enough to support the energy consumption projected by the IPCC over the next century? The answer to this question is simply, yes they are.

Here it is necessary to differentiate between 'reserves', which are sources that can be exploited at close to current costs, and 'resources' which are theoretically maximum recoverable sources, including the development of unconventional and currently marginal sources, and including current reserves. The amount of resources is much larger than that of reserves. The process of exploring and developing fossil fuels can be thought of as one of converting a resource, which may not be economically recoverable, to reserves, which are. Over time, technology has tended to make possible the extraction of fossil fuels that previously may have been considered only as resources. An example is deep sea-oil, which is now being economically extracted.

While unconventional gas reserves include coal-bed methane, ultradeep gas reserves and gas in aquifers, the vast resources of gas hydrates are not included. Oil shales, tar sands and heavy crude oil are unconventional oil resources and are more carbon intensive than conventional crude oils. Table 2 shows the currently known economic

reserves and the identified resource base for coal, oil and gas based upon a number of separate estimates.

Table 2 Fossil Fuels: Economic Reserves and Resource Base

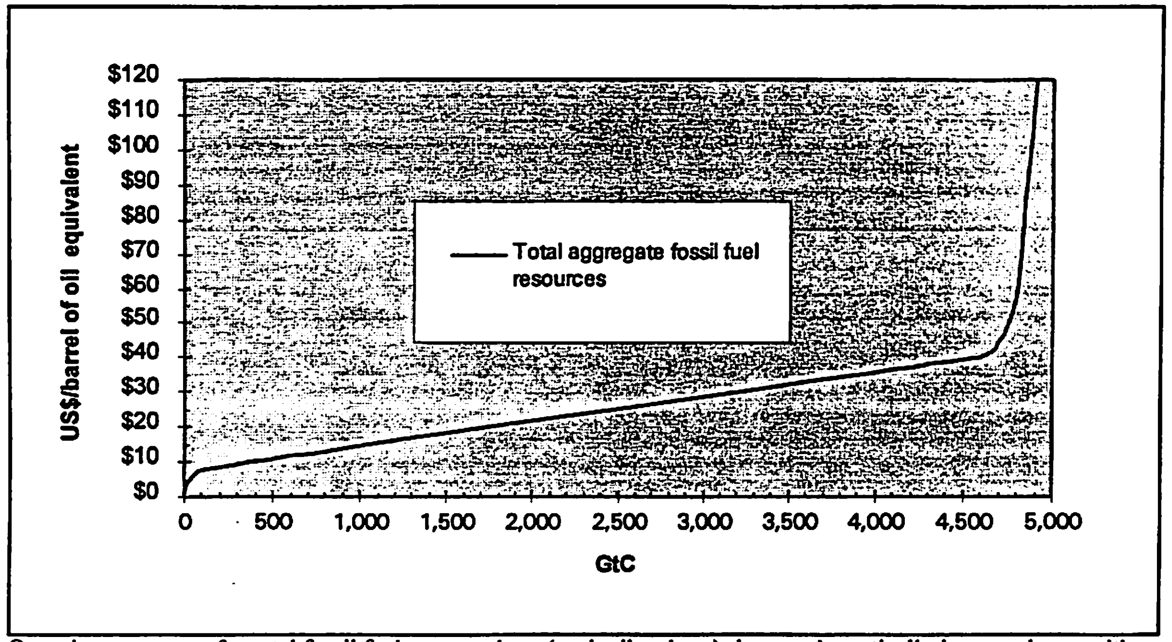
	IPCC 1995 Reserves Identified /Potentials by 2020-2025 GtC	WEC 1993 Conventional reserves GtC	IIASA 1997 Reserves GtC	IPCC 1995 Resource Base Maximum Potentials GtC	WEC 1993 Resource Base Maximum Potentials GtC	IIASA 1997 Resource Base GtC
Gas - conventional	72	69	81	138	133	243
Unconventional gas	103		111	403		260
Oil - conventional	110	114	124	156	167	243
Unconventional oil	130		151	296	497	427
Coal	638	646	1,034	3,173	3,622	3,505
Total	**1,053**	**829**	**1,501**	**4,166**	**4,419**	**4,678**

Economic reserves and resource base for fossil fuels based on a number of different estimates. IPCC 1995,1997: Intergovernmental Panel on Climate Change; WEC 1993: World Energy Council; IIASA 1997: International Institute for Applied Systems Analysis. WEC gives no figures for unconventional gas sources. All figures are in billions of tonnes (gigatonnes, Gt) of carbon. Recent industry figures for oil reserves span the values listed in this Table.

The figures in Table 2 show that reserves of fossil fuels range between 829 and 1501 billion tonnes of carbon depending upon the source of the estimate. Coal predominates with between 638-1034 billion tonnes while oil and gas total 182-205 billion tonnes. Unconventional sources of oil and gas total between 133-262 billion tonnes. Beyond these reserves, the resource base in total is estimated at between 4116-4678 billion tonnes of carbon with oil in excess of 650 billion tonnes and gas accounting for 500 billion tonnes.

On the basis that the IPCC expects around 1400 billion tonnes of carbon to be emitted by fossil fuels over the next century, it is obvious that to meet this scenario substantial quantities of fossil fuels currently listed as resources will need to be capable of exploitation. Notwithstanding assertions that oil will become scarce, there is every reason, based upon the development of the oil industry in the past, to expect that this exploitation will actually take place. The history of the oil industry demonstrates that it has become ever more skilled in developing technology. This is helped by increases in the price of the commodities brought to the markets. Simply stated, higher prices encourage commercialisation of resources, and this process is supported by increased investment in exploration and development. If productivity gains in the industry proceed at historical rates then, ultimately, exploitation of resources will not be limited by prohibitive costs until well beyond the 1400 billion tonnes of carbon utilisation projected by the IPCC. This is illustrated schematically in Figure 1, which shows the cost of developing and exploiting fossil fuel resources, taking into account technological development expressed as the cost of the energy equivalent to a barrel of oil.

Figure 1 IIASA quantity-cost curve for total fossil fuel resource base



Quantity-cost curve for total fossil fuel resource base (coal, oil and gas) shown schematically in accordance with the IIASA analysis conducted in 1996. This takes account of technological development and shows that a considerable proportion of the resource base can be exploited without intolerable increases in cost despite a gradual rise in costs as total exploitation rises. Prices quoted are tied to 1990 prices.

Overall, the data show that fossil fuel resources are not likely to be exhausted at or before the point where the IPCC business-as-usual scenario is fulfilled and the ecological targets outlined above have been exceeded by a very large margin. Indeed, potentially, the resource base could fuel the IPCC scenario some three times over. In addition, economic costs are not likely to prove a significant factor in inhibiting the increased commercialisation of fossil fuel resources. Nor are economic factors likely to restrict the future availability of fossils fuels. They will not, therefore, provide a resolution to the problems of carbon dioxide emissions and associated climate change. Existing reserves coupled with exploitation of a small proportion of existing resources can easily fuel the IPCC business-as-usual model. The implication is that positive changes in policy will be needed to restrict fossil fuel exploitation in order to restrict carbon dioxide emissions due to the consumption of fossil fuels.

How much Fossil Fuel Can We Afford to Burn?

Under the IPCC business-as-usual scenario, the magnitude and rate of temperature change forced by increased carbon dioxide concentrations are well in excess of those that natural systems are thought to be able to accommodate. They are also above the values where unpredictable and seriously damaging changes may occur. Moreover, the reserves of fossil fuels together with estimated resources are more than adequate to enable the IPCC scenario to be fulfilled. The central question then is, simply: How much fossil fuel can we actually afford to burn if the ecological targets defined earlier are to be met?

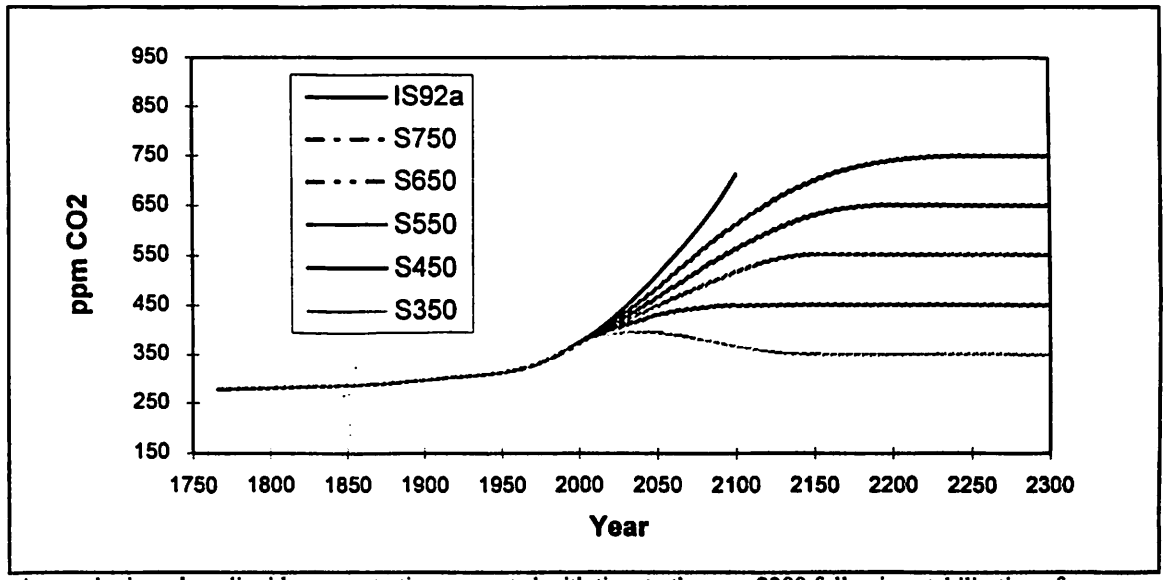
The question can be answered by performing a reverse calculation. Starting with a warming target in degrees Celsius, and then making assumptions as to the climate sensitivity, the relative significance of other greenhouse gases and other technical

matters, the concentration of carbon dioxide which would lead to this level of warming can be calculated. The carbon dioxide concentration level will vary

according the assumptions: the higher the climate sensitivity or the larger the relative role of other greenhouse gases, the lower will be the carbon dioxide concentration corresponding to the warming limit. Having established a carbon dioxide concentration corresponding to the warming limit, it is possible to then calculate a carbon budget that will lead to this carbon dioxide level. The calculation is relatively simple in theory but in practice makes use of the results of complex climate models. It is essentially carried out in two parts. Firstly, what is the concentration of carbon dioxide that would limit change to the targets outlined above? Secondly, how does this translate into allowable emissions of carbon dioxide and hence consumption of fossil fuels. The carbon budget, then, is the amount of fossil fuel that can be burned if the targets are to be met. This is the most useful method of estimation since it allows for the fact that it could take anywhere between several decades and a century for atmospheric temperature to stabilise after actual carbon dioxide concentrations are held to a standstill. At present, for example, only 30-50 per cent of the temperature rise due to carbon dioxide emissions since pre-industrial times has taken place and the planet is thus committed to a further rise in temperature under any but the most drastic emission-reduction regimes over the next few decades. The method also allows the various uncertainties in the sensitivity values, other greenhouse gases and global carbon cycling to be more easily identified and evaluated.

The IPCC has conducted a number of modelling exercises designed to work out what level of emissions would result in a series of chosen stabilised carbon dioxide concentrations. The results of this exercise are shown in the figures below. Figure 2 shows the carbon dioxide concentrations pathways in the atmosphere with time used by the IPCC to stabilise at the various chosen levels of between 350 ppmv and 750 ppmv. Of course, the date at which stabilisation is achieved influences the carbon dioxide levels in the interim, and the various set dates for stabilisation are given in the legend to the Figure.

Figure 2 IPCC CO_2 Concentration stabilization scenarios

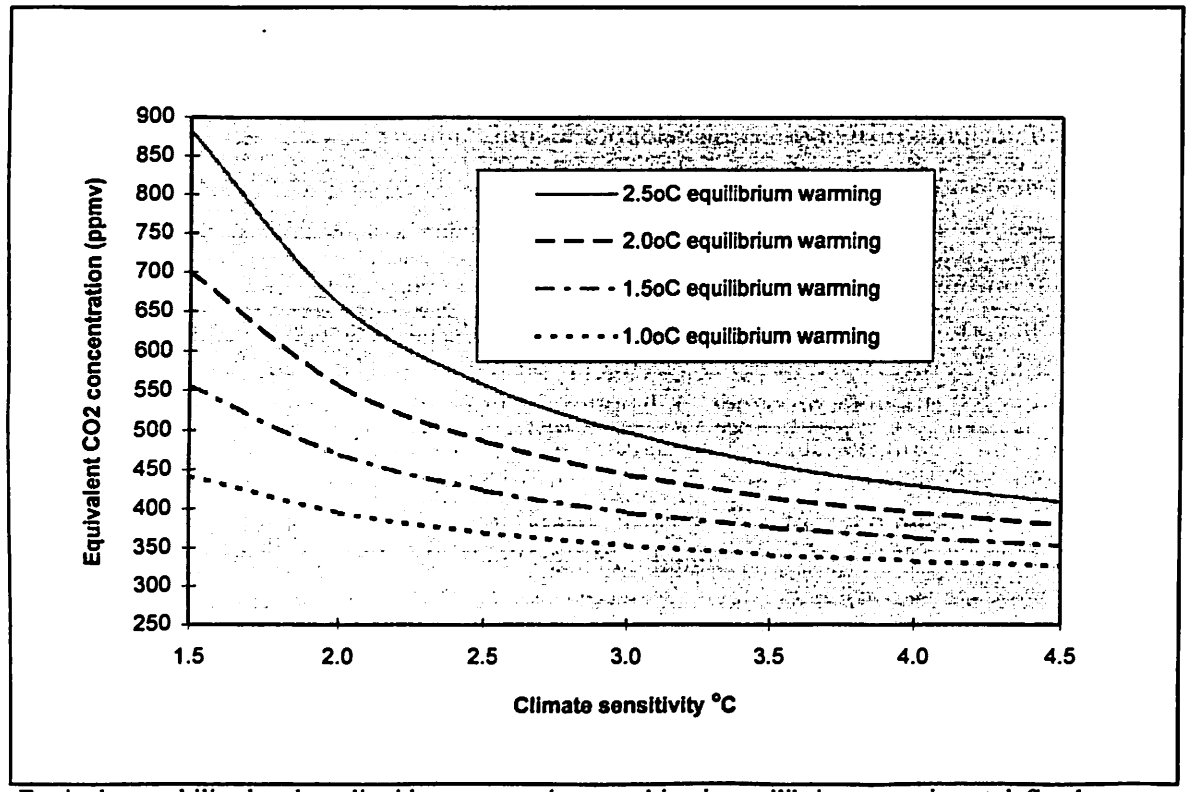


Atmospheric carbon dioxide concentrations expected with time to the year 2300 following stabilisation of concentrations at various set points. S350: 350 ppmv in 2150; S450: 450 ppmv in 2100; S550: 550 ppmv in 2150; S650: 650 ppmv in 2200; S750: 750 ppmv in 2250.

Whilst different concentration trajectories can be chosen, for a given stabilisation levels different pathways produce similar carbon budgets. There is a regular relationship between a concentration level and the corresponding carbon budgets. This kind of information can be used to calculate the carbon budgets for the carbon dioxide concentrations corresponding to the temperature limits. Finally, as a check, further modelling exercises using simple climate models can be done using the calculated budgets to estimate the actual impact in terms of long-term temperature and sea-level rise.

Figure 3 shows equivalent carbon dioxide concentrations (that is, including the effects of other greenhouse gases), resulting in a given long-term temperature rise at a particular climate sensitivity. Using the sensitivity value of 3.5°C, it is clear that the scenario of temperature stabilisation at around 1°C above pre-industrial levels involves stabilising actual carbon dioxide at below current levels and below the lowest IPCC scenario of 350 ppmv. This does not in itself, however, provide an adequate protection unless it is explicitly tied to provisions for limiting the rate of change and hence the rate of change of associated climate change.

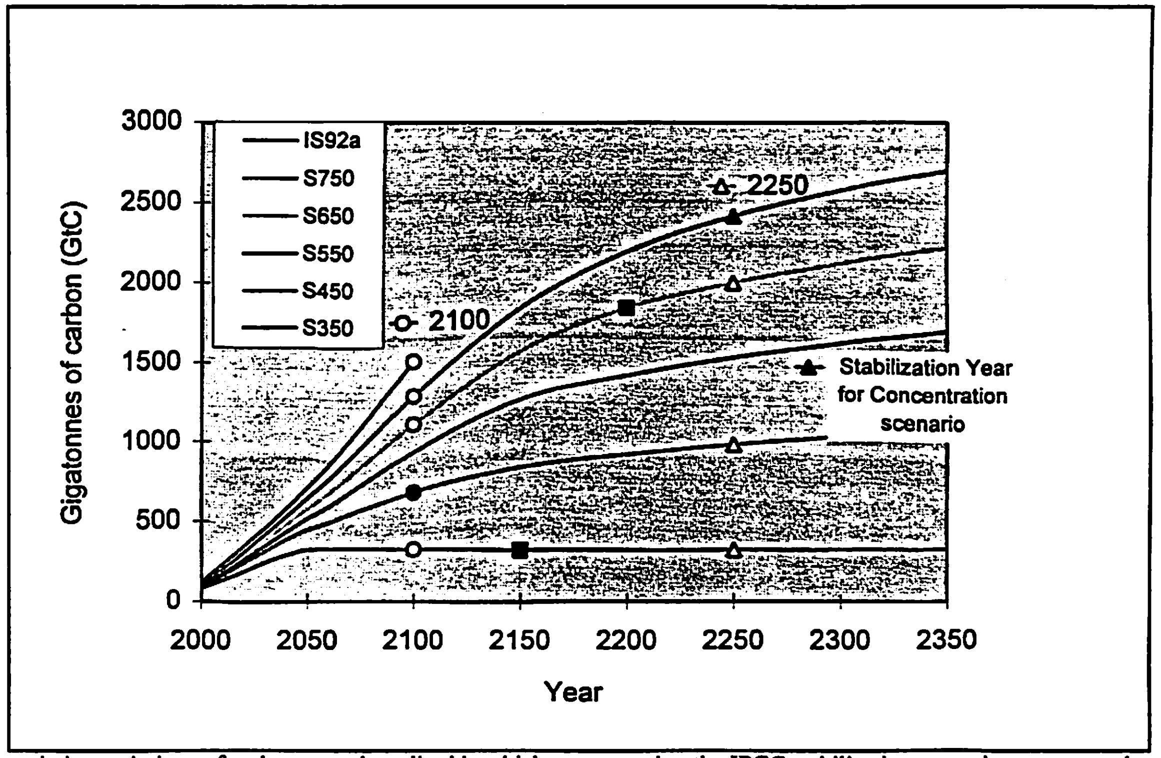
Figure 3 Equivalent CO_2 stabilization levels for temperature targets vs. climate sensitivity



Equivalent stabilised carbon dioxide concentrations resulting in equilibrium warming at defined temperatures. To limit warming to 1°C, equivalent carbon dioxide levels must be stabilised at below 350 ppmv.

Finally, the amount of carbon that we can afford to burn in the form of fossil fuels can be estimated for each of the scenarios as shown in Figure 4. These data indicate that to stabilise carbon dioxide concentrations at 350 ppmv it will only be possible to emit around 250 billion tonnes of carbon. This figure must include the impacts of deforestation, which modifies that quantity to even lower levels.

Figure 4 Cumulative carbon budget for CO_2 stabilization scenarios



mulative emissions of carbon as carbon dioxide which correspond to the IPCC stabilisation scenarios represented in Figure 3. This covers the period 2000-2350 and in each case, the black point on the curve indicates the date at which stable CO2 levels are achieved.

When the effects of deforestation are incorporated, and using a sensitivity value of 3.5°C, it is possible to arrive at a more refined value for the carbon budget and an amount of carbon that can be emitted over the next century. Even so, it must be recognised that, due to uncertainties in the climate sensitivity, in the role of other gases and in carbon cycle models, there are uncertainties of the order of 50 per cent in the values derived for stabilisation of temperature. (When calculating a carbon budget corresponding to final stable carbon dioxide levels, the uncertainties are much smaller, of the order of 15 per cent.) The carbon budget values for the temperature target are as follows:

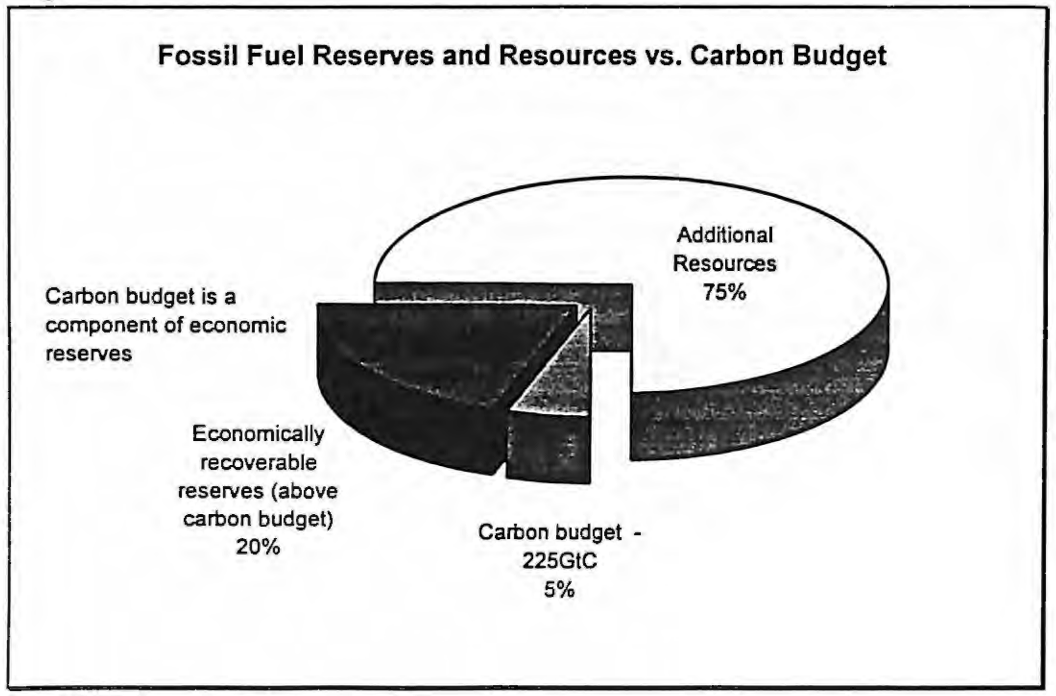
* 145 billion tonnes of carbon if deforestation continues at the present rate.

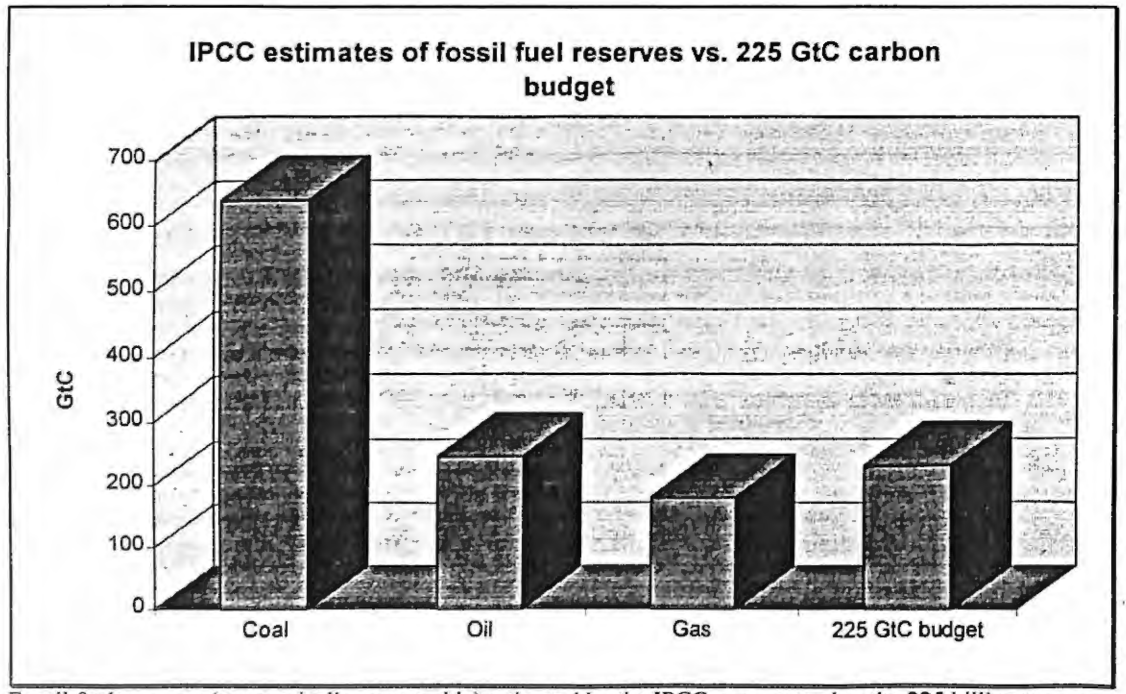
* 225 billion tonnes of carbon with major initiatives to halt the destruction of forests, stabilising them at current levels and starting major regeneration of forests in the next century.

* 270 billion tonnes of carbon, given urgent and extensive action to halt forest destruction and planting enough forests to lock up an extra 40 billion tonnes of carbon.

From the data relating to oil reserves and resources it can be seen that the carbon budget of 225 billion tonnes is around one-quarter of the known reserves and a very small fraction indeed of the total estimated resource base of coal, oil and gas. The sobering implication of this figure is that at current rates of fossil fuel use this budget will be exhausted in less than 40 years. If energy demand continues to grow at the present rate of 2 per cent per year, this budget would last for less than 30 years. Again, logically to meet the ecological targets specified earlier, 75 per cent of the known economically recoverable reserves of conventional fossil fuels can never be used as fuel. This translates, in turn, to 95 per cent of the total estimated resources which cannot be used as fuel. This is shown graphically in Figure 5.

Figure 5

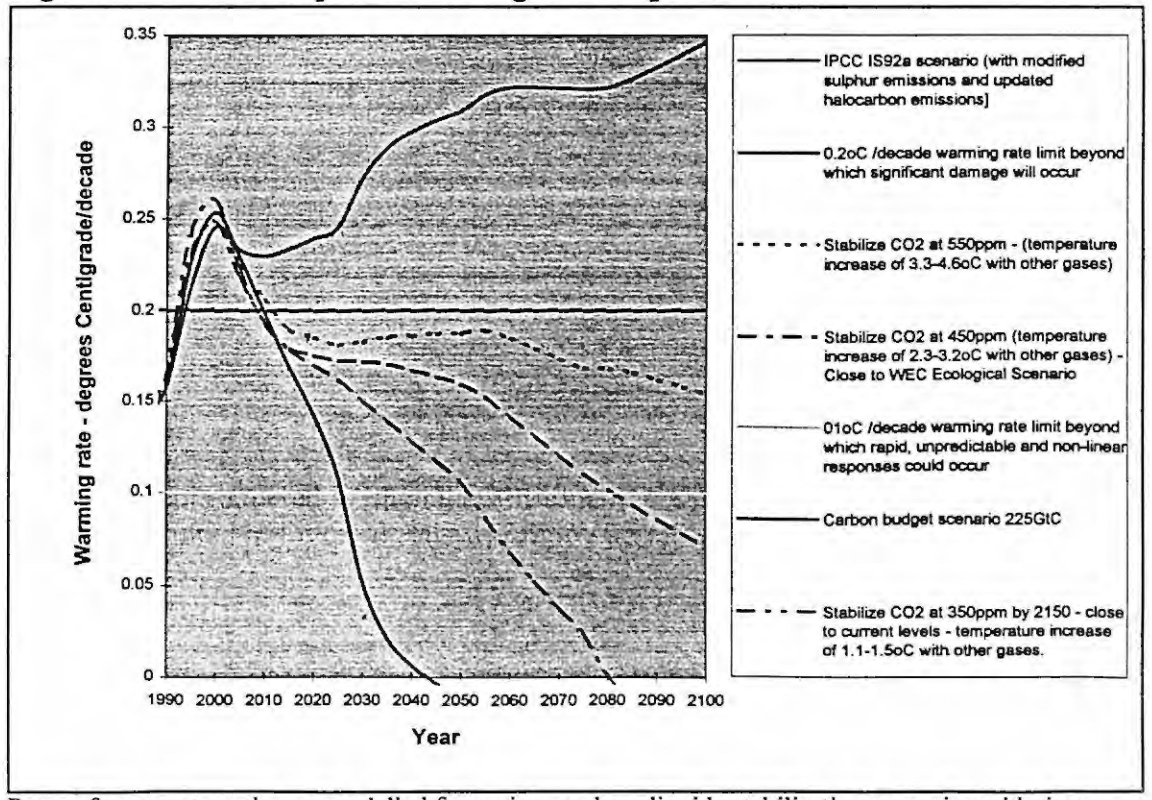




Fossil fuel reserves (economically recoverable) estimated by the IPCC as compared to the 225 billion tonne carbon budget. If all existing reserves are used then the 225 billion tonne budget will be exceeded by a substantial margin. The pie chart shows the 225 billion tonne budget in relation to known resources of fossil fuels.

If this budget is adhered to, then the warming rate will conform to the approximate pattern illustrated in Figure 6. The warming rate falls below 0.1°C per decade before 2030.

Figure 6 Rates of temperature change for CO_2 scenarios

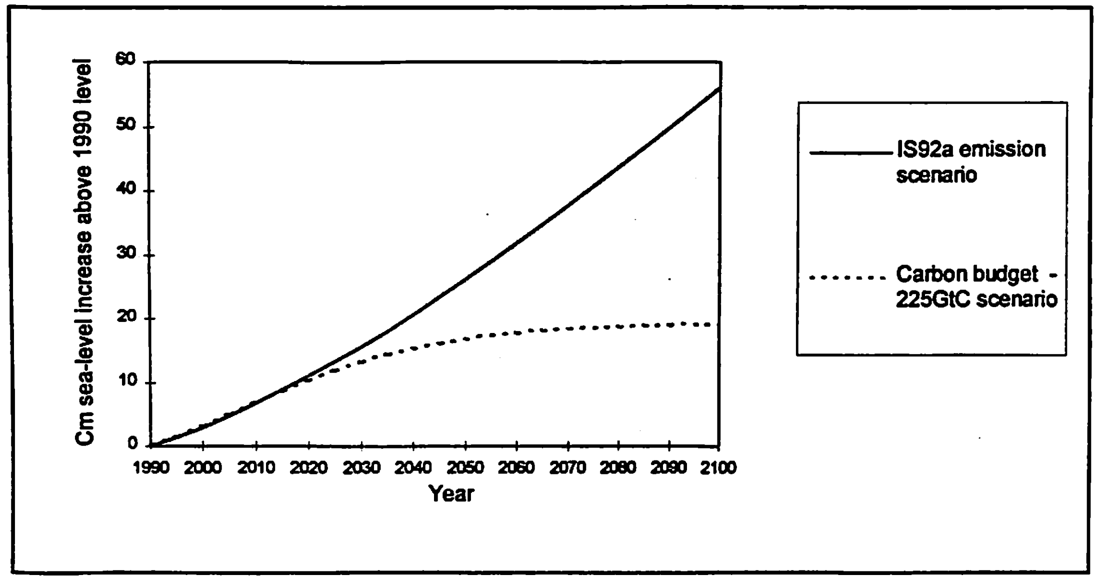


Rates of temperature change modelled for various carbon dioxide stabilisation scenarios with time. Under a carbon budget of 225 billion tonnes, rates of temperature change would fall into line with ecological targets, several decades before stabilisation in the year 2150 as modelled by the IPCC.

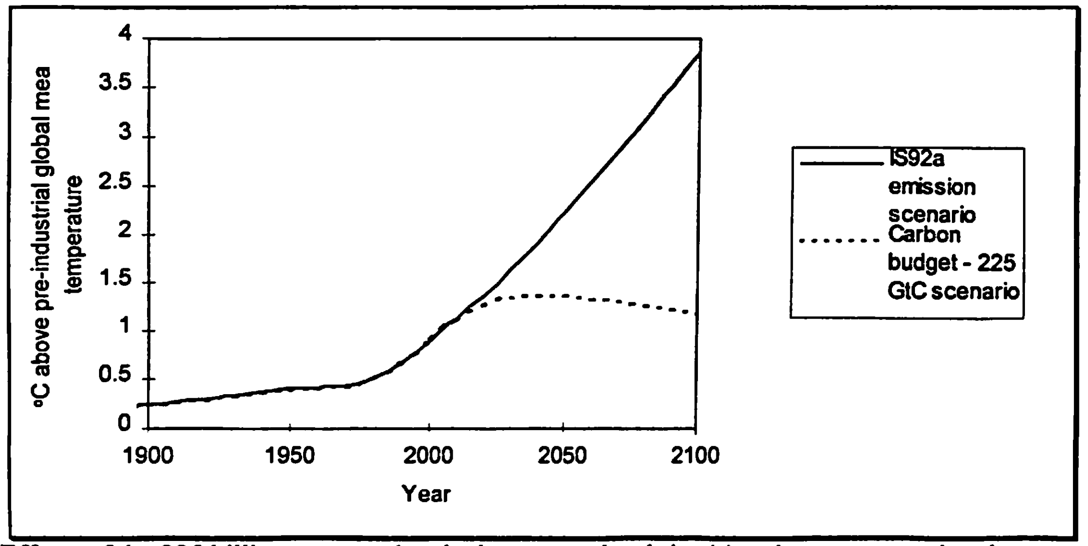
The effect of the 225 billion tonne carbon budget on sea-level rise and long-term temperature commitment are shown in Figure 7.

Figure 7 Sea-level rise and temperature increase for 225 GtC carbon budget

(a) Sea-level rise above 1990 levels



(b) Temperature increase above pre-industrial levels



Effects of the 225 billion tonne carbon budget on sea-level rise (a) and temperature rise above pre-industrial levels (b). This budget enables the ecological targets defined in the text to be met in the requisite period to 2100.

Implications for Emissions Reduction

Obviously, the setting of a carbon budget of this size when compared to the business-as-usual scenario implies the setting of policy measures designed to control emissions and to shape the future structure of the fossil fuel industry. Current scenarios proposed by the European Union of a 2°C long-term permissible temperature rise could clearly lead to severe ecological impacts. This policy decision needs to be revisited urgently. Allowing carbon dioxide levels to double is also clearly out of the question even if climate sensitivity is only 2.5°C. Adhering to the ecological targets means that both the rate and magnitude of carbon emissions needs to be brought under control.

In terms of targeting the rate of emissions, one proposed approach is the 'Safe Emissions Corridor' concept as developed by the IMAGE modelling team. This

suggests that in order to avoid ecologically dangerous climate change industrialised countries will need to reduce carbon emissions by between 30 per cent and 55 per cent by 2010. Even so, their scenario predicts a final sea-level rise of 40-60 cm over the next few centuries, with a 20 cm rise occurring by 2100. The most progressive policies advocate only 20 per cent emission cuts by 2005 based on 1990 levels. If the 225 billion tonne budget was adhered to this would, therefore, imply even larger cuts by 2010 and 2020.

In order to maximise the amount of energy which can be recovered per unit of fossil fuels consumed it will be necessary to utilise only those fuels that are less carbon intensive: oil and gas. Reserves of these fuels are ample to meet future demand. This implies a wholesale reduction in dependence upon coal as a fuel if energy production is to remain at current levels. However, transfer to oil and gas must be regarded as a short-term measure.

Conclusions

On the basis of a set of defined ecological targets designed to limit long-term temperature increase it is possible to calculate the amount of fossil fuel which can be burned to produce energy up to the year 2100. In order to limit the absolute change and the rate at which it occurs, it will be necessary to stabilise atmospheric carbon dioxide concentrations to a final value below current atmospheric levels.

The quantity of fossil fuel burned will have to be restricted to a median figure of 225 billion tonnes of carbon. This is much less than existing resources which are capable of being developed to commercial exploitation. It represents around a quarter of existing reserves and a small fraction of total resources. The greater carbon intensity of coal means that, for a given supply of energy, more carbon dioxide is emitted than from the use of oil and gas, although reserves and resources of coal are predominant. The carbon budget of 225 billion tonnes also relies upon initiatives being taken to halt and reverse deforestation.

Currently, the most progressive policies advocate a reduction in carbon dioxide emissions of 20 per cent by the year 2005. Enacting such policy worldwide is an immediate and vital step if the Earth's climate is to be stabilised, and must be followed by cuts of up to 55 per cent by the year 2010. Failure to meet these emission-reduction targets will increase the risk of severe ecological impacts and climate instability.

In order to meet the ecological targets, therefore, a number of measures are required:

* Phasing out of the use of coal, since coal has the highest carbon intensity of the conventional fossil fuels and only a small fraction of known coal reserves can ever be used if targets are to be met.

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* Transferring subsidies from coal production and use to support renewable energy systems.

* Beginning the phase-out of coal-fired power stations and coal mining.

* Placing significant constraint on the development and exploration of known oil and gas reserves.

* Cancelling plans to expand exploration efforts for oil and gas reserves.

* Ceasing exploration and development of unconventional oil and gas reserves.

* Adopting policies to reduce emissions of CO_2 and other greenhouse gases.